A Systematic Approach to the Design of Embodiment with Application to Bio-Inspired Compliant Legged Robots

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1 Introduction

1.1 Motivation

The development of bio-inspired legged mobile robots has come a long way. Many existing legged mobile robots are capable to master the challenges of real world scenarios today: for example, the outstanding four-legged robot LS3 by Boston dynamics can autonomously follow a person while breaking through very rough terrain for example [1]. Like most mobile state-of-technology robots today, the LS3 follows a design approach based on rigid kinematic chains with stiff actuation.

Bio-inspired elastic legged robots have a highly nonlinear passive dynamic behavior which severely differs from stiff robots. Therefore, widely used control approaches and architectures for stiff robot designs, like a cascade of linear joint position controllers, do not well apply to elastic robots. It is rather important to consider and optimally adjust active and passive dynamic effects as for example elasticity. Without the capability of elastic elements to store and restore energy or passively react to disturbances, for example, the robots have reduced performance and robustness and the remarkable locomotion performance of humans and animals can not be achieved. Moreover to achieve sufficient robustness regarding interactions with the environment, which is required for the application in real world scenarios, the robots must quickly identify and react to disturbances. Therefore, many sophisticated sensors, high power actuators, and fast computers with high clock speed are necessary when applying conventional feedback control schemes. Therefore it is required to apply feedforward control in addition to feedback control in order to coordinate motions sufficiently fast. On the other hand it turns out that limitations that arise from the application of linear controllers lead to a set of constraints regarding the design of the hardware.

The design approach presented in this thesis follows a different design philosophy. Motivated by locomotion of humans and animals, passive mechanical elastic and damping elements are implemented to function as passive position and velocity controllers. Reactions that result from the interaction of the robot hardware with its corresponding environment can be considered as passive control actions therefore. In this concept the influence of the environment to the robot is an integral component of the functional principle of the robot itself, including its hardware, feedback control, and feed forward control. The concept of regarding the situatedness of a robot in physical space with all according implications is known as embodiment [92, 62]. This new approach offers chances in the advancement of legged mobile robot development: By transferring control to well-designed robot-environment interactions utilizing physical effects, the active control effort, which includes the requirements to sensors, actuators, and information processing, can be reduced. Furthermore, the application of elasticity can potentially increase the energy efficiency of the considered robot significantly.

The new approach however also involves some challenges: Robot hardware that follows the embodiment concept has strongly increased complexity when compared to conventionally designed robots. The proper design of the mechanical components therefore is difficult. The central challenge in designing robots which follow the embodiment concept shifts from the design and construction of electronic control loops to the optimal layout of the robot's mechanics and the according passive dynamics and control. An optimally designed embodied robot uses both passive and active control elements to increase efficiency by utilizing physical effects while maintaining versatility granted by active control.

1.2 Contribution

The embodiment concept serves as theoretical background to achieve an approach to efficiently design a legged mobile robot following the design philosophy based on the utilization of passive dynamics and control properties. In [62] Bongard and Pfeifer introduced eight design principles to describe complete embodied agents[1] which are based on observations of intelligent agents, as for example animals. The set of which is therefore well suited to identify and describe an embodied agent. Although the principles offer a detailed analysis and description of embodied agents, a systematic approach to design an embodied agent is still missing to date. Within this thesis Bongard's and Pfeifer's principles are analyzed, assessed, and completed with respect to the application to the design of legged mobile embodied robots. The resulting enhanced principles are then mapped to a state-of-technology development process, which involves a model-based multi-objective optimization. The new approach is referred to as *design of embodiment*.

The design of embodiment approach combines the setup of active and passive control in order to achieve the desired goals of the robot. This is possible by investigating the passive and active control parameters with their respective properties during a set of simulated experiments. Only by considering all involved parameters during robot operation a consistent decision towards a suitable configuration can be achieved. The simultaneous consideration of all desired robot motion goals grants the design of a versatile embodiment and additionally provides insight in the considered system's dynamic coherences as byproduct. It must be considered however, that the presented design of embodiment approach is only a tool in a design process conducted by a instructed engineer: the overall design process is complex and requires additional knowledge regarding the considered problem.

To design an embodied agent according to the design of embodiment approach, an array of steps must be conducted:

- A mathematical representation of robot, relevant environment, and active control must be modeled.
- Parameters must be identified and set up for optimization.
- Multiple design goals must be specified and described as objectives for an optimization process.
- A multi-experiment and multi-objective optimization must be conducted.
- The results of the optimization must be analyzed to setup the robot design accordingly.

In every step the principles of embodiment according to Bongard and Pfeifer must be considered.

To evaluate the presented design of embodiment approach, four example design problems are conducted within this thesis. Among the presented examples two detailed investigations and optimizations of control parameters of the BioBiped2 robot, which is depicted in Figure 1.1, is discussed. The detailed analysis of these examples show, that it is possible to systematically design and set up an embodied agent in the definition of the design principles presented in [62] with the design of embodiment approach. In particular the desired properties in legged robot locomotion can be improved with this approach.

1.3 Structure of this thesis

The remainder of the thesis is structured as follows. To put the presented approach in context, Chapter 2 presents the state of research regarding the two relevant construction and actuation approaches, which are

[1] The term agent is used, when a statement can be applied to human, animal or robot likewise.

Figure 1.1.: The BioBiped1 robot in a real-world environment
Image source: [2] by courtesy of Max Aguilera-Hellweg

designing based on rigid kinematic chains, and designing with highly elastic joint actuation. Furthermore the states of technology in robot embodiment and methodologies for robot design are presented.

The derivation of the design of embodiment concept is discussed in Chapter 3. Here first Pfeifer's and Bongard's principles to design an embodied agent are discussed, assessed, and extended with respect to the design of legged mobile robots. Then these enhanced principles are mapped to a state-of-technology development process.

The in-detail description of this development process is subject of Chapters 4 to 7. Within these chapters emphasis is placed on the special requirements arising from the concept of embodiment and respective approaches for implementation. In Chapter 4 the generation of a mathematical representation of robot, environment, and active control is discussed. Chapter 5 presents typical design goals for legged mobile robots and discusses possible approaches for their mathematical implementation. The design of embodiment approach requires a new classification of parameters to consider the different key properties of active and passive control elements. Chapter 6 presents a new approach to classify the involved parameters based on their relevant properties for system design. Chapter 7 discusses the formulation of a mathematical optimization problem based on the desired model, goals, and parameters. Besides special requirements from the embodiment concept, requirements from the multi-experiment and multi-objective optimization problem arise.

Chapter 8 presents four example design problems with different focus and rising complexity. The example problems are laid out with the design of embodiment approach. Furthermore some of the resulting configurations are compared to results achieved with conventional design approaches or in real-world experiments. A subsequent examination shows, that the resulting configurations of the design of embodiment approach can be considered as embodied agents.

In a final conclusion in Chapter 9 the presented approach and the achieved results are summarized. The chapter is complemented with an outlook on open problems and future challenges.

2 State of research

To put the presented development approach in context to existing approaches, relevant aspects of the state of research are discussed in this chapter. In the first section of this chapter two fundamental design approaches for legged mobile robots are presented. The second section focuses on the state of research regarding the concept of embodiment in the context of robot development. In the third section conventional methodologies for model-based robot design are presented. The chapter concludes with a classification of the new design of embodiment approach with respect to the state of research.

2.1 Design and actuation approaches for legged mobile robots

Legged mobile robots have achieved remarkable results in locomotion. Robots as for example the two-legged humanoids Honda Asimo [75], LOLA [52], or BioBiped [73] feature outstanding motion capabilities, which allow them to perform dynamic locomotion.

When considering actuation approaches for mobile robots, two typical mechanical concepts can be seen in current robot designs: A robot design based on rigid kinematic chains with stiff actuation, and robots designed with highly elastic actuation. The following sections present the pros and cons of these different design approaches. In a concluding classification the presented robot design approaches are considered with respect to their control task distribution.

2.1.1 Robot design based on rigid kinematic chains with stiff actuation

Constructing legged robots based on rigid kinematic chains with stiff actuation is a well established approach. Robots which are constructed following this approach are known to perform dynamically stable walking and even slow running in well known environments. Besides in legged locomotion, this kind of design and actuation approach can be found in most robot manipulators. Tasks for such robots typically comprise the fast and precise processing, measuring, or transportation of work-pieces and assemblies. To allow for control of these robots with common control approaches following assumptions are made [80]:

- The robot is considered as **rigid kinematic chain of links and joints**. The exclusion of significant oscillations or deformations of the links allows for a rigid-body model of the structure. To transfer this theoretical aspect of ideal rigid links to the actual hardware construction, the real robot is constructed to prevent oscillations. This typically results in the usage of relatively high dead load of the rigid links with respect to the load capacity when compared to human or animal limbs.
- The robot is usually **fully actuated** with stiff actuators. In fully actuated mechanical systems, the number of control inputs corresponds to the number of actuated joints. To allow for a convenient and comprehensive control, each joint is driven by an individual actuator. Kinematic dependencies can be excluded by this approach. To allow for mathematical modeling of the robot as kinematic structure, the actuators are considered stiff: They do not have the ability to store or restore energy. A transfer of the model to the real robot is enabled by the application of stiff actuators without inherent physical elasticity.
- To enable sufficiently quick reactions to disturbances, the robot is equipped with sensors to capture the current joint configurations. This joint data must be gathered at a sufficiently **high frequency**.

In a walking motion the sensor information can be used to calculate stability measures, as for example the zero moment point (ZMP [91]), to allow for proper balancing motions.

A suitable actuation and a well known industrial environment assumed, the robot can be controlled very fast and accurately with conventional control approaches. The achievements of robots with a design based on rigid kinematic chain can be observed in many examples from production and automation processes. Even legged mobile robots like ASIMO [33] or LOLA [52] which follow this construction approach, show outstanding performance in locomotion. This approach however, has several restrictions and drawbacks when considering the application in new scenarios as for example unstructured environments.

- **Physical interactions can be dangerous for robot hardware:** High accelerations of robot links with high masses result in high forces which are transferred through the kinematic chain. Especially when it comes to unscheduled contact situations this can result in the damage of the joint actuator or the respective gears. In wanted and/or predicted interactions, the robot link is required to decelerate to sufficiently low velocity in order to protect the joint actuators and gears [29].
- **Limited ability to recover mechanical energy:** Typically stiff actuators do not have the capability to store and restore mechanical energy [64]. During periodic motions which involve contact situations, like legged locomotion, energy is usually completely lost.
- **Low robustness regarding variations in position and time of interactions:** In unstructured scenarios most interactions vary slightly in time and position of contact with respect to the expected setting. This deviation to the expected interaction can often not be sensed and processed sufficiently fast to react properly [64]. In consequence such robots cannot perform e.g.,locomotion over uneven terrain at high speed.

In summary it can be said therefore, that robots which follow a rigid construction approach are well suited for the application in well defined and structured environments. Moreover, established strategies for development and control can be applied. When extending the area of application however to new frontiers including unstructured outdoor environments, rigid robots with stiff actuation are not optimally suited.

2.1.2 Robots designed with highly elastic joint actuation

New areas of application require new concepts of robot design and actuation. The rigid locomotion concept defies any example in nature. Another approach for robots with bio-inspired locomotor systems is based on the utilization of physical effects. By the application of robots in unstructured scenarios, new aspects become important in which rigid robots do not perform optimally as discussed in Section 2.1.1. When targeting robust dynamic locomotion over long distances for example, the rigid approach is not optimally suited due to deficiencies in robustness, versatility, and energy efficiency. The utilization of physical effects however can reduce many drawbacks that occur with rigid robots in these new scenarios:

- Like in rigid robots, the robot is also considered as chain of rigid links and joints. The structure of joints and links already provides inevitable dynamic properties by means of mass and inertia. However, to allow for the occurrence and exploitation of advantageous dynamical effects, elements with elastic or damping properties can be introduced to the robot's structure. Elasticity can be integrated by adding joint elasticity or elastic tendon-like couplings between links and/or joints for example. It allows to recover contact energy, to achieve a potential increase of robustness, and to achieve a reduction of active control effort [62]. The benefits of additional physical effects are discussed in Section 3.1.6 in more detail.

- By the application of closed kinematic chains by means of four-bar or pantograph mechanisms (see Section 4.1.1), it is not required to actuate all existing joints. McGeer even managed to construct passive dynamic walking machines without any additional actuation [56]. By means of such structures complex motions can be generated with simple actuation, while simultaneously increasing the complexity of the robot's hardware. It is also possible to combine the advantages of these kinematic gears with elastic or damping elements. Kinematic couplings in context of passive dynamic walkers are discussed in Section 3.1.3 in more detail.
- Intelligent layout and setup of the robot's hardware can lead to a reduced demand of sensors [64]. The dynamic elements fulfill passive control functions to quickly respond to disturbances. In a well-laid out system, these physical control properties are adjusted in order to achieve the desired reactions.

This fundamentally different approach to robot design leads to different properties in robot operation. All stated fundamental weaknesses of the kinematic design can be prevented by utilizing physical effects:

- **Physical interactions may not be dangerous for the robot hardware:** Instead of a direct coupling of link and actuation, which can lead to damages in the actuator or gears, elastic elements can be installed in series within the drive train. Peak forces that emerge from impacts are filtered by the elastic elements and stress on gears and actuators is reduced [50].
- **Energy can be recovered:** The application of elastic elements in series with the actuation allows not only for the filtering of possible peak forces resulting from interactions, but also for energy saving. Contact energy for example can be stored in the elastic elements as potential energy and re-used to amplify the lift-off motion [73]. This is especially relevant for robots that are autonomous with respect to their energy supply.
- **Increased robustness in variations regarding position and time of interactions:** Physical effects occur instantaneously and are independent on any signal processing delays [64]. Therefore a robot, which is equipped with suitably adjusted physical elements, can react very quickly on disturbances. Especially when considering disturbances that result from walking motions, a fast reaction is required to maintain stability. Therefore, the application of physical elements can increase robustness.

A robot constructed with highly elastic joint actuation can therefore be applicable in unstructured environments more efficiently then its rigid equivalent. However, this design approach also has some drawbacks. It is more difficult to construct and to operate a robot with highly elastic actuation:

- **Challenges in the construction of robots with highly elastic joint actuation:** The implementation of elements with complex dynamic properties increases the complexity of the robot's kinematic and dynamic structure and behavior. Instead of a chain of rigid links, forces are transferred, stored, and damped in-between the links and joints. To achieve an overall increase of the robot's efficiency, a proper layout of the structure is therefore required. Also the additional physical elements increase the number of possibilities to adjust the robot. Not only the kinematic structure of the robot is therefore required to be adjusted properly, but also all additional passive control parameters, which influence the robot's behavior.

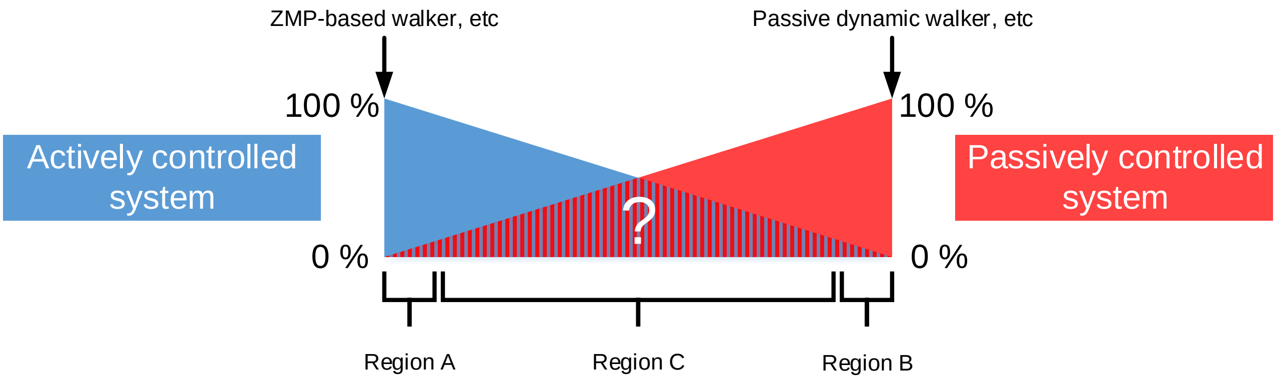


Figure 2.1.: *A graphical representation of possible task distribution between control and mechanical systems in generating behavior. Most of the current robots are driven under the task distribution either around the left or right extremity.* [41]

Image source: own representation based on [41]

In addition the application of physical elements reduces the versatility of the robot by adding mechanical constraints. This reduces the working space of the robot. Although concepts to change properties of spring and damper exist, these elements cannot change their properties without adding even more complexity by means of sensors and actuators to the robot.

- **Challenges in the operation of robots with highly elastic joint actuation:** The additional elements with dynamic properties increase the requirements for control algorithms: The increased complexity of the robot's hardware typically results in a highly non-linear dynamic system. Common linear control approaches can only be applied with workaround solutions, as for example cascade control. Cascade control approaches however have a decreased control frequency with an increasing number of cascades. This leads to a slow reaction to disturbances with more complex systems. A fast reaction to disturbances however is crucial for dynamic motions and fast interactions with real world scenarios. It is therefore required to establish new approaches for the efficient and robust control of robots with highly elastic actuation.

Considering locomotion tasks in unstructured scenarios the advantages of robots with elastic actuation over stiff robots are relevant. The utilization of interactions with the environment allow for a potential increase in robustness, efficiency, and performance. However, the application of robots, which follow this design approach, is challenging because concepts for the construction and the operation are missing.

2.1.3 Classification based on control task distribution

Robots that are constructed following the presented design and actuation approaches can alternatively be classified with respect to their control task distribution. As discussed before, control actions can be performed by the control system (**active control**), or by the mechanical system (**passive control**). Figure 2.1 presents a possible approach to classify existing robots accordingly. The figure depicts three specific regions:

- **Region A**: Robots that belong to this region are controlled by means of conventional control loops, which involve sensor, controller, and actuator. The robot structure in these approaches is mainly based on rigid kinematic chains with stiff actuation as discussed in Section 2.1.1.
- **Region B**: A typical class of robots that belong to region B in Figure 2.1 are the passive dynamic walkers. These robots do typically include no or almost no sensors and actuators. The behavior is therefore controlled only by the interactions between mechanical construction and environment. Although performing dynamic motions, these robots can only be applied in environments with very specific properties and are therefore not suited for application in real world scenarios. Passive dynamic walkers are addressed in more detail within the evaluation of the concept of cheap design in Section 3.1.3.
- **Region C**: Another approach is to construct passive robots with complex and potentially elastic couplings in-between links and joints. Like in passive dynamic walkers interactions with the environment are utilized to passively perform control actions and to reduce the requirements regarding the active control in this approach. In addition active control elements are implemented to guarantee the robustness and versatility of the robot, which is required for the application in real world scenarios. As the detailed analysis in Section 2.1.2 unveils, this robot construction and actuation approach has important properties which are relevant for the desired application of robots in real world scenarios.

The target of this thesis is to evaluate a systematic approach to design and set up legged mobile robots of region C. To achieve this approach, the established embodiment concept from artificial intelligence which describes the control properties of mechanics, is systematically analyzed and applied.

2.2 Embodiment

According to the concept of **embodiment**[1], it is necessary for an intelligent system to have a physical representation in the real world. This allows for another perspective on intelligence: The understanding and combination of symbols is no longer the metric to measure intelligence, but the capability to interact with the constraints given by the environment [15].

This however connects the development of robots with the construction of intelligent systems: A robot always meets the condition of being embodied, rendering it potentially intelligent. Moreover the development of artificial intelligence when following the embodiment concept is always accompanied by the construction of robots. Observations and derived concepts from embodiment research are therefore possible sources for new approaches in the development of robots that interact with the environment.

In the following Section 2.2.1 the embodiment concept with respect to robotics will be discussed. Section 2.2.2 will present state of research methods to apply the embodiment concept to robot development.

2.2.1 Embodiment in robotics

When considering the concept of embodiment, artificial intelligence (AI) belongs to the engineering problem of constructing a robotic system [14]. According to Polani [68] *AI belongs to the realm of*

[1] Within this thesis the term embodiment always refers to **physical** embodiment as described by [92]. According to this definition, an embodied agent is required to have a physical representation in any form, which is capable to interact with the environment.

engineering, and rightly so, because it strives to (construct) intelligent systems. The application of specially designed mechanics is especially relevant in systems with rich interaction with the environment, as these interactions can be utilized as source for passive control actions.

As discussed in Section 2.1.2 the construction of these dynamic legged mobile robots is still very challenging. Conventional development approaches for bio-inspired robots focus either on the actual construction of the robot hardware, or on the layout of (active) control structures. The concept of embodiment presents a new approach, that moves robot development to a combined layout and setup of hardware and control.

Definition 2.1 (Embodied agent)**.**

> Following the definition of **physical embodiment** as described by Ziemke [92] which is also used by Brooks [15] as **physical grounding**, an embodied agent needs to have a physical body of any form. It moreover must be equipped with sensors and actuators to connect to the environment.

Implications of embodiment

The fact of being embodied implies several effects, which are illustrated in Figure 2.2. The figure depicts the three layered structure of interactions of embodied agents observed by Pfeifer et al. in [66], including the information layer, the morphology/body dynamics layer, and the task environment. Interactions in-between the morphology and the task environment as for example movement of the agent result in instantaneous mechanical feedback and physical stimulation of the applied sensors. Moreover, sensors can also be stimulated by the mechanical system itself. In the information layer the sensor signals are processed and suitable motor commands are generated.

These implications of embodiment affect robot operation in several ways. The layered structure as shown in Figure 2.2 leads to a shift of some control processes from the layer of information processing to the morphology layer. The overall behavior of the agent results from a dynamic interplay of morphology, control, and environment [66].

A further implication of embodiment is the resulting interdependency of embodiment, environment, and control: An agent can only operate in its respective ecological niche [34], but is typically an expert in its niche, too.

The implications of embodiment with respect to control properties of mechanical elements have been evaluated within different concepts:

- The exploitation of physical effects by the embodiment can allow to achieve more efficient performance. In the evaluation of hardware experiments with the elastic four-legged walking robot Puppy [64], Pfeifer and Iida evaluated, that instead of increasing the control complexity, the application of embodiment techniques lead to a decrease in control complexity. Puppy is equipped with rigid links and actuators. However, not all degrees of freedom are actuated. As can be seen in Figure 2.3, elastic elements are assembled within every leg to create an elastic pantograph.

  With these elastic elements the robot hardware can implicitly perform control tasks. This utilization of physical elements for motion control is considered as **morphological computation** in [64]. The fast control actions required in interactions with the real world are partially performed by the applied elastic elements. A reduction of the active control effort could be achieved in this example because computation tasks were accomplished by the morphology of the embodied agent. A properly designed agent based on the concept of embodiment therefore can in fact lower the active control effort to perform complex tasks [63].

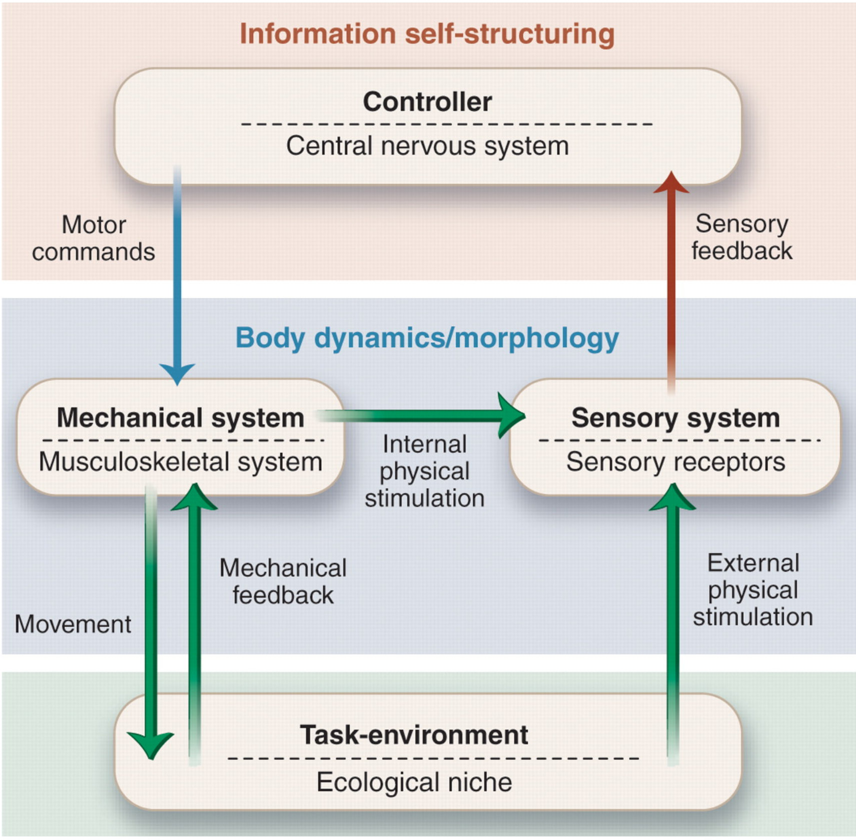


Figure 2.2.: The fact of being embodied implies instantaneous feedback of the task-environment to the morphology of the system resulting from interactions with the environment. The layer of body dynamics also includes the reception of sensor stimuli with respect to the morphology. In a higher level control layer the sensor signals are processed and (feed-forward) motor commands are generated.

Image source: [66]

- In [40] Ishiguro investigates the role of morphological computation in robot control in case studies. He suggests, that *a certain amount of computation should be off-loaded from the control system to the mechanical system.* Performing all control actions by hardware however, as can be seen in passive dynamic walkers, leads to systems with decreased performance, versatility, and robustness. It is therefore important to find a suitable balance of control system and morphological computation.

- The concept to perform motion control tasks by the embodiment is also discussed from the perspective of biology as **intelligence by mechanics** by Blickhan [11]. According to Blickhan, human and animal legs have the ability to stabilize, without sensing the respective disturbance. The structure of the leg therefore provides intelligent control.

2.2.2 Designing morphologies

Currently the concept of embodiment is mostly applied to describe properties of intelligent agents. This section presents state of research approaches to formalize the embodiment concept in order to generate design instructions for intelligent embodied agents.

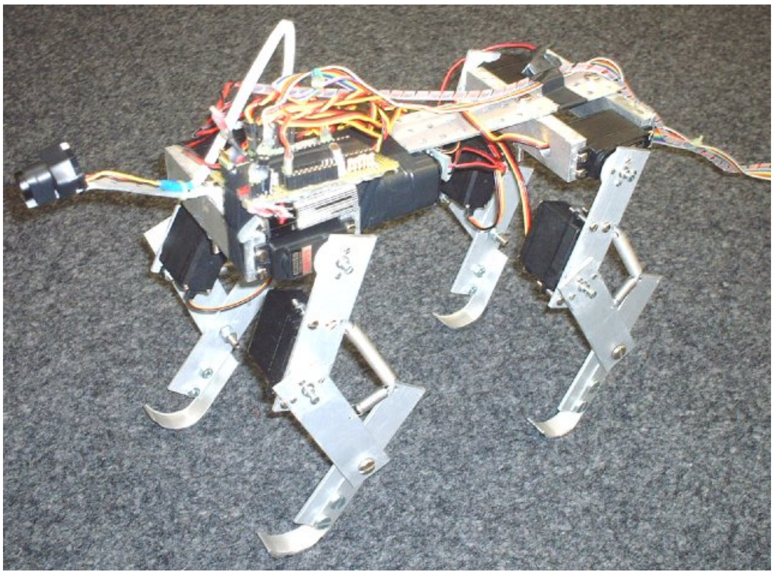


Figure 2.3.: Elastic four-legged robot Puppy

Image source: [59]

Mobiligence project

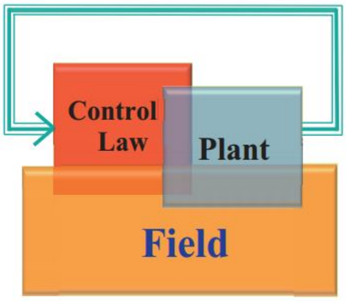
A concept to address the issue of formalization has been initiated by Asama with the **mobiligence project**. Within this project mechanisms regarding locomotion tasks of humans and animals are evaluated to transfer and analyze theories of intelligent adaptive behavior to robotic systems.

According to [60] a relevant requirement for this approach is the **implicit control theory**, which includes the differentiation of **explicit and implicit control laws**. Figure 2.4a depicts the control structure of a creature according to [60]. As can be seen, the control law, the plant, and the field overlap, meaning the control is partly distributed to plant and field. The used notations are equivalent to the notations of the embodiment concept [83]. The term field hereby is equivalent to environment, plant to embodiment and (explicit) control law to active control. As can be seen in Figure 2.4b, the implicit control law is located in-between the explicit control law and the other components of the structure.

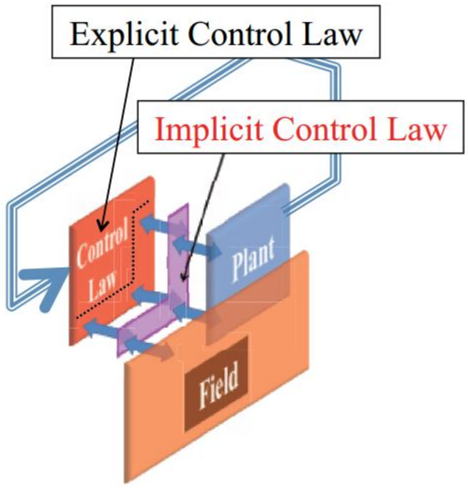
In more detail an implicit control can be found (a) in-between the control and the field (field dependent sub-implicit control law), (b) in-between the control and the plant (plant dependent sub-implicit control law), and (c) in-between all involved components control, field and plant (plant and field dependent sub-implicit control law). The control law which is not performed by plant or field, is addressed by the explicit control law.

The differentiation of the control laws is used to deduce individual feedback control loops for the explicit control law and the three implicit control laws (a), (b), and (c). The ideas given by the mobiligence project are well suited to describe the control of a considered agent. The used differentiation forms a starting point for an eventual formalization of the embodiment concept.

Experiments with the Swiss Robot, the Aggregator Robot and the Coronoc Robot showed, that although only simple explicit control was applied, complex behavior of the robots was observable [83]. For the experiments the simple wheeled robots were required to cluster objects by pushing during forward motion. Even with a simple control law, all of the considered robots were capable to perform the desired clustering. According to [83] the existence of implicit control laws is therefore evident. By means of a detailed analysis of the robot's behavior the origin of the complex control actions could be found and formalized in simple programs.



(a) Control structure of humans and animls



(b) Implicit control law

Figure 2.4.: Figure 2.4a shows the control structure of humans and animals according to [83]. The field is hereby equivalent to the environment, the plant is equivalent to the embodiment of the agent and the control law to the applied information processing from the embodiment concept. Figure 2.4b indicates, that in-between the (explicit) control law and the other components, there exists an implicit control law.

Image source: [83]

The implicit control theory is not designed for the development of complex robots. Instead the concept is suitable to describe the distribution of active control processes within the examined agents. When trying to extract development guidelines from this concept, the differentiation of implicit and explicit control must be elaborated more sharply. No specific strategies are provided to systematically use the detected differentiation between implicit and explicit control laws in the development of robots.

Moreover complex passive dynamic interactions, as for example contacts with the boundaries or the individual behavior of the respective agent were not considered in the defined control laws. The application to the development of legged mobile embodied agents is therefore not easily possible.

Design principles for intelligent embodied agents

Another approach to formalize the embodiment concept is given in [62], where Pfeifer and Bongard present design principles to design an intelligent embodied agent. These principles represent a summary of properties of an embodied agent and are discussed in the present thesis in Chapter 3 in detail.

However, Pfeifer's and Bongard's principles are missing a systematic approach to construct intelligent embodied agents accordingly. According to [71], these ... *principles give some information about general requirements during the design process, but specific strategies for implementing robot control systems are lacking*. Iida, Pfeifer and Seyfarth stated in [38]: *While we still do not fully understand how to design "adaptive mechanics", it is important to note that mechanics is significantly related to motor control and perception, hence navigation and locomotion cannot be independent problems.*

Since the properties of an embodied agent are described by the principles, it is possible to apply them as list of requirements for the development of an embodied agent by implication. Within this thesis the implied technical requirements are extracted from these principles and are applied to a suited development approach.

2.3 Methodologies for robot design

In the present thesis a design approach is evaluated to design and set up an embodied legged mobile robot. For that, principles which describe an embodied agent are applied to an established model based development approach for mechanical structures. In order to identify suitable development approaches for the application, typical conventional approaches are presented in this chapter. These approaches are evaluated regarding the requirements from the principles of embodiment and regarding the requirements from the considered class of robots with highly elastic actuation.

2.3.1 Standardized design methodology for mechatronic systems

To guarantee, that the development process is successful, and the final product corresponds to the desired quality measures, typically the norm ISO 9001 [43] is applied. This norm however is very general and does not provide specific guidelines how to proceed in the design and setup of legged mobile robots with highly elastic joint actuation.

A more detailed approach to design such a robot is described in guideline VDI 2206 [89]. In [16] for example, Buschmann follows this iterative approach to develop the legged robot LOLA. First the hardware properties are achieved from CAD (computer-aided design) data. Afterwards a dynamic simulation is performed to identify the respective dynamic loads. The CAD data is then adapted to meet the requirements. This iteration loop can be terminated once the hardware properties meet the desired requirements. The development is performed intuitively based on results gathered with simulation experiments. By the assessment and a possible re-design of the resulting structure, it is guaranteed, that the final robot corresponds to the design goals.

In a subsequent step, excluded from the hardware design, the joint-angle trajectories are designed. A sophisticated calculation which considers the dynamic properties as well as the current walking parameters of the robot, generates the joint torques for the next three steps of the robot.

The standardized iterative design process has the advantage, that even complex hardware design is possible. By the consideration of additional information, as for example mechanical strength, more specific requirements can be addressed. In the case of mechanical strength, this could include a topology optimization to identify a topology with high stiffness and low weight for example. It is even possible to investigate the hardware behavior with respect to a set of load cases for example, to guarantee the desired versatility of the robot. However this approach has also disadvantages for the design of legged mobile robots. Although the versatility can be considered, possible interdependencies between robot and environment are not regarded. The utilization of interactions of robot and environment is desired to achieve efficient and robust agents. It however requires the consideration of the respective robot during operation. Since only specific load scenarios are considered, but not the effects of physical interactions during operation, the design of an intelligent embodied agent is therefore not easily possible with this conventional approach.

2.3.2 Optimization-based approaches

A further model-based development approach, which can be applied to design a legged mobile robot, is based on optimization, as for example the hardware oriented optimum design process [5]. Also for the design of active control processes optimization-based approaches can be applied, as for example the multi-objective parameter synthesis [28]. The application of this approach requires an engineer to explicitly formulate the optimization variables, suitable objectives, and constraint functions. Sophisticated optimization algorithms can then be applied, to find the optimal solution for the stated problem formulation. This systematical analysis leads to a better understanding of the problem and can therefore help to construct a better system [5] or set up optimal control parameters respectively.

This general approach can easily be applied to all problems, which can be formulated mathematically. Especially it includes the optimal design of multi-body dynamics, which is relevant for this thesis.

A typical optimization-based approach to design an optimal system represented by multi-body dynamics is discussed by Bestle and Eberhard in [20]. Figure 2.5 shows a schematic illustration of this established approach. Three ingredients are required to find the optimal system (top row in Figure 2.5):

- **Model**: The dynamic system needs to be formulated as mathematical model.
- **Objectives**: All design goals must be included in suitable criteria to assess the respective performance.
- **Parameters**: The identified design parameters must be included in the optimization problem as design variables.

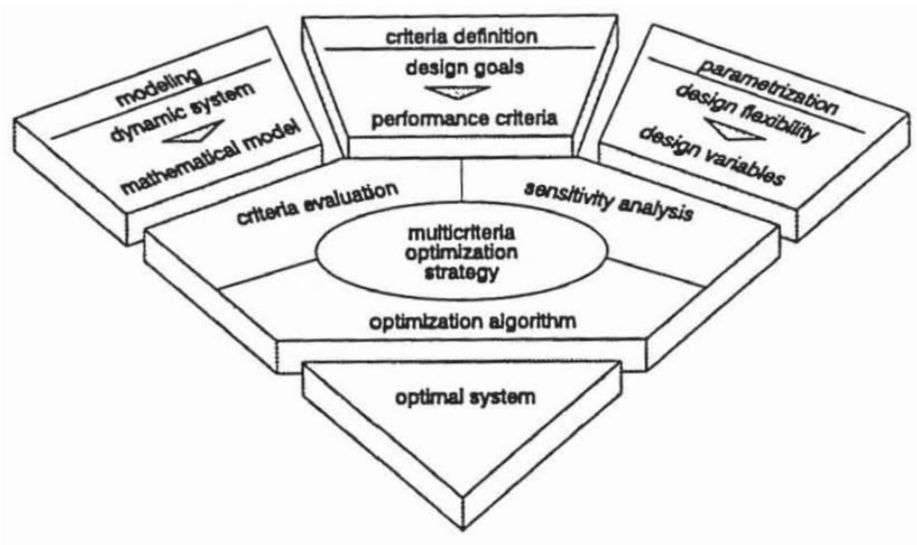


Figure 2.5.: Components of an optimization-based development approach

Image source: [20]

The resulting differential equations are solved numerically. Often it is suitable to perform a sensitivity analysis in order to receive gradient information so more efficient optimization algorithms can be applied. For the consideration of multi-objective problems, additional strategies need to be applied. Besides a simple ranking of the existing solutions, Bestle and Eberhard present approaches to reduce the multi-objective problem to a single objective problem [9]. These approaches include the concepts scalarization and hierarchization.

The optimization-based approach is also suited to design active control [28]. By considering dynamic motion simulations with included parametrized control processes, an optimal design of these can be performed.

However, the optimization-based approach also has disadvantages. It is difficult to formulate the desired motion goals as objectives for optimization. In the conventional iterative approach presented in Section 2.3.1, an explicit formulation of motion goal objectives is not required. The system can be adapted intuitively during each iteration. Moreover in the optimization-based approach the applied dynamic models can be very complex and therefore require long calculation time. Since these calculations typically have to be repeated very often in conventional optimization approaches, the optimum design process can be very time intensive.

Nevertheless, this approach provides all constraints to be applicable for the design of embodiment:

- It is possible to design a **versatile** robot by including multiple objectives.
- The robot can be analyzed **during operation** by implementing a dynamic simulation of the robot in operation.
- **Performance and robustness** during operation can be assessed with sophisticated objectives or motion goals.
- It is possible to include and simultaneously assess parameters for **active and passive control**.

2.4 Classification of new design of embodiment approach

The analysis of current legged robot designs shows, that it is important to consider and utilize compliant hardware elements to properly shape passive and active control to achieve dynamic locomotion as robust and as efficient as for humans and animals. The presented concept of embodiment offers a new perspective to the control properties of robot morphologies. According to this concept, the embodiment of the robot must not only be considered as important source of the robots dynamic properties, but its morphology must be adapted and utilized in order to increase robustness, performance, and versatility in interaction with the robot's environment regarding the motion goals. However, systematic approaches to apply these insights to a development approach for legged mobile robots are still not well developed. Therefore this thesis combines the fundamental design principles for an embodied agent [62] with a model-based optimization approach to formulate the design of embodiment approach. By means of the presented development concept, the theory of embodiment is transferred to a development and design methodology for legged robots.

In this chapter the new development approach **design of embodiment** is presented. The approach can be applied in the development of legged mobile robots, which have rich interactions with the environment during operation. Design of embodiment is based on the eight design principles for intelligent embodied agents by Pfeifer and Bongard [62]. The remainder of this chapter is structured as follows:

In the first Section 3.1 of this chapter, the design principles are interpreted and formalized with respect to the desired application in robot development. The detailed analysis of the design principles allows for understanding of special requirements of an embodied agent. Furthermore, the relevance of each existing principle is evaluated, and additional ideas are complemented.

In the second Section 3.2 of this chapter the resulting technical requirements for the design of embodiment approach are presented. For that the set of principles is reviewed and enhanced regarding the desired application, which is the development of legged mobile robots.

In the subsequent chapters these enhanced principles are applied to an established model-based development process. The development process includes four steps:

- Chapter 4: **Modeling** robot, environment, and active control
- Chapter 5: **Design goals** of robots interacting with the environment
- Chapter 6: **Parameters** for robot design and control
- Chapter 7: **Optimization** of embodiment

The approach is laid out such that an agent constructed following the design of embodiment approach features all relevant characteristics of an embodied agent.

Used terminology

For convenience and to provide better understanding for the reader, basic concepts which are used in the remainder of the thesis are introduced beforehand.

Definition 3.1 (Environment - ecological niche - scenario - situation)**.**

- **Environment** summarizes all possible influences that arise from interactions with the physical world. Although it is possible to assign an agent everywhere in the environment, agents are in general not constructed to manage the influences outside their respective boundaries (ecological niche).
- The **ecological niche** is a subset of the environment. In general the environment is not equal to the ecological niche of an agent. The ecological niche is the complete set of environmental factors, which guarantee the prosperity and performance of the considered agent.
- **Scenario** is one specific combination of motion task and environment. An agent must be constructed, such that it can manage all the required scenarios. The complete set of scenarios of an agent describes its ecological niche.
- **Situation** describes an explicit configuration and set of parameters of agent, environment and information processing. During a scenario typically multiple situations occur.

Definition 3.2 (Active and passive control of legged mobile robots)**.**

- The term **active control** is used in this thesis for control elements, that include information-processing steps during the control cycle. The sense-plan-act cycle, which must be applied in active control, is moreover split into several physical subsystems. Usually the respective information is acquired by a sensor. The processing of the information is done by a microprocessor. The resulting reaction is applied to an actuator, that executes the respective motion. The active control is somehow equivalent to neural computation in [40].

- **Passive control** on the contrary is performed by physical elements without any information-processing. They moreover do not require additional elements for sensing or acting. The sense-plan-act cycle of active control is reduced to a sense-act response to deviations. This sense-act process is performed in a single physical element, leading to a fast reaction speed. A typical example for a passive control element is a spring. The variation in length is sensed and a resulting force is instantaneously applied. It has to be considered, that all objects with physical representation have passive control properties. Real world objects are influenced by mass, inertia, damping and compliance, when considering the dynamic properties for example. Complex control can be achieved by suitable setup of participating elements. The passive control is equivalent to morphological computation in [40].

Definition 3.3 (Levels of active control with respect to legged mobile robots)**.**

- **Motion control** describes the control level required for trajectory planning and -execution of the agent. The level of motion control includes simple feedback control actions to achieve the targeted configuration of a respective joint, as well as feedback control systems with multiple inputs and multiple outputs to control a complex dynamic motion of an agent. It also includes feed-forward motion primitives that define desired trajectories.

- **Behavior control** directs the high level goals of the agent. In this control level, global decisions concerning the next actions of the agent are made. These actions can be based on an evaluation of the current situation via the available sensors (feedback), or even proactive, based on internal metrics (feed-forward). To achieve a certain target, as for example to reach a desired destination, the behavior control must identify, which motion tasks are required.

3.1 Formalization of the embodiment concept with respect to motion

In the following subsections the principles for designing an intelligent embodied agent introduced by Pfeifer and Bongard in [62] are systematically approached in detail. The discussion is focused on motion and interactions, as they are considered the most important ingredient in embodied intelligent agents. Intelligent embodied robots are distinguished from systems without embodiment by the implicit capability to interact with the environment. The high importance of interactions for embodied intelligence is further emphasized by Brooks in [15]: *... ongoing physical interaction with the environment (is) the primary source of constraint on the design of intelligent systems.*

The discussion of the principles commences with the citation of the principle from [62], followed by an interpretation with respect to the development of legged mobile robots and manipulators with series elastic actuation. Subsequently the principles are assessed based on the relevance for the design of the considered robotic systems. Finally, they are formalized to allow for a consideration in a development process.

3.1.1 Design principle 1: The three constituents principle

Statement

Designing an intelligent agent involves the following constituents: (1) definition of the ecological niche, (2) definition of the desired behaviors and tasks and (3) design of the agent [62, p. 100, Sect. 4.3].

Interpretation

According to the first principle, the development process of an agent involves the consideration of additional factors besides the actual agent's hardware. Important additional components that influence the agent are its ecological niche and the definition of tasks and behaviors. From the definition of Pfeifer and Bongard in [62], the following categorization can be extracted.

1. The **ecological niche** can be interpreted as the aggregated constraints of the environment which affect the agent. When only considering the dynamic behavior of the agent, the constraints for legged mobile robots can be reduced to
   - **physical constraints** like gravity or ground properties,
   - **energy constraints** for possible autonomous operation of the agent, and
   - **disturbances** like unexpected interactions.
2. The **tasks and behaviors** of the agent must also be defined beforehand.
3. The **design of the agent** in robot development processes consists of two parts:
   - The selection and design of the **structure** of the robot and active control, and
   - the selection of the according **parameters**.

   When considering the three constituents, the robot is the only variable, making it the desired object to adapt. The identification of optimal robot parameters and predefined robot structures therefore is the goal of the design of embodiment approach.

Formalization

The three constituents principle states to consider the design of the actual robot hardware together with its physical constraints and the desired motion goals. All three constituents define certain constraints, which must be considered from the beginning of the robot development process. In order to suitably address these constraints in the development process, is is required to allocate, in which development step the respective constraint is approached. Therefore the constraints are divided into constraints, which are task and environment independent, and constraints, which are task and environment dependent. The latter includes for example certain variations in ground contact properties or varying obstacles for example.

This separated consideration of the respective constraints within the development process allows for a convenient allocation of the constraints to the development steps. This allocation is discussed in more detail in Section 3.2. The mapping of the three constituents to the categories independent of and dependent on task and environment, which are relevant for the design of embodiment approach are illustrated in Table 3.1.

	task and environment independent	task and environment dependent
ecological niche	gravity[1]	parameters, disturbances, energy constraints
tasks and behaviors		dependent by definition
design of the agent	robot structure	robot control parameters

Table 3.1.: The three constituents mapped to the two categories: independent of and dependent on tasks and environment.

The newly introduced categories are considered in two different steps in the development process:

1. Task and environment independent constraints are considered in the generation of the **robot model**. The robot model therefore includes aspects from two of the three constituents:
   - The task and environment independent constraints of the ecological niche are for example gravitational forces. Also contacts can be task and environment independent. A variation of contact properties however, as for example different damping coefficients for different surfaces, can be realized by a parametrized implementation of the contact in the model, while defining the parameters in the task and environment dependent category.
   - The robot structure is typically also independent from tasks and environment. This typically includes both the structure of the hardware, and the structure of the active control. In the design of embodiment development process, the implementation of the parametrized model is done during the modeling step.
2. Task and environment dependent constraints are considered in the generation of motion **goals**. In the design of embodiment approach, simulation experiments are performed. The goals are formalized as objective functions in an optimization process. The assessment of the quality of the currently applied configuration is done based on these objective functions. Here variations of expected interactions, disturbances, as well as other task dependent constraints like obstacles are defined and evaluated. The category of task and environment dependent constraints includes aspects from all of the three constituents:
   - The ecological niche includes task and environment dependent factors like disturbances or different contact properties.
   - The desired behaviors and tasks are by definition task dependent.
   - The design of the agent can be adapted by means of parameters to meet specific constraints. The appropriate setup of these task dependent parameters of the robot is a central feature of the design of embodiment approach.

3.1.2 Design principle 2: The complete agent principle

Statement

The complete agent principle states that when designing agents we must think about the complete agent behaving in the real world [62, p. 104, Sect. 4.4].

[1] When considering legged robots which are desired to perform locomotion, gravity is typically task and environment independent. This is because legged locomotion is only possible with applied gravity. In more general scenarios, gravity can be a task and environment dependent constituent.

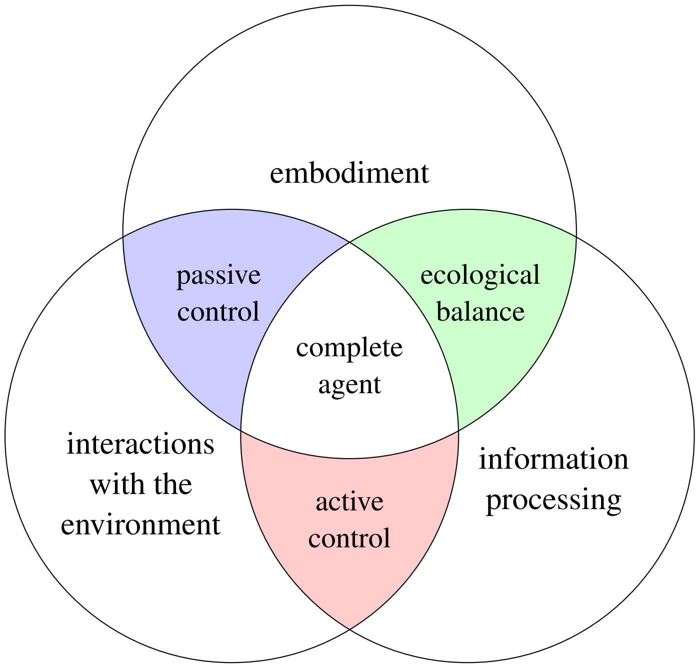


Figure 3.1.: According to the second principle, the complete agent includes the embodiment, information processing and the interactions with the environment. The figure presents the respective interdependencies between these components, which are discussed in more detail in the text.

Image source: own representation

Interpretation

The second design principle emphasizes the importance of a comprehensive consideration of the agent and the according interactions with the environment in agent design.

According to Pfeifer and Bongard, the term **complete agent** covers all components, which are required to define the agent and its behavior:

- The embodiment, as the physical representation of the robot, includes all hardware parts of the robot. This also covers the physical properties of sensors and actuators, like masses or the generated forces.

- The information processing are all signals without physical representation. Information processing in a robotic system are the sensor signals, feed forward signals or other signals that occur during computations. These signals have to be processed and applied to an actuator to take appropriate effects on the embodiment.

- The third component that also takes large effect on the behavior of the robot and is also part of the complete agent, is the interaction with the environment. The interaction with the environment has an effect on the embodiment and on the sensor signals. A consideration of these interactions is therefore crucial for the layout of the agent.

Formalization

Figure 3.1 shows the specified three members of the complete agent principle together with their connections from control perspective.

- The interactions between the embodiment and the environment are manifold. To direct and adapt the behavior of the agent regarding the desired goals with the embodiment only, passive control approaches can be applied. The application of passive control is discussed in more detail in Sections 3.1.3 and 3.1.6. The layout and adaption of the passive control parameters is a central part of the design of embodiment approach.

- The interactions between the environment and the information processing must happen via active sensor and motor components. Therefore, depending on the number of sensors and actuators, only a small number of interactions can occur. Due to the abstract nature of the information processing, a fast and simple adaption of the sensed data is possible, allowing to react to even complex events with a suitable motor actuation. Also a generation of complex feed-forward signals is possible, that can be applied easily to actuators.

- Embodiment and information processing also interact during agent's operation. A possible way of influencing this interaction by arranging the embodiment is discussed in the evaluation of the fifth design principle in Section 3.1.5. Moreover it is required to balance included sensors, controllers, and actuators based on their performance. A detailed discussion of this topic follows in the evaluation of the sixth principle in Section 3.1.6.

The principle of the complete agent implies to simultaneously consider active control parameters, passive control parameters, and the arrangement and dimensioning of active control elements in the development of embodied agents.

The comprehensive setup of the passive and active control parameters is therefore a central part of the design of embodiment process. During the design of embodiment approach, passive and active control are not distinguished concerning this typical classification. To achieve an optimal setup of all involved control parameters, they have to be categorized with respect to new classes however. The categorization is subject to the adjustability regarding the control properties of the respective parameter and the desired versatility, as discussed in Section 3.1.9. A more detailed discussion on the new categorization of the control parameters in the design of embodiment approach is presented in Chapter 6.

3.1.3 Design principle 3: Cheap design

Statement

The principle of cheap design states that if agents are built to exploit the properties of the ecological niche and the characteristics of the interaction with the environment, their design and construction will be much easier, or "cheaper" [62, p. 107, Sect. 4.5].

Interpretation

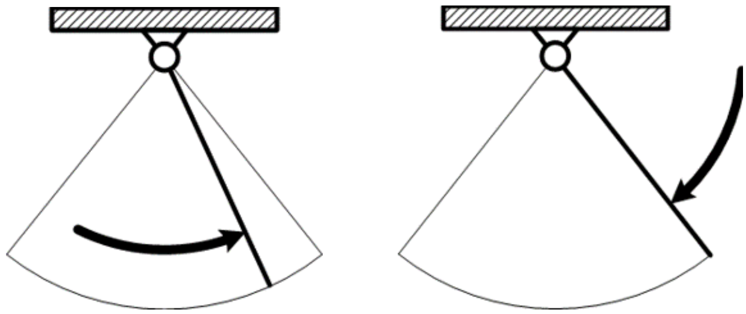
The third principle states to exploit physical effects in robot operation to achieve cheap design. This exploitation has to be considered in the development process, since it depends on the hardware design and setup. According to Iida [37], cheap design involves three factors:

- **The principle of cheap operation** By the exploitation of physical effects, operational costs can be reduced. The operational costs involve the consumed energy and the applied active control effort.

- **The principle of sensory-motor coordination** By the structuring of sensor information, information processing can be simplified. This topic is equal to design principle five and therefore discussed in Section 3.1.5 in detail.

- **The principle of cheap behavior learning** By a suitable setup of the embodiment, the exploration space to learn behaviors can be reduced. The topic of behavior learning is considered separately from the design principles in [62]. Due to the complexity of its nature and its reduced importance for the actual development of embodied agents, the principle of behavior learning will not be addressed in this thesis.

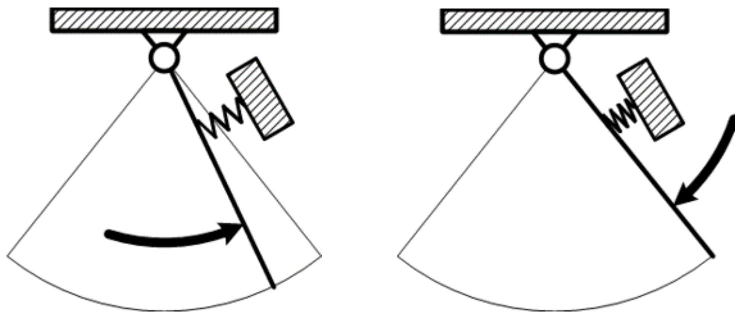
By the utilization of physical effects that influence the motion behavior of the agent, important properties of the agent can be improved.



(a) (b)

Figure 3.2.: "Expensive design": The pendulum is actuated in the joint and desired to oscillate in the marked area. Without the exploitation of physical effects the operation is not "cheap".

Image source: own representation



(a) (b)

Figure 3.3.: "Cheap design": By the application of a suitable elastic element the operation is supported. Less energy must be applied. Another obvious approach is the application of a torsional spring. The presented setup however is related to the examples presented in Sections 8.3 and 8.4

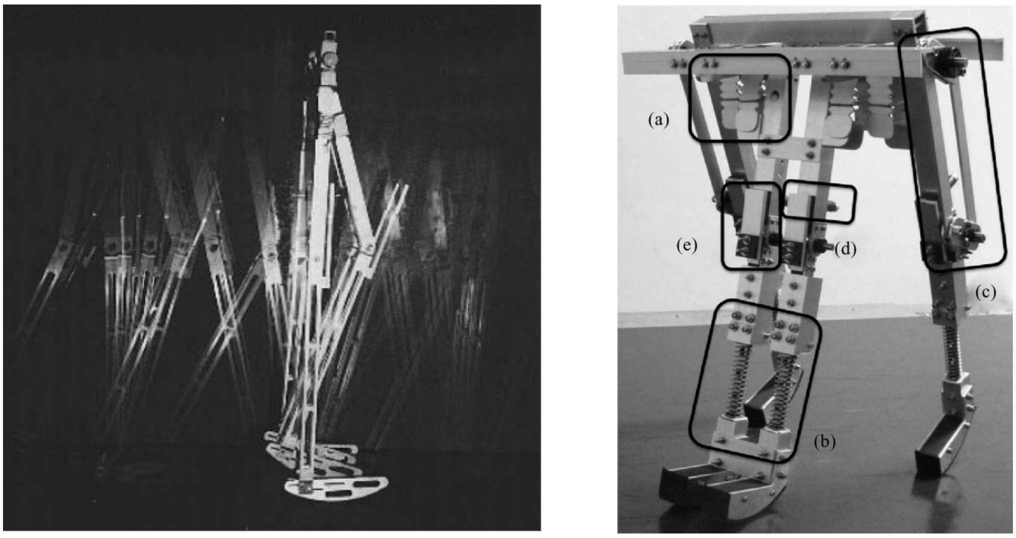
Image source: own representation

Figures 3.2 and 3.3 present an example for the application of physical effects to support the operation of a mechanical device. In the example, a pendulum, which is actuated at the rotational joint, is desired to oscillate within the marked area. Without the additional application of physical effects[1], the accelerated pendulum (see Figure 3.2a), is decelerated as soon as the required configuration is reached, and again accelerated (see Figure 3.2b) as targeted. Every acceleration and deceleration requires a certain energy effort. In addition active control including sensor capabilities and model knowledge is required to initiate the direction change at the right moment in time.

[1] Gravity is applied but not relevant in this example.

When introducing elastic elements that apply a suitable force to the pendulum when the direction change is necessary, the energy efficiency of the mechanism can be increased. The impact energy decelerates the pendulum and is concurrently stored in the spring (see Figure 3.3a). A reuse of the energy for accelerating the pendulum is possible (see Figure 3.3b). However, to fully utilize the effect of the elastic element, the pendulum has to be decoupled from the actuator. If it is not decoupled, the pendulum is decelerated by the properties of the actuator and the potentially present gearbox. The decoupling can be achieved for example by a mechanical clutch or the application of another spring between link and actuator (see Section 4.1.1). The application of suitably installed elastic elements therefore decreases the required energy effort and the active control effort in this example. The desired motion is achieved nevertheless.

McGeers passive dynamic walkers [56] are examples for machines with very rich exploitation of physical effects. They are able to perform bipedal walking motions on a downward slope with a specific angle, without any motor actuation, sensing, or computation. The walking motions are therefore energy efficient and do not require any active control effort. By a slight variation of the ecological niche however, like a variation of the slope angle, the machine looses its capability to walk. The ecological niche of the robot is narrowed by the application of passive control elements. Figure 3.4a depicts a McGeer-like mechanism by [26].



(a) McGeer-like passive dynamic walker

(b) Elastic passive dynamic walker PDR400 by Ishigura

Figure 3.4.: Figure 3.4b shows a strobo-photo of a replica of a McGeer passive dynamic walker by Garcia [26]. The passive dynamic walking robot PDR400 depicted in Figure 3.4b uses elastic elements for passive control [61]. The passive control elements are highlighted in the picture: (a) Torsion springs in the hip joints, (b) linear springs in the legs, (c) parallel-link mechanism,(d) shock absorbers, (e) hyperextension mechanism.

Image source: Figure 3.4a: [26], Figure 3.4b: [61]

Another example for an agent with only passive control is the PDR400 presented in [61]. This legged mobile robot is depicted in Figure 3.4b. Experiments showed, that by the application of elastic elements the robot was able to achieve a running motion in a well-known environment. An adaption of the applied spring coefficients resulted in a variation of the achieved gait. Although the ecological niche of the agent is narrowed by the use of passive dynamics, an increase in versatility is achieved by changing the properties of the elastic elements. The examples show, that operation with sole passive control is possible on the one hand, but not always desired on the other hand. Although the application of cheap design and therefore a broad exploitation of physical effects is reached, the ecological niche is narrowed, resulting in a reduction of applicability and a loss of versatility.

The principle of cheap design however, does not focus on the actual implementation details of physical exploitation. It rather states, that ... *the more and better the exploitation, the simpler the agent will be* [62, p. 108, Sect. 4.5]. To construct an intelligent embodied agent it is therefore recommended to utilize physical effects wherever possible. However, pure passive control reduces the versatility of the agent, resulting in an agent that is specialized to one specific task in one specific ecological niche. In the relevant scenario of real world locomotion, the respective agent is desired to operate in a complex ecological niche. Moreover the agent is usually required to achieve various different goals. Conflicting requirements for different scenarios and goals render the application of sole passive control impossible. An agent with only passive control is therefore not suited to perform with sufficient quality in relevant real world scenarios.

Formalization

Hence the principle of cheap design must be adapted to meet the requirements of an agent that is desired to perform in real world scenarios. A new approach to achieve an efficient realization of versatility to handle such scenarios is presented in Section 3.1.9. This concept of versatility extends the principle of cheap design by adding the constraint, that passive control is preferred only as long as all required goals can be achieved. The formalization of cheap design is included in the formalization of versatility.

3.1.4 Design principle 4: Redundancy

Statement

The redundancy principle states that intelligent agents must be designed in such a way that (a) their different subsystems function on the basis of different physical processes, and (b) there is partial overlap of the functionality between the different subsystems [62, p. 113, Sect. 4.6].

Interpretation

The fourth principle suggests to construct an agent such that it can gather and use redundant information to increase its reliability with respect to varied conditions. The redundant information must be gathered using different channels of interaction. By the use of information from multiple sources, a possible failure can be compensated, to maintain the ability to achieve the desired goal.

This principle is very complex and influences especially the application of active control elements. Nevertheless, also passive control can include redundant information.

The fourth design principle misses a differentiation between redundancy and complementarity. When having visual and haptic feedback of an object for example, the actual sensor-information is partly complementary: It is not possible in this example to gain information about the color of the object through haptic interaction on the one hand. On the other hand it is not possible to see the temperature or the weight of the object. The dimensions of the object however can be captured visually and haptically. Information regarding the dimensions are therefore redundant in this context.

Complementary information can be used to improve the quality of the gathered data. By the application of sensor fusion, mixed mode information can be combined to gain a more detailed model of the respective object. This topic is also addressed in the principle of sensory-motor coordination in Section 3.1.5.

In dynamical systems, redundant subsystems that are based on different physical processes, are in general difficult to realize. The application of different dynamical subsystems, which operate based on different physical processes, implies the parallel implementation of mechanisms with equal resulting properties regarding the respective task. This is a contradiction when targeting devices that also are based upon the principle of cheap design. A system with redundant passive subsystem cannot be considered simple or "cheap".

Since the principle of cheap design states to use passive control wherever possible and to avoid active control, the additional application of active control loops for the sole increase of reliability is also contradictory.

Instead of considering redundancy on component-level, redundancy can also be seen on task-level. By the ability to move in different gaits for example, the task of moving from A to B can be performed with redundant modes of operation regarding the task-level. This redundancy is considered within the concept of versatility in the presented approach. A more detailed discussion on the implementation of the new principle of versatility follows in Section 3.1.9.

The central goal of the principle of redundancy can be split in two parts.

- **The increase of robustness of the agent with respect to changed conditions regarding the interactions with the environment**: Coping with different scenarios cannot be realized by increasing the redundancy of the agent's subsystems, but by increasing its versatility. To guarantee the operation in the desired modes of operation, the principle of redundancy therefore must be addressed from the perspective of versatility. An approach on how to handle versatility with respect to cheap design is presented in Section 3.1.9.

- **The increase of robustness of the agent with respect to failures in the agent itself**: This however requires additional information on construction details, that are not part of a functional development as the presented design of embodiment. Possible failures of the agent and the respective reactions that can be incorporated during the development already, are therefore not discussed within this thesis.

Formalization

The principle of redundancy is replaced by the principle of versatility. The formalization of the principle of versatility is discussed in Section 3.1.9.

3.1.5 Design principle 5: Sensory-motor coordination

Statement

The principle of sensory-motor coordination states that through sensory-motor coordination structured sensory simulation is induced [62, p. 117, Sect. 4.7].

Interpretation

In the fifth principle Pfeifer and Bongard discuss the importance of tuning the correlation of sensor, motor and embodiment to improve the classification of objects and scenes [62, 77].

The detailed description of the principle and evaluation of the examples in [62] allows for a distinction of the principle into three general factors:

- **Linking of sensors and actuators**: By directly coupling sensors to actuators, desired behavior can emerge. Similar to reflexes in humans and animals, a hardwired connection of a sensor input to the corresponding responsive actuator can increase the efficiency and generate distributed control structures. Instead of a complex control model, which has a potentially high computational effort, multiple decentralized processes are applied. In related publications fully reflex based control could be applied to generate robust walking in simulation [54].

- **Sensor fusion**: By the coordination of sensors with respect to the embodiment, certain correlations in sensor stimuli can occur. To utilize the respective correlations either a model is required beforehand, or a model must be acquired through learning processes during operation. An example of beneficial structuring of sensors can be given by the arrangement of the human eyes: By locating two eyes in proper distance, two pictures with overlapping information from different viewpoints can be seen. To allow for the generation of three dimensional data, the pictures are required to be matched. This requires the information of how the sensors are located within the embodiment. The arrangement of sensors however depends on the ecological niche and is required to be tailored accordingly for an agent. A sensor fusion can also be arranged by the merging of time delayed sensor signals from different perspectives. Viewing an object from multiple sides allows for a better model of the object. The model generation in this case requires the knowledge of position changes and time delay between the observations.

- **Reafference**: By the coordination of sensor and motor with respect to the embodiment, the identification of objects can be simplified. A moving agent generates sensor signals. Based on a defined regular state, the expected sensor responses can be calculated beforehand. A deviation from the expected signal requires special attention for example in terms of a balance motion to maintain stability. This principle is known as reafference-principle in biological systems.

Formalization

Although the concept of the presented design of embodiment approach tries to maintain stability by designing suitable passive control elements, sophisticated techniques to improve the active control are required nevertheless. The concepts of sensor fusion and reafference are established approaches, which can be applied to recognized deviations of stability measures in order to initiate compensatory motions to maintain stability during locomotion. Sensor fusion and reafference must therefore be considered in the active control of the robot.

Moreover the linking of sensors and actuators is especially relevant in the design of active control structures. If passive control cannot be applied for any reason, it is important to achieve fast reactions to possible disturbances by active control. Direct linking of sensor to actuator can increase the respective reaction speed.

3.1.6 Design principle 6: Ecological balance

Statement

The principle of ecological balance has two parts. The first states that given a certain task environment, there has to be a match between the complexities of the agent's sensory, motor, and neural systems. The second aspect is closely related to the first; it states there is a certain balance or task distribution between morphology, materials, control, and environment [62, p. 123, Sect. 4.8].

The sixth principle is divided into two parts which are considered separately in the following sections.

Part 1: Balancing complexities of sensor, motor, and information process

Statement

The first (part) states that given a certain task environment, there has to be a match between the complexities of the agent's sensory, motor, and neural systems. [62, p. 123, Sect. 4.8]

Interpretation

A balancing of complexities between the involved factors sensor, motor, and information process must be performed. Target of this balancing is to achieve an agent which is able to sense the required information, conduct the according computation in information processing and in morphology and perform the necessary motor commands and passive reactions to achieve the goal. In a balanced agent none of the involved components is fitted with (a) less capacity then required, or (b) more capacity then required. Although it can be possible in both cases (a) and (b) to achieve the goal nevertheless, the agent is not balanced and possibly looses the beneficial properties given through the embodiment. These properties are discussed in the second part of this principle in Section 3.1.6.

Formalization

This first part of the principle focuses on the balancing of the complexity of sensor, motor and information processing. These active control components must be considered regarding their active and passive control capacities:

- The dimensioning with respect to **active control** properties, as for example frequency of sensors or power of motors, can be performed isolated from the design of embodiment process. During the design of embodiment process the involved sensors, motors, and controllers can be considered to have sufficient capacity regarding active control to achieve the desired motion goal of the robot. The dimensioning of these components can be performed based on the results of the design of embodiment approach to optimally fit the requirements. Alternatively the active control properties can be restricted beforehand.
- **Passive control** properties as for example mass and inertia of active control components have to be considered in the design of embodiment. Passive control properties of active control components include:
  - The passive control properties of a **sensor** are its mass and inertia. Typically the sensor is considered to be rigid and welded to the neighboring object, such that neither compliance nor damping properties of the sensor need to be taken into account.
  - **Motors** do also have mass and inertia as passive control properties. Additionally motors can apply torques or forces to the embodiment. In a development process, the applied torques and forces can be considered as sufficient for the desired task however. The same holds for all relevant motor properties. A dimensioning of the motor can be conducted when the requirements are determined by the design of embodiment. Alternatively the motor properties can be restricted according to the requirements.
  - **Information processing** does not have a physical representation and is therefore not relevant in the design of the embodiment. The computation speed is typically considered as sufficient during the development of the embodied system.

The comprehensive layout of embodiment and information processing (the ecological balance; see also Figure 3.1) can therefore be simplified to a successive setup: The embodiment is laid out first, while considering the design principles. The requirements regarding specific properties of active control elements, like sensors, motors, and information processing, result from the design of embodiment. A detailed setup of these components can be done in a second development iteration.

The implementation of constraints regarding the capacities of motor, sensor or information processing to the design of embodiment is possible by adding objectives to the optimization (see Chapter 5 and 7).

Part 2: Balancing morphology, materials, control and interactions with environment

Statement

The second part [...] states (that) there is a certain balance or task distribution between morphology, materials, control, and environment [62, p. 123, Sect. 4.8]

Interpretation

The second part of the principle of ecological balance states, that balancing task distribution between morphology, materials, (active) control and the environment is required for an embodied agent. Relevant improvements that can be achieved by the embodied agent through a balancing of the mentioned components as presented in [62] are in detail:

- The reaction speed is increased.
  Physical elements like springs react instantaneously on applied forces. The operation is not delayed by signal transmission, electronical processing, or motor inertia.
- By the coupling of hardware elements, underactuated kinematic structures are generated.
  Such structures have less actuators than degrees of freedom and can be applied to generate complex motions from simple actuation signals.
  - The active movements are constrained. This leads to a reduction of the actuation control complexity. Instead of coordinating several independent actuators, the desired motion can be achieved by simple control signals. An example is given by the closing motion of a human hand. The coupling of the finger joints allows for a simple grasping motion by the sole actuation of less tendons than degrees of freedom.
  - The passive movements are constrained. The swinging motion of a human leg for example is partly induced by passive coupling. The complexity of the agent's control is therefore even more reduced. Typical approaches to achieve mechanical couplings in legged robots are presented in Chapter 4.
- The energy efficiency is increased.
  In contact situations, contact forces can be stored in elastic elements. This force can be re-used to accelerate the respective link.
- According to Pfeifer and Bongard, the application of cheap design increases the naturalness of the acquired motion.

The interactions between morphology and environment, as well as the interactions between materials and environment can be summarized as passive control. The requirement of the principle can therefore be reduced to the demand, to balance active and passive control. A balancing of the task distribution between morphology and materials however is not required, since the control actions performed by these factors are not convertible. The principle can be interpreted as suggestion to apply elastic, compliant and damping elements in embodied agents to increase the possibilities of the embodiment to perform more complex passive control.

When considering the application of passive control together with active control additional beneficial effects which are not mentioned by Pfeifer and Bongard can be achieved:

- Resulting from a fast reaction to disturbances an increased robustness regarding variations in position and time of interactions with the environment can be achieved. The application of damping elements helps in reducing oscillations to further improve stability. Utilizing the passive and active control to increase the robustness, requires a careful design of the embodiment however.

- The catapult effect can be used to increase the output power of an actuator. To apply the catapult effect, energy must be stored in the applied elastic element of a series elastic actuator. By releasing the stored energy in an explosive motion, the output force can be increased. With this technique, the resulting power can exceed the actuator's power.

- By decoupling the actuator from the respective link by means of a series elastic actuator, the actuator can be protected to prevent damages. The peaks of a contact force are not directly applied to the sensitive actuator and gearbox, but filtered by the elastic element.

- The decoupling of actuator and link does not only protect the actuator, but also humans which interact with the agent and the environment the robot is deployed in. The projected inertia is reduced by the application of the elastic element, resulting in less dangerous contact situations.

The presented advantages resulting from the ecological balance principle are grounded on the directed utilization of passive control with respect to the desired task. When also considering the principle of cheap design (see Section 3.1.3) balancing the task distribution does not refer to an equal balance between active and passive control. According to the principle of cheap design the main control effort should be managed by passive control, since *Exploiting morphological computation makes cheap rapid locomotion possible because physical processes are fast and for free* [64]. To achieve an intelligent embodied system, the control actions must be shifted to passive control wherever possible.

As discussed in Section 3.1.3 however, systems with passive control are subject to restrictions.

- Passive control elements are difficult to set up.
  The passive control properties of a system are defined by its embodiment and the environment. Possibilities to adjust passive control parameters of an embodied agent are mentioned in the statement of this principle: morphology and materials.

- Passive control elements typically cannot adapt their control properties.
  Mass, inertia, stiffness and damping are typical passive control factors. These factors are constant in general and can usually only be adapted with active control effort.

- Passive control elements reduce the versatility of the agent.
  As discussed before (see Section 3.1.3 and 3.1.4) versatility is typically required in an embodied intelligent agent. An approach to achieve passive control while maintaining the required versatility is discussed in the next Section 3.1.9.

Instead of balancing the control effort of the involved components as stated in design principle six, a resulting design must be adjusted to prefer passive control over active control. This requires to detect relevant passive control elements and find a suitable setup while maintaining versatility.

Formalization

The setup of passive and active control requires a definition of the adjustable passive control structures. Which part of the embodiment can be adjusted in order to adapt the passive control properties of the agent to the respective task must be decided before the development process by the engineer. The selection and classification of parameters is discussed in Chapter 6.

The actual setup of the passive control elements which are selected to be adjustable during the development process is very difficult as stated by Pfeifer and Bongard: *Finding the proper stiffness for each situation, however, is a hard problem and will require a lot of research* [62, p. 127, Sect. 4.8]. Besides stiffness, the other adjustable passive control elements damping, compliance and kinematic structure, including mass, inertia and couplings, must be evaluated also.

The principles stated by Pfeifer and Bongard focus on the realization of one task only. As discussed before, real world scenarios comprise a complex ecological niche, together with multiple desired goals of the agent. The setup of a proper design of the passive and active control, that considers multiple tasks in a complex ecological niche, is discussed in Section 3.1.9.

3.1.7 Design principle 7: Parallel, loosely coupled processes

Statement

The principle of parallel, loosely coupled processes states that intelligence is emergent from a large number of parallel processes that are often coordinated through embodiment, in particular via the embodied interaction with the environment [62, p. 134, Sect. 4.9].

Interpretation

According to this principle, there are many parallel processes in an agent, that are coordinated through interactions within the embodiment or in-between the embodiment and the environment. Each action of an agent can be interpreted as an independent subroutine, that is triggered through interactions. This principle is known in high level control of autonomous robots as reactive control: the robot reacts to sensory inputs according to simple rules (sense-act). The converse approach to reactive control is the deliberative control. Here the robot generates a model of the scenario and applies a complex solution (sense-plan-act).

In Cruse's stick insect experiments [17], he identified a reactive control in the leg coordination of the animals. The experiments showed, that the legs of the insect were controlled locally and independently. A coordination to achieve the required walking speed was performed via the ground contact.

The coupling of control processes can also be seen in passively coupled systems. Two pendulum clocks hanging next to each other synchronize their movement. This historic phenomenon is for example discussed in [82]. The identified reason for the synchronization are interactions with the environment: The apparently independently operating clocks are coupled through the wall and atmospheric oscillations. This loose coupling allows for a passive synchronization of the processes.

Formalization

The application of this principle concerns both the passive and the active control of the agent. Passive control elements are reactive control elements, which are triggered by interactions with the environment by nature. An additional coupling can be implemented however, by the installation and setup of respective (passive) kinematic structures (see Section 4.1.1). This way more complex reactions to interactions can be achieved by the robotic system.

In active control, the reactive coupling can be realized by the application of state machines or reflexes (see Section 3.1.5) for example. The design of this reflex-like behavior must be considered in the development of active control structures. Systems with reactive control approaches, which apply reactivity on behavior control as well as on motion control, are discussed for example by the group of Berns [71]. The application of parallelization to the structure of active control is discussed in Chapter 4.

This principle can also be considered in the agent's behavior control. Hereby behavior control is considered in the definition of goals: Only motions or motion types which are considered within the list of applied goals can be selected by the behavior control during operation. To enable the choice between gaits for example, the resulting embodied agent must be capable to perform these gaits. The robot is guaranteed to perform the desired motion goal by the application of respective goals in the design of embodiment approach. The design of actual behavior control however is not part of this thesis.

3.1.8 Design principle 8: Value

Statement

The value principle states that intelligent agents are equipped with a value system which constitutes a basic set of assumptions about what is good for the agent [62, p. 137, Sect. 4.10].

Interpretation

As stated in [62], the principle of value is only imprecisely defined in literature. The fundamental idea of this principle however, is to generate a metric on how to rank possible actions. Based on this ranking the next action is selected. Although this principle targets the classification of behavior control decisions, the concept of value can also be extended to motion control.

Defining value is of great importance in the setup of mobile and interacting agents. The value of an action can be defined by the goal of the respective agent. Due to the separate consideration of ecological niche and task, these goals can be divided into subgroups:

- Managing the **implicitly defined** challenges of the ecological niche.
- Achieving the **explicitly defined** desired task.

The decision of what specific goal is more important is typically difficult to postulate. This is especially visible, if different motion goals require an opposing layout of the passive control elements of the agent. Therefore a general problem of the principle of value is its ambiguity.

Formalization

To achieve an agent, that automatically prefers actions of high value with respect to its current task, two steps are required.

1. In a first step the goals are required to be formalized. Typical goals for legged mobile robots and manipulators are presented in Chapter 5. This chapter includes the goal to manage the challenges arising from interactions with the environment and the ecological niche, as well as the achievement of typical motion tasks.
2. A second step requires the assessment of different configurations of the agent in simulation experiments to find the optimal configuration with respect to the defined goals. Better configurations regarding the goals have a higher value. By means of this metric, the resulting configurations are ranked. This second step is formalized as multi-objective optimization process in the presented

approach and discussed in detail in Chapter 7. The versatility is addressed as discussed in Section 3.1.6, by sticking to passive control wherever possible, and applying active control wherever needed.

In summary the principle of value can be formalized by setting up and applying metrics for each desired action.

3.1.9 Additional design principle: Efficient versatility

Problem

All considered passive control elements have fixed control properties. These control properties can be dependent on a current configuration like position, velocity or force, but cannot be varied independently, like elements that are actively controlled. The requirements to the embodiment and therefore to the passive control structures are defined by the ecological niche and the respective tasks of the agent. This complex set of requirements results in different, possibly opposing demands to the passive control elements. Passive dynamics walkers as discussed in Section 3.1.3 are only capable to perform one task in one specific ecological niche. Not applying any active control reduces the versatility in this example. An important target of the design of embodiment approach is the adaption of passive interactions, such that the active control is reduced to a minimum, while achieving the desired performance and versatility of the agent.

Formalization

In different scenarios, the agent is exposed to different requirements with respect to the interactions with the environment. An approach pursued by the design of embodiment, is to find optimal configurations for the active and passive control elements for each scenario defined by the ecological niche and the tasks. By considering the agent in the simulation of multiple complex motion tasks, the versatility is considered explicitly.

The results of the simulation must be evaluated carefully to find the optimal design of the embodiment. The desired optimal embodiment has the ability to utilize physical elements to generate forces, that correspond to the requirements defined by the ecological niche and the tasks. To switch between these forces, either the active control or passive control parameters must be adjusted.

In the design of embodiment approach, the setup of control parameters is performed by a multi-objective optimization. Typically this kind of optimization generates a set of optimal solutions. Possible results of the multi-objective optimization are:

- The different optimal configurations vary only in active control parameters:
  The passive control elements must be set according to the results of the optimization. The active control is adjusted according to the respective situation.

- The different optimal configurations vary in passive control properties:
  Strategies to approach this challenge are presented in Section 7.2.3

A detailed description of the selection of passive control elements is discussed in Chapter 6. The multi-objective optimization and the evaluation of the results is discussed in detail in Chapter 7.

3.1.10 Summary

The preceding sections presented an evaluation of the principles to design an intelligent embodied agent presented by Pfeifer and Bongard with respect to their application in the development of legged mobile robots. Furthermore the important design principle of efficient versatility is added to guarantee the required versatility in legged robot locomotion. The summary presented in Table 3.2 shows design suggestions deduced from the individual design principles. Each principle is summarized in a conclusion and is completed with a statement on the relevance of the principle with respect to the development of a legged mobile robot.

It turns out, that most principles are of high relevance in the development of an intelligent embodied legged robot. The general suggestion to include ecological niche and task in the development is emphasized. Another key requirement to an embodied agent is to focus on the setup of interactions with the environment. The selection of suitable motors, sensors or components that perform the computation for active control elements however, can be considered (nearly[1]) independently from the design of the embodiment. Although passive control properties of these elements must be considered, the embodiment together with its ecological niche and tasks define the requirements for the active control. The active control elements can be selected after the design process according to these demands. Nevertheless it is possible to constrain the capacities of sensors, motors or computers during the design of embodiment in terms of resolution, frequency or maximum speed for example, to achieve realistic and realizable agents.

The set is completed with the new principle of efficient versatility. It considers ideas mentioned in other principles (cheap design, redundancy, ecological balance, parallel processes, value) and presents a possibility to settle inconsistencies, especially the contradiction between the principles of cheap design and redundancy discussed in Section 3.1.4. By explicitly addressing the problem of different, possibly opposing goals of an agent, resulting from the complexity of the ecological niche and the considered tasks, the formalization of this requirement is enabled. The principle of versatility replaces the principle of redundancy to a great extend by addressing a similar issue from another perspective.

3.2 Transfer of the embodiment concept to a robot development process

The design of embodiment approach is based on a model-based multi-objective optimization hardware-development approach as presented in Section 2.3.2. Like the approach from Eberhard and Bestle [20], the design of embodiment approach is defined by the four steps **modeling**, **definition of goals**, **parametrization**, and **optimization**. In the following sections, the transfer of the design principles presented in Section 3.1 to the requirements of a technical optimization with these steps is presented.

The extracted requirements to develop an embodied intelligent agent are defined such that they can be used to evaluate the quality of the design of embodiment approach: The final development approach must include all aspects to guarantee the creation of an intelligent embodied agent.

3.2.1 Linking the principles to optimization

The transfer of the embodiment concept in terms of the principles introduced by Pfeifer and Bongard to a robot development process is initiated by the connection of each principle to the steps **modeling**, **definition of goals**, **parametrization**, and **optimization**. At first, each principle is discussed and mapped to the respective elements.

[1] Except for their passive dynamic properties, like mass or inertia. See Section 3.1.6 for more details.

Principle	Conclusion	Relevance
Three constituents	The requirements in form of ecological niche and desired tasks of an agent need to be considered in agent development.	**High relevance**: This principle guarantees the capability of the agent to achieve the desired goal in the targeted environment.
Complete agent	Both the interactions between embodiment and environment (passive control), as well as the interactions between information processing and environment (active control) need to be considered in agent development.	**High relevance**: The comprehensive consideration and setup of active and passive control guarantees to utilize interdependencies.
Cheap design	Passive control elements should be preferred over active control.	**Medium relevance**: This aspect is covered by the principle of efficient versatility.
Redundancy	Construct the agent robustly with respect to variations by implementing redundancy.	**Low relevance**: Robustness while maintaining cheap design is realized by the application of efficient versatility.
Sensory-motor coordination	An appropriate setup and coupling of sensors and actuators can increase the performance of the agent, while reducing the active control effort. Furthermore reafference and sensor fusion can increase the amount of available information.	**Medium relevance**: In order to reduce the active control effort, these concepts must be considered. The influence on the embodiment however is only implicit.
Ecological balance 1	Balance the complexity of sensor, motor and information process.	**Medium relevance**: The requirements of sensor, motor and information processing are defined during the design process. A balancing of the complexities can be performed based on the results of the development process afterwards.
Ecological balance 2	Balance the task distribution between active and passive control by the application of complex kinematic structures, elasticity, damping and compliance.	**High relevance**: The setup of interacting structures is a key feature of embodied agents.
Parallel processes	Tasks should be performed distributed, but loosely coupled via the embodiment and the interactions with the environment.	**High relevance**: Although passive control is performed locally by nature, an intelligent layout of the agent can increase the capability to couple processes. The layout of active control procedures must be considered in the design of the agent.
Value	Define values for different goals of the agent.	**High relevance**: The definition of value implicitly defines the desired optimal configuration of the agent.
Versatility	Prefer passive control over active control while maintaining the required versatility of the agent defined by ecological niche and tasks.	**High relevance**: by enhancing passive dynamic systems with additional versatility, embodied agents with increased performance can be realized.

Table 3.2.: The table presents a summary of the preceding sections. The principles to design an intelligent embodied agent are summarized and evaluated with respect to their relevance for the development of an embodied legged mobile robot.

The three constituents (see Section 3.1.1)

Constraints defined by the three constituents (definition of ecological niche, definition of tasks, and development of the agent) are assigned to either one of the new subgroups **task and environment dependent**, and **task and environment independent** constraints. Constraints that are task and environment independent need to be implemented in the **model**. Task and environment dependent constraints must be considered only during the respective task or in the respective environment and are therefore required to be considered in the step of **goals**.

Complete agent (see Section 3.1.2)

All elements of the complete agent (embodiment, environment, and information processing) interact with each other. Interactions between embodiment and environment in terms of contacts or impressed forces like gravity for example can be considered as passive control, and interactions between information processing and environment as active control. Both types of interactions must be taken into account by a proper selection of a suitable model structure and the according parameters for the model-based optimization. A mutual adaption of parameters, which represent key properties of active and passive control is required to allow for an efficient operation of the robot. In the presented development process, this adaption is performed via the setup of **parameters**. Suitable structures for robot, interactions, and information processing, which allow the application of active and passive control, must be considered within the **model**.

Cheap design (see Section 3.1.3)

According to this principle, passive control is preferred over active control to achieve the desired cheap design. Cheap design is characterized by the exploitation of physical effects to achieve a faster and more energy efficient operation, which can be controlled with low effort due to its reduced control space. To allow for the exploitation of physical effects, not only the respective physical elements must be implemented in the robot, but they must also be adjusted to meet the requirements. Therefore, to allow for cheap design, the structure (**model**) and **parameters** of the robot must be selected properly.

Redundancy (see Section 3.1.4)

The robot must be capable to perform under varying conditions in all required scenarios. Instead of constructing the robot with redundant sub-systems on component-level, a consideration of redundancy on task-level is required. This redundancy on task-level can be considered within the newly added principle of versatility, which is addressed in Section 3.1.9.

Sensory-motor coordination (see Section 3.1.5)

The principle of sensory-motor coordination encourages the application of reflex-like control structures in motion control by directly connecting sensors and actuators. Also reafference and sensor fusion as concepts for active control can enhance the agent's performance. Since the active control can involve both, task independent and task dependent parts (see Section 3.1.1), the principle of sensory-motor coordination must be considered in the design of the active control structure (**model**) and of goal specific properties (**goal**).

Ecological balance 1 (see Section 3.1.6)

This principle states to select active control elements with adequate capacity. Active control elements with lesser power then required reduce the capabilities of the robot, whereas elements with more power then required increase the complexity and therefore are not cheap design. In the presented design of embodiment approach, this selection of active control elements however is done based on the results of the model-based optimization. The model-based optimization is arranged such that the interdependencies are considered. The requirements of the active control elements are uniquely determined by the optimization. A subsequent setup of the elements required for active control is therefore possible. Hence the consideration of the first part of the ecological balance principle is implicitly considered in all steps of the design of embodiment approach.

Ecological balance 2 (see Section 3.1.6)

Active and passive control parameters must be selected, in order to optimally achieve the desired motion goals of the robot. This is done in the design of embodiment approach during the **optimization** step. Beforehand a careful selection of **parameters**, which must be considered for the model-based optimization, is required.

Parallel processes (see Section 3.1.7)

According to this principle, the active and passive control of the robot must be performed in parallel, loosely coupled processes, which are coupled through the interaction with the embodiment. To achieve this coupling concerning the passive control, the structure of the **model** must be designed properly. The layout of the structure of the robot and the active control however cannot be automated entirely and requires engineering expertise. The layout of the robot's structure must be considered in the **model** step.

Value (see Section 3.1.8)

Desired operations of the robot are rewarded by the objective functions defined in the step of **goals**. The configuration of the robot, that optimally meets all requirements, is computed as numerical solution of the model-based **optimization** problem.

Efficient versatility (see Section 3.1.9)

To meet the requirement of managing the complex ecological niche while achieving multiple tasks, a proper selection of multiple **design goals** must be defined, representing all tasks and constraints. By necessity a multi-objective **optimization**, that includes multiple experiments, arises from the multiple goals in an optimization process. Possible approaches to solve multi-objective optimization problems are discussed in Chapter 7. The evaluation and selection of optimal **parameters** from the set of optimal solutions during a complex decision process is furthermore required.

3.2.2 Modeling robot and environment

Although no explicit advice is given for the generation of a model, important conditions regarding the framework of the model are stated by Pfeifer's and Bongard's principles. Different aspects of the presented principles need to be considered in the modeling of the robot and the environment:

- Task and environment independent constraints need to be considered in the model of robot and environment (Section 3.1.1).
- The structure of robot, active control, and interactions with the environment must be able to perform passive control (Section 3.1.3).
- The structure of robot, active control, and interactions with the environment must be designed to allow for parallel processing of the tasks (Section 3.1.7).

- The active control must be designed such that it allows for the application of reflexes. Also the application of reafference and sensor fusion must be considered here (Section 3.1.5).

The model must include all elements of the robot, the environment, and those interactions, which are independent from task and environment. The structure of the active control must also be selected within this step.

The generation of a suitable model is discussed in more detail in Chapter 4.

3.2.3 Design goals of robots interacting with the environment

In the definition of the design goals multiple principles need to be considered:

- Task and environment dependent constraints must be defined in the goals of the robot (Section 3.1.1).
- To achieve a versatile robot, the definition of multiple goals based on the tasks and the ecological niche is required (Section 3.1.6).
- The design goals must be defined to reflect the requirements and tasks of the robot. The requirements are defined through the ecological niche and the tasks (Section 3.1.8).

To combine the design goals with the robot and environment model, a set of simulation experiments is generated. In these simulation experiments the robot performs the desired operation in varying configurations. The required active control, consisting of feed-forward control and feedback control, must be applied during these simulation experiments.

Typical goals for legged mobile robots are presented in Chapter 5.

3.2.4 Parameters for robot design and control

To perform a parameter based optimization of the model with respect to the defined goals, parameters must be defined. Different requirements must be considered for the parameters according to the principles:

- Active as well as passive control parameters are desired to be included in the set of optimization parameters (Section 3.1.2).
- The parameters must be selected, such that all defined goals are achieved optimally (Section 3.1.9). If multiple objectives are applied, a decision process to find the best suited configuration from the set of optimal solutions is typically required.

Before starting the optimization, the parameters which are taken into account for the optimization have to be selected. A detailed discussion on the selection and possible selection criteria is presented in Chapter 6.

3.2.5 Optimization of embodiment and classification of results

During the optimization the defined parameters are optimized with respect to the desired goals of the robot. According to the design principles, the optimization is subject to the following requirements:

- Active and passive control parameters must be optimized together in one optimization step (Section 3.1.6).
- The ambiguity of the ecological niche and the applied goals calls for the application of a multi-objective optimization approach (Section 3.1.9).
- Desired motion behaviors must be ranked with higher value (Section 3.1.8).

The multi-objective optimization and the subsequent decision process is discussed in more detail in Chapter 7.

3.2.6 Summary

The detailed analysis of Pfeifer's and Bongard's design principles for an intelligent embodied agent and the accompanying formalization of these principles allows to generate a set of rules. These can directly be applied to a model-based multi-objective optimization process. The transfer of relevant concepts from the design principles to the development of legged mobile or manipulating robots is guaranteed by a careful analysis and consideration from multiple perspectives. The relevant principles are transferred to the established optimization components **model**, **design goals**, **parameters**, and **optimization**.

New important concepts that contributed to a successful mapping of the principles to the optimization components are presented in this chapter:

- The consideration of the whole robot as passive control allows for a comprehensive consideration of all effects that influence motions in legged locomotion.
- The separate consideration of passive and active control allows for a realization of cheap design, while guaranteeing the achievement of the desired motion goals.
- The introduction of the principle of efficient versatility allows for approaching this problem. Only by formulating multiple design goals, the required versatility can be achieved.
- Constraints given by the ecological niche, tasks, and the embodiment are restructured as task and environment independent and task and environment dependent constraints.
- The simultaneous optimization of active and passive control parameters is important to identify and utilize interactions between robot and environment.

4 Modeling robot, environment, and active control

The step of modeling robot, environment, and active control comprises two components:

1. **The determination of the structure of the considered robot, environment, and active control**: It must be considered, that the generation of these structures define characteristics of the resulting robot. The success of the presented approach highly depends on the generation of suitable structures and therefore requires engineering expertise. The subsequent optimization cannot compensate for bad decisions in the setup of the robot and active control structure.

2. **The implementation of a mathematical model which includes the determined structures**: This is required to apply an optimization algorithm as scheduled within the design of embodiment approach.

As discussed in Chapter 3, several special requirements must be considered when generating a model for the design of embodiment approach. Instead of presenting general concepts to create models for model-based development approaches, the scope of this chapter is rather the discussion of special requirements and difficulties, which must be considered when applying the design of embodiment approach.

The evaluation of the principles to design an embodied agent in the Chapter 3 shows, that a comprehensive consideration of agent, environment, and active control is required. Furthermore, it must be considered, that only the task and ecological niche independent constraints of all three constituents are required to be modeled (see Section 3.2.2). Task and ecological niche independent constraints are considered within the definition of goals, which is discussed in Chapter 5. The structure of the robot, active control, and interactions must be designed such that they can perform passive control and allow for parallel processing of distributed tasks. Finally the active control must be designed such that it allows for the application of reflexes, reafference and sensor fusion.

In the following sections a differentiation between structure and parameters of hardware and active control of a robot is discussed. Also techniques to achieve efficient passive control by target-oriented design of the embodiment are presented. Possibilities to implement the resulting robot structure as equations of motions or other suitable descriptions are only discussed shortly in this chapter however. Since there are no special requirements resulting from the design of embodiment approach regarding the actual mathematical implementation of the model, more detailed elaborations of typical approaches can be found in numerous related publications [5, 35].

4.1 Robot model

The model-based optimization, which is discussed in more detail in Chapter 7, is based on a multibody dynamics simulation. The considered dynamic behavior of the regarded robot can be defined mathematically by dynamic equations, which typically are a system of coupled non-linear second order differential equations. These equations are derived from a **structure** of the robot and corresponding **parameters**.

The structure describes the topology of the robot's framework.

It includes several components:

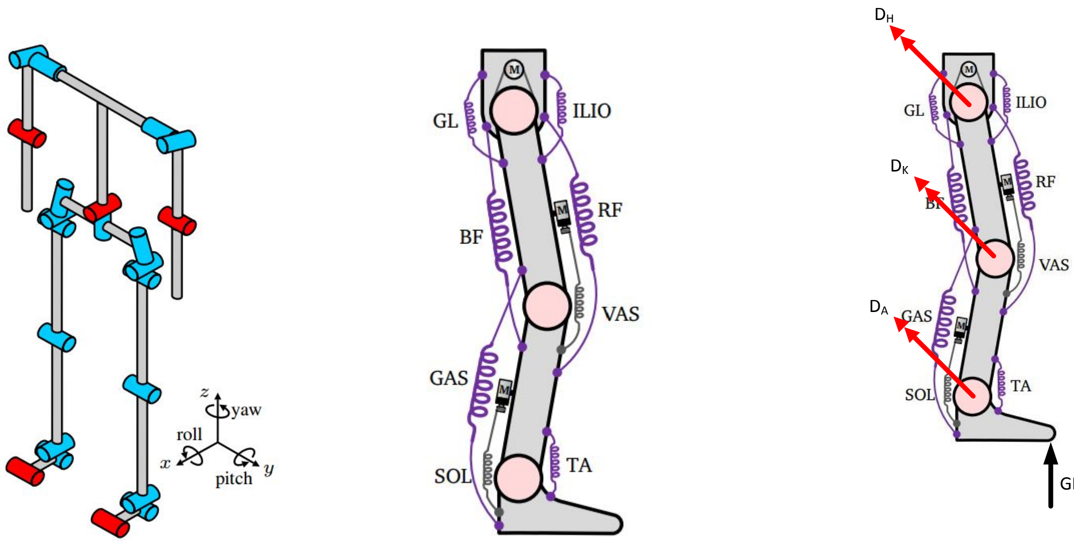
- **Joints**: Joints are defined by arrangement, type, and orientation. Figure 4.1a shows the arrangement and orientation of the humanoid robot LOLA [53] for example.

- **Links**: Links are rigid elements with mass, dimensions, and respective inertia. They are typically applied between two joints.

- **Forces**: Forces (or torques respectively) can be applied to joints or links. By the application of elastic forces or damping forces between links and/or joints, the utilization of passive control is enabled. To allow for the consideration of these forces in the design of embodiment approach, the structure, i.e. the origin and direction of these forces must be included in the robot structure. The respective structures of these elements are discussed in Section 4.1.1.

Figure 4.1 depicts two robot structures as examples. In Figure 4.1a the kinematic structure of the humanoid walking robot LOLA [53] is shown. Although the figure only presents the kinematic properties of the robot, excluding any dynamical effects, the complex assembly of the included joints is depicted. Apart from the joints, the arrangement of the links can be seen in this picture.

Figure 4.1b shows elastic elements in addition to the kinematic structure of the BioBiped robot, including the actuation. The figure only shows only one leg in 2D from side perspective. With respect to the



(a) (b) (c)

Figure 4.1.: The figures depict examples for robot structures: (a) shows a pure kinematic structure of the humanoid walking robot LOLA [53], excluding forces. (b) shows a kinematic structure including elastic elements of the humanoid walking robot BioBiped [73]. The elastic elements are used to imitate some properties of human muscles. The labels indicate the names of the corresponding muscles in a human: Gluteus Maximus (GL), Iliopsoas (ILIO), Rectus Femoris (RF), Biceps Femoris (BF), Vastus (VAS), Gastrocnemius (GAS), Soleus (SOL), and Tibialis Anterior (TA). Regarding the kinematic structure, the picture implies three rotational joints with equal rotational axis. (c) completes Figure (b) with information about damping (D_H, D_K, and D_A) and ground reaction forces (GRF). The double ended arrow depicts a torque which is applied to the respective axis.

Image source: Figure (a) [53], Figure (b) [73], Figure (c) own representation based on [73] required robot structure for the design of embodiment approach, some points of origin of forces are not included however. The missing information about damping and ground reaction forces is depicted in the complemented Figure 4.1c. Damping is depicted as red isometric arrow, implying torsional damping in the applied rotational joints. The different labels indicate the damping of the hip D_H, knee D_K, and ankle D_A. The ground reaction force (GRF) is applied as point contact at the tip of the foot.

The parameters define the configuration of the robot.

To allow for an optimization, some parameters in the structure of the robot are left variable in order to be optimized. Each configuration is defined by a set of constant parameters for these variables. They typically include:

- **Dimensions**: This includes relative positions of joints, center of mass, and inertia. Center of mass and inertia can be calculated from the component's geometry and the material density.
- **Positions**: Relative coordinates of points of origin of forces and torques must be defined.
- **Coefficients**: Coefficients or characteristic curves of the applied elastic and damping elements and (ground) contacts are relevant for the considered applications.
- **Optional assemblies**: Parameters can be used to define optional assemblies or variants. A binary parameter can define if components, as for example the biarticular structure Gastrocnemius in the BioBiped robot, are assembled or not. Parameters can also be used to select one specific assembly from a set of assemblies, as for example different foot designs.

As stated above, the design of a robot can be separated into two steps accordingly:

1. The design of the robot's structure. This process cannot be automated and requires expert's knowledge to incorporate all principal requirements. General concepts and approaches to layout a robot structure are presented in the remainder of this Section.
2. The determination of parameters. This complex step is automated within the presented design of embodiment approach. A more detailed discussion on parameters is presented in Chapter 6.

Each robot structure is specifically tailored to potentially meet all constraints given by task and ecological niche. A general approach on how to design the robot's structure however cannot be given.

In a typical bio-inspired approach, the designer applies concepts from biology to layout the kinematic structure of the robot. Examples for anthropomorphic layout of kinematic structures can be seen in Figure 4.1. According to the principles to design an embodied agent (see Section 3.2.2), the kinematic structure must be completed with additional elements with suitable physical properties to allow for the capability to perform passive control. The following section presents techniques to introduce dynamical couplings within the robot's structure.

It is claimed in the design principles in Section 3.2.2 to distribute tasks and apply local passive control. In the subsequent Section 4.1.2, methods to distribute passive control tasks are presented therefore.

4.1.1 Utilizing physical effects

In this section several typical approaches to introduce couplings between links and/or joints in order to allow for adapted passive control properties are introduced.

As discussed in Section 3.1.3, elastic elements have several properties which can support the desired behavior of embodied agents. From a control theory perspective, an elastic element with linear properties acts analogous to a linear active P-control regarding the step response. Elastic elements can therefore be applied to accomplish similar tasks as a active P-control. These tasks can include position control or the reduction of peak forces in contact situations for example.

To consider elastic elements as linear is typically a valid assumption in simulation approaches. By the application of Hooke's law, the resulting force F_k [N] of a linear elastic element can be calculated from the displacement $x_\Delta = x - x_0$[m] and the spring coefficient k [N/m]. The variable x represents the current length of the spring, while x_0 represents the equilibrium length of the spring.

$$F_k = k \cdot x_\Delta \tag{4.1}$$
$$F_k = k(x - x_0) \tag{4.2}$$

Although active P-control and elastic element are equal in terms of their step response, some beneficial properties of the active P-control cannot be transferred to the elastic element:

- A common passive linear spring cannot vary its equilibrium position. The P-control in contrast can easily be adjusted to adopt any target value.
- A common passive linear spring cannot change its spring coefficient. The P-control can be adjusted to have an arbitrary P-gain, which is the corresponding value.

Although the elastic element and the P-control have similar properties especially when considering the step response, the P-control is easier to adapt to the respective requirements during operation.

To utilize elastic elements into the construction as claimed before, additional techniques can be used however. Some of these techniques, which are used in relevant applications, are presented in the following list:

- To change the equilibrium length x_0 of the spring, the mounting position of the spring can be varied instead. The approach to change the position of the mounting position of the applied spring with an additional actuator is presented as **series elastic actuation** by Pratt [70]. By combining the elastic

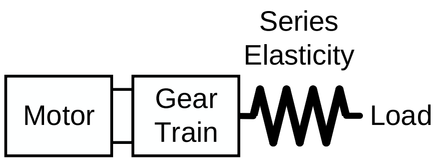


Figure 4.2.: The configuration of a series elastic actuator: Motor and gear train are connected via an elastic element to the respective load.

Image source: own representation based on [70]

element and a conventional DC-motor for example, the beneficial attributes of these components can be utilized. Besides the already discussed properties of the elastic element, these include the high energy density and the predictable behavior of the motor, as well as the acquired experiences with it. Series elastic actuation is applied for example in the bio-inspired legged walking robot BioBiped [73] or in the bio-inspired robot manipulator BioRob [50].

- The spring coefficient of an applied spring can be adapted with an additional actuator. By changing the pretension of an elastic element with non-linear spring coefficient the resulting force is equal to a force of a spring with varied spring coefficient. This approach is applied for example within the MACCEPA actuator [87]. Several more approaches of series elastic actuators with variable spring coefficient are available [85, 4]. These approaches however require a time interval to vary the spring coefficients, due to inertia of the involved actuators. This immutable fact must be considered during the design and simulation of the model.
- Another approach to implement elasticity is to emulate the effects of elasticity with active control approaches. This **impedance control** does not require actual elastic elements: The current configuration is determined and desired resulting forces are calculated and applied based on an exact model of the considered robot [3]. With this approach a wide variety of spring coefficients can be achieved quickly during operation. This emulated spring however, does not imply all benefits of elastic elements which are presented in Section 3.1.3. The variable impedance is not capable to store energy or to react immediately to disturbances for example. Moreover a detailed and exact model of the situation is required to calculate the desired elastic force. In unknown real world scenarios however, this detailed model knowledge is often difficult to obtain. Variable impedance is therefore not suitable as replacement for actual elastic elements for the application within embodied agents.

Linkages

Linkages are kinematic couplings, which are used to convert motions. In a steam engine for example, the translational piston motion is converted by linkages to rotational motion which is used to accelerate the train. Linkages utilize kinematic constraints to achieve the desired conversion. These additional kinematic constraints are introduced by the application of additional links and joints to the structure, typically generating a closed kinematic chain. By the application of these directed conversions of motions, passive control can be incorporated into the embodiment. It must be considered however, that by the application of linkages due to the increase of passive control capacity, typically the degrees of freedom of the considered robot are reduced. Linkages can be implemented in the dynamics model with strategies to include closed kinematic chains. Approaches to address this problem are presented for example in [93].

According to the guidelines discussed in Section 3.1.3, passive control should be applied whenever possible. Hence, if all required tasks can be accomplished and the required versatility is guaranteed, linkages should be applied. The following paragraphs present two typical structures of linkages.

Pantograph mechanism

Pantograph mechanisms allow for maintaining constant angles across one link. By the application of one additional link and two additional rotational joints, the degree of freedom of the considered rotational joint is lost. An illustration of a pantograph mechanism can be seen in Figure 4.3d. The kinematic constraints of the pantograph mechanism ensure, that the angle of the considered rotational joint is equal to the corresponding neighboring joint. The parallel assembly depicted in Figure 4.3d causes the marked angles to be equal.

The series of images shown in Figure 4.3 illustrates the bio-inspired origin of (elastic) pantograph mechanisms. Figure 4.3a shows the skeletal structure of a dog's hind leg. An approximation of the kinematic links is thereby emphasized with black lines, whereas the rotational joints are marked with circles. Figure 4.3b shows the muscular structure of the considered dog's hind leg. Muscles that participate in

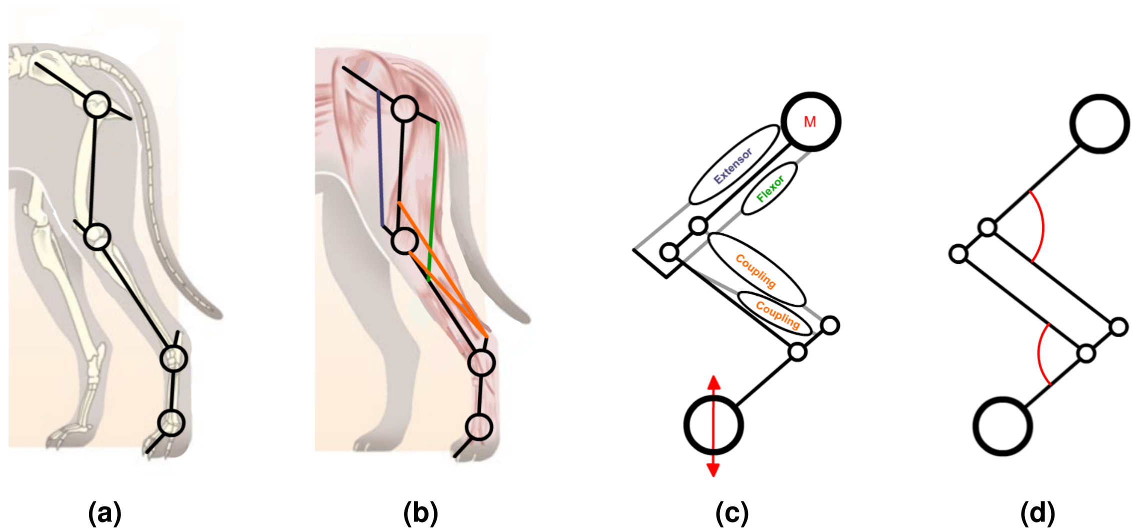


Figure 4.3.: The series of images illustrates the bio-inspired origin of (elastic) pantograph mechanisms. Detailed explanations can be found within the text.

Image source: Figures (a) and (b) own representations based `http://www.royal-canin.de/`, Figure (c) own representation based on [23], Figure (d) own representation

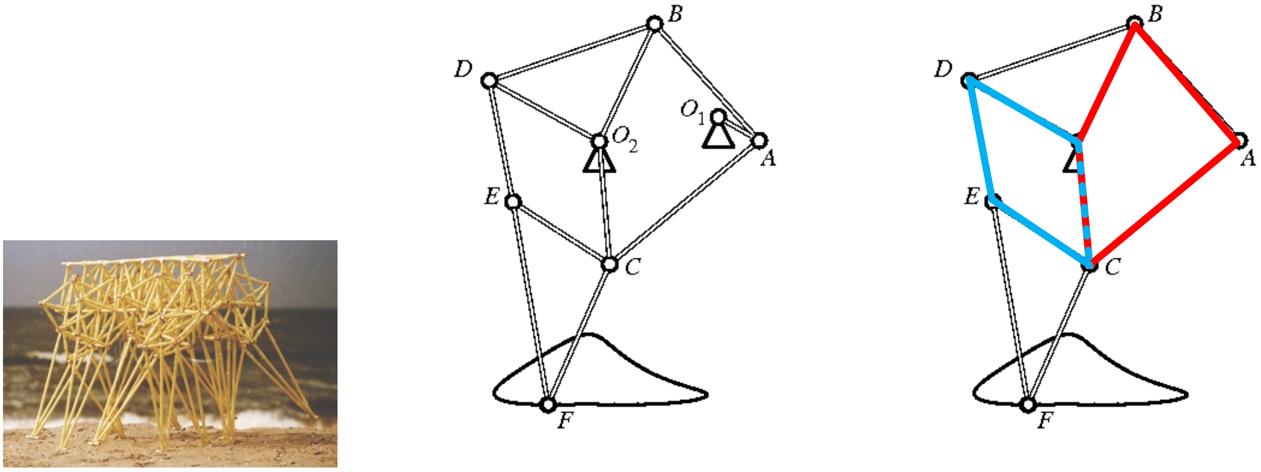
the actuation of the knee are marked in green (flexor) and in blue (extensor). Muscles to actuate the ankle are depicted in orange. It must be considered, that only a subgroup of the dog's muscles is presented in this picture. By reducing the structure and considering the actuators of the knee as rigid couplings (see Figure 4.3c), the pantograph mechanism can be extracted (see Figure 4.3d). The pantograph mechanism can convert rotational motions to parallel motions: "thigh" and "foot" always move in parallel due to the kinematic constraints. The angles marked in red are equal as mentioned above.

Instead of applying a rigid link, the pantograph can also be implemented with elastic properties. This enables moreover the utilization of all advantages resulting from elasticity discussed in Section 3.1.3.

Four-bar mechanism

The four-bar mechanism is a variation of the pantograph mechanism. By the application of non-parallel linkages, the corresponding angles are not kept equal, but follow a specific trajectory. Figure 4.4a shows a picture of Jansen's Strandbeest [44]. These constructions are capable to perform robust locomotion on flat terrain with only one rotational actuator. By the application of four-bar mechanisms the rotational motion of the actuator is converted to the desired contact point trajectory. Figure 4.4b shows the kinematic structure of one "leg" of a Strandbeest. By rotating joint O_1 the joint A follows in orbit and the rest of the construction with it. Besides at joint O_1 the structure is mounted with a rotational degree of freedom at joint O_2. The curve at F illustrates the motion of the contact point during one cycle. The motion is achieved, by coupling two four-bar mechanisms which are highlighted in blue and red in Figure 4.4c. By the application of complex passive control, the complexity of the active control could be reduced. Instead of multiple particular trajectories to describe the pathway of the individual links and joints, one simple rotation is sufficient to achieve the desired foot trajectory. It must be considered however, that versatility is reduced in comparison to a non-coupled chain of rigid links. The coupling typically reduces the degrees of freedom and therefore the working space of the considered system.

Four-bar mechanisms can also be equipped with elastic elements. Combining the linkages with elastic elements results in trajectories which are preferred against other possible trajectories, by creating a force potential: The elastic force acts on the considered link to move it from the current position to the desired



(a) **(b)** **(c)**

Figure 4.4.: Figure (a) shows a picture of Theo Jansen's Strandbeest. Figure (b) depicts the kinematic structure of one leg of a Stranbeest and Figure (c) illustrates the two applied four-bar mechanisms.

Image source: `http://www.tm-aktuell.de/TM5/Viergelenkketten/Strandbeest.html`

position. The desired configuration in this case is a set of angle ratios which is defined by the equilibrium configuration. By a proper layout the elastic four-bar mechanisms can even be utilized to increase the robustness of a walking robot by helping to synchronize joints [79]. The synchronization is crucial to guarantee robustness with respect to the landing configuration.

By proper design of the applied four-bar mechanism, desired complex trajectories can be achieved despite using only simple actuation. As claimed by the guidelines to design an embodied agent, the control is (passively) performed by the embodiment. Parts of the active motion control are replaced by the embodiment.

Dampers

Another factor which influences the dynamic properties of a robot, is the applied damping. Like linear elasticity can be compared to P-control, linear viscous damping is acting analogous to D-control when considering the step response. Damping can thus be applied to reduce overshooting and oscillations. In viscous damping the resulting force F_d[N] is proportional to the respective velocity $\dot{x}$[m/s]. The damping coefficient d[Ns/m] can be interpreted as the equivalent of the gain in a D-control.

$$F_d = d \cdot \dot{x} \tag{4.3}$$

In real world scenarios applied joints typically involve damping. To enable a suitable mapping of the generated model to the real world application, damping must be included in the model. Since the viscous damping is not depending on the position but only on velocity, only one parameter can be adapted to vary the properties. Several approaches on how to adapt damping coefficients are presented in [85].

4.1.2 Distributing tasks in passive control

Passive control actions are typically triggered by interactions with the environment. Considering spring and damper, the interaction always occurs locally: The resulting force is acting at the location where the displacement or velocity is applied. The task distribution claimed by the guidelines to develop an embodied agent is achieved already by the application of these passive control structures. The task distribution regarding active control is addressed in Section 4.3.

4.2 Physical interactions with the environment

The possibilities of an agent to interact with its surroundings are manifold. In the design process of a legged mobile embodied agent which is based on a dynamic simulation, only a subgroup of the possible interactions are relevant however. Since only motion tasks are considered, the relevant interactions are limited to force transfers. The following sections will discuss the typical interactions given by the ecological niche of the considered agents.

4.2.1 Gravity

The gravity as an impressed force effects all masses of the robot with the acceleration:

$$g = 9.81\text{m/s}^2 \cdot (-e_z) \tag{4.4}$$

with $-e_z$ being the vector pointing downwards. Typically the gravity takes effect for the complete ecological niche of the respective robot and is not dependent on niche or tasks. Therefore this force can be applied within the model of the robot.

4.2.2 Contacts

A more complex type of interaction is a contact. This type of interaction is especially important when considering walking motions: During a step cycle each leg has a contact phase, in which the respective leg touches the ground and therefore establishes a contact. The contact includes three different events and/or states:

- The **touchdown** is the moment of transition from the no-contact state to the contact state. It is characterized by its singular nature: at the touchdown high forces are transferred typically.
- The **contact phase** is the period, in which the involved bodies transfer mechanical energy.
- The moment of transition from the contact state to the no-contact state is labeled **lift-off** when considering legged locomotion.

The phase in between the lift-off and the touchdown is typically labeled flight phase. Contacts are typically task and environment dependent regarding their parameters. When considering the general effect, the contact is an independent event regarding task and environment however: the process of a contact results always in the application of forces to the involved objects based on their dynamic properties. The resulting movement is therefore influenced by the configuration and condition of the considered object. According to the principle of the three constituents (see Section 3.1.1), the structure of the contact therefore is part of the model, while the parameters are (depending on the task and ecological niche) part of the defined goals of the agent. It is therefore required to set up a structure for the contact.

Describing a contact in simulation is difficult, due to several reasons:

- At the impact, typically very high forces are transferred. In one step of the applied numeric iteration, the applied force is increased from zero to a high value. This singularity is difficult to compute.
- The structural properties of a contact are difficult to determine. Typically the structure of a contact is composed as topology of springs and dampers. A suitable topology with exact results for an arbitrary application however is still topic of research.
- Since a suitable generic structure is unavailable, the identification of parameters by means of real world experiments is also very difficult.
- When considering multiple simultaneous contacts, the determination of friction and stiction requires detailed information about the considered system's dynamics. Thus the computational effort of the simulation must be increased even further for exact results.

Considering these difficulties, a contact model can only be an approximation of the corresponding contact. Since the model is planned to be applied in a complex simulation, the computational effort must be considered also.

Typical approaches to describe a contact in simulation include point contacts and surface contacts. Although every approach to model contacts is supported within the design of embodiment approach, it is required to consider the presented difficulties and allow for a realistic result while maintaining reasonable computational effort. Possible approaches on how to design efficient and realistic contact models are presented in [48, 51, 55, 74].

4.3 Structure of active control

As discussed in Chapter 3, there are two general approaches to apply control to a robot: by active or passive control actions (see Definition 3.2). According to the principle of cheap design (see Section 3.1.3), passive control strategies should be preferred over active control when designing an embodied agent. It turns out however, that some control actions cannot be realized by passive control actions, as they are not caused by interactions with the environment for example.

To proactively induce motions to joints and therefore initiate a locomotion of the respective robot, an active control signal must be generated and applied to the actuators of the considered robot. This **feed-forward** signal can be applied in several different ways:

- A suitable trajectory of voltages can be applied directly to the DC-motor of the respective joint. (The same holds for other types of motors with their corresponding native control signal. Hydraulic actuators for example require a trajectory of suitable pressures.) The motor and all connected links are actuated correspondingly, reaching the respective joint angle or position and applying the respective force or torque. Typically this approach requires detailed knowledge about the dynamic system behavior to carefully design the trajectory in order to achieve the desired motions. In well designed embodiments however, the intrinsic robustness of the robotic system can reduce this disadvantage by allowing for a wide range of possible stable trajectories. The missing necessity of applying additional control entities is a major advantage of this approach.

- Often the desired trajectories for the considered joints exist in joint space. The definition of motions in joint space is more convenient then the consideration of motor voltages. To achieve a corresponding motion, additional joint angle/position feedback controllers are applied. The increase in convenience to define trajectories as target angle or positions is achieved by the application of additional feedback control entities.

- Equally it is possible to not apply target angle or position trajectories, but target force or torque trajectories. Suitable sensors and feedback control loops are required. In this case the predefined feed-forward trajectory must include a series of target forces or torques.

All three approaches can be used within the design of embodiment approach. Besides the different possible approaches to implement active feed-forward control, there is a theoretically infinite set of possible trajectories to apply. It proves to be difficult to select suitable trajectories which can be used to achieve the desired goals in the simulation experiments. Based on the requirements resulting from the desired motion, from the concept of embodiment, and from the requirement to apply an optimization approach, a more detailed analysis must be performed and a set of relevant trajectories must be deduced. In the following sections the respective requirements are discussed and possible approaches for a suitable implementation are presented.

4.3.1 Requirements for active control regarding the desired motion

The active control trajectory must be designed such that the desired motion is performed by the robot while interacting with the environment. The desired motion is hereby implicitly or explicitly defined by the applied goals (see Chapter 5).

It is impossible to guarantee in advance, that the desired motion will be achieved with a certain feed-forward trajectory. Insufficient trajectories that are not able to actuate the robot such that the respective goal is achieved, can be identified at the latest after the completion of the optimization: If a considered goal cannot be achieved with the given configuration of robot and active feed-forward structure, either the structure of robot, or the feed-forward control, or parameter boundaries must be adapted. Just like the selection of a robot structure, the selection of suitable feed-forward trajectories therefore requires engineering expertise.

When considering walking motions however, the motion characteristics must be reflected within the actuation trajectory: A key feature of the behavior of a walking robot is the **periodic** interaction with the environment. It is therefore important to consider the recurring interactions with the environment within the feed-forward trajectory. The selected trajectory must be able to reflect the natural frequency of the system to guarantee energy efficient locomotion and robustness with respect to disturbances in interactions. By inducing a signal with suitable oscillation, the natural frequency of the robot is met and a dynamic motion can be achieved. The trajectory for walking motions therefore must be periodic and must allow for an adaption regarding the frequency.

4.3.2 Requirements for active control resulting from the embodiment concept

The concept of embodiment rises several requirements concerning the application of active control (see Section 3.2). The particular claims are presented and discussed in the following paragraphs.

Only task and niche independent constraints must be considered in the robot model

A possible solution to realize this requirement in the robot model, is to divide the active control into structure and parameters. The structure of the active feedback control can be interpreted as a function $f(P,t) = y$ with P being the set of parameters. The current time is considered with the variable t, while information about the current state of the robot is disregarded. The resulting value y is dependent on the application and can be a force, torque, or voltage for example. The adaption of parameters is equivalent to adapting the active control properties. These can be varied to adapt the robot's behavior in order to meet the requirements of the different goals. The structure f is part of the robot model, whereas the optimal parameters P are evaluated during the optimization process.

Sufficient variation of parameters must be enabled

A potentially optimal structure of active feed-forward control trajectories must be able to adapt by parameter variation to optimally meet the requirements of all considered goals of the robot. It is therefore required, to design the structure of the trajectories such that all required motions are possible to achieve.

The optimal trajectory is typically unknown before the optimization. To not exclude possible optimal solutions that are not thought of apriori, the structure should be designed to generate generic trajectories.

A reasonable selection of parameter boundaries during the optimization process must be guaranteed. This can be achieved by including information of observations of prior simulation experiments and engineering expertise.

Active control must be designed to allow for parallel processing of motion tasks

Distributing the active feed-forward control is a difficult task, since usually the trajectories are implemented centrally, disregarding contextual information. A typical feed-forward approach is coordinated by the time parameter only. Even if multiple decentralized feed-forward trajectories can be implemented, a central coordination must be provided nevertheless.

Possible approaches to still achieve a distributed active control system are discussed in Section 4.3.4.

Application of reflexes by direct connection of sensor and actuator

The concept of embodiment suggests to prefer passive control before active control concerning the reaction to interactions with the environment. To include this claim to the active control structure, a bio-inspired approach which combines active feedback and feed-forward control can be applied. Examples for such approaches are discussed in Section 4.3.4.

Application of reafference and sensor fusion

In the concept of reafference, only deviations from the expected sensor signal are considered as disturbances. The active control process must therefore only react to these disturbances to guarantee stable system behavior. However, this concept requires an expectation of correct behavior of the system to compare the sensor results to. The setup of this expectation model is not part of the design of embodiment development process and therefore not considered in this thesis.

By means of sensor fusion the sensor signal of multiple sensors can be combined to enhance the sensor information. This approach can be used to identify the current state within a motion cycle of a robot for example. It is therefore relevant when considering the application of a bio-inspired state machine as discussed within Section 4.3.4.

4.3.3 Requirements for active control resulting from optimization

The necessity to apply an optimization algorithm to find an optimal configuration for control parameters results in requirements for the active control structure. To reduce problem complexity and therefore computational time of the optimization algorithm, the amount of optimization parameters must be as low as possible. Therefore the structure of feed-forward control must be designed, such that it allows for achieving all desired goals of the considered robot, while simultaneously having the least possible amount of parameters for adapting the signal to achieve these goals.

To enable an optimization in a reasonable amount of time, the number of optimization parameters must be set as a function of the available computational resources for the implementation of the optimization.

4.3.4 Approaches to realize active control in the robot model

Considering the stated requirements, different approaches to form the structure of active feed-forward control can be applied. Typical techniques to realize feed-forward trajectories and the corresponding coordination of multiple joints are presented and assessed regarding the requirements in the following sections.

Parametrized trajectory

A straight forward approach to meet the requirements is the application of parametrized trajectories for each involved joint. As discussed this trajectory can be provided either native regarding the applied actuator (typically voltages for DC-motors), or as target trajectory for joint angle, joint position, joint force, or joint torque.

When considering periodic motion as required during legged locomotion, a periodic signal is required. In this context only a basic approach for periodic functions is presented. The extension to more complex functions, as for example Fourier series is straight forward. According to the requirements, this signal must be adaptable to induce the natural frequency of the considered robot. Typically a suitable periodic signal with adaptable frequency is a sine wave signal.

$$F(a, f, p, t) = a \cdot \sin(f \cdot t + p) \tag{4.5}$$

In this approach the parameters include the amplitude a, the frequency f, the phase shift p, and the system time t. The optimal active feed-forward control trajectory depends on the respective application however. A general approach on how to set up a generic structure of the control trajectory is therefore not possible.

The application of parametrized trajectories meets the requirement to divide active feed-forward control into task and niche dependent and independent factions. It must be considered, that additional techniques are required to coordinate the joints of the robot among themselves.

Central pattern generator

A possible approach to coordinate motions of different sub-systems of the considered robot is by the application of a central pattern generator (CPG). This superior control device generates stimuli to the respective subsystems of the robot in order to chronologically coordinate them. Locally defined active feed-forward trajectories are typically applied to the robot, as soon as a stimulus is received. Studies show, that animals make use of central pattern generators [39], and there is also evidence, that even locomotion in humans is controlled by CPGs [47].

A CPG offers the possibility to easily adapt the walking scheme without interfering with the actual trajectories of the respective legs. Instead only the timing of the CPG must be adapted to achieve different motions or gaits. The application of CPGs however disagrees with the stated requirement to distribute the active control. To the contrary the control is centralized by the application of CPGs.

Optimal control

A perfect trajectory of control signals would lead to an optimal behavior of the considered agent regarding the respective target. The optimal control approach tries to find this sequence of optimal control inputs by optimizing complex functionals, which describe the system's behavior. Although there are similarities, the application of optimal control concepts to the design of embodiment approach is not possible.

- The equations used in the design of embodiment approach include discontinuities which must be localized before the required analytic solution of the considered system behavior can be found. This is inconvenient especially since the involved discontinuities are a key property of dynamic legged locomotion. The discontinuities must be tracked and treated separately.
- An enormous computational effort is required to solve the involved complex ordinary or partial differential equations of the robot interacting with the considered environment [6].
- Using the optimal control approach in combination with an optimization to find the optimal passive control parameters results in very long computation periods: An optimal trajectory has to be found for each passive control configuration which is considered during the optimization process. The duration is even increased by the number of parameters and goals.

The optimal control approach is not well suited to simultaneously evaluate active and passive control, while considering the different properties of the control strategies. Due to the complexity of the considered model, which includes interactions with the environment, the optimal control requires excessive computational effort, which can typically not be provided.

State machine and Walknet

The idea to centrally coordinate the sequence of actuation contradicts with the requirement to distribute motion tasks across the embodiment. An alternative approach which is (like the CPG) inspired by biology, includes a distributed coordination of involved subsystems by integrating feedback control. This behavior based approach is for example discussed within the Walknet concept in [19]. According to this approach, the coordination is not achieved by a CPG, but by signals originating from sensors and other subsystems. The created distributed coordination guarantees a context dependent control, utilizing active feed-forward and active feedback control strategies. The approach from [19] is illustrated in an example of a stick insect (see Fig 4.5, left). Figure 4.5 (middle) shows connections in-between the insect's legs (L1: front left, L2: middle left, L3: rear left, R1: front right, R2: middle right, R3: rear right). It also lists the conditions and actions which are applied to coordinate the motions of the respective legs. Arrows indicate the pathways of the stimuli. If question-marks are labeled, the respective corresponding

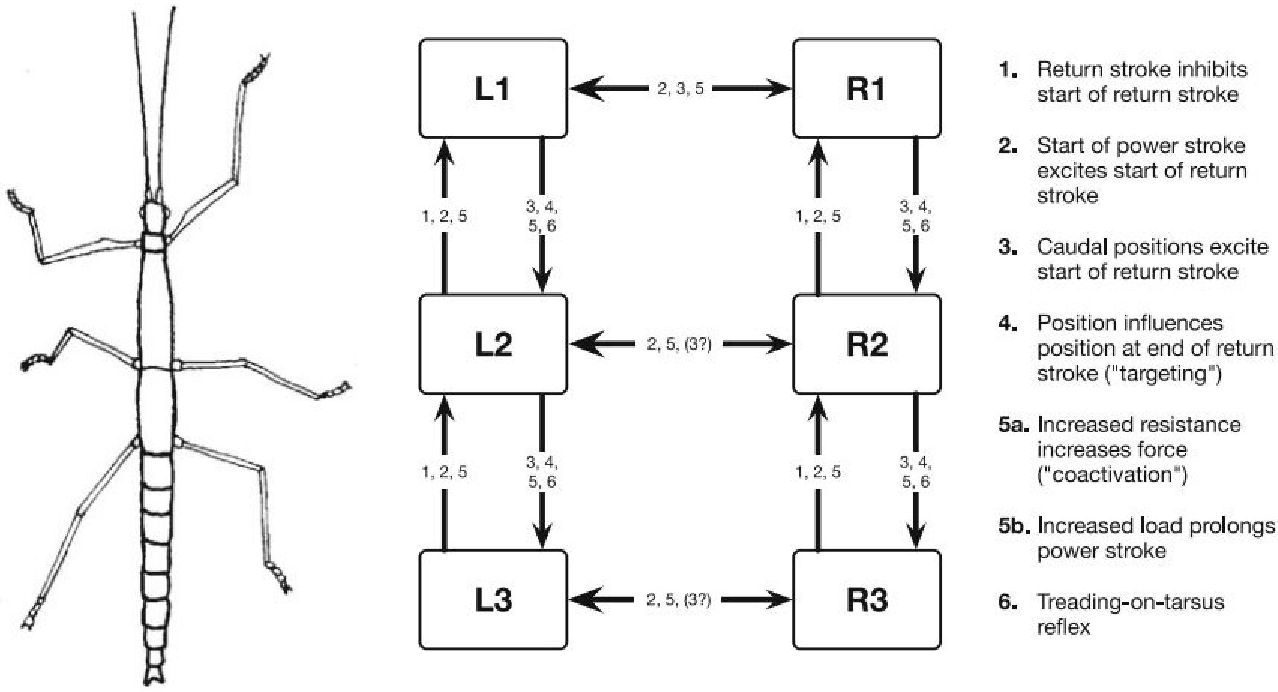


Figure 4.5.: Coordination of insect legs. Each leg is triggered by stimuli which are generated by other legs. This approach is similar to the sensor morphology discussed by Pfeifer in [63]. It allows for a distributed coordination of the involved subsystems.

Image source: [78]

observations in living stick insects are ambiguous. The presented topology of coordination allows for efficient distributed control of the legs. After the stimulus initiates the motion of a respective leg, a locally pre-programmed feed-forward trajectory is executed. An interaction of feedback and feed-forward control is performed. This way not only disturbances can be absorbed by including context sensitive information, but also the natural frequency of the system is considered implicitly. An additional evaluation of the optimal frequency is therefore not required. This is especially important when considering scenarios with large disturbances in the position and/or time of interaction: The varied interaction frequency is automatically reflected in the active feed-forward control by using contextual information. The application of a constant frequency as in parametrized trajectories without feedback information, would result in erratic behavior of the robot.

The bio-inspired approach shown in Figure 4.5 can be realized in a robot by the application of a state machine for example: Locally defined (active feed-forward) trajectories are triggered by stimuli, which can be generated by sensor information of the same or other subsystems. By hard-wiring the sensors to the respective actuators, the sensory-motor coordination can be adapted as requested by the principles to design an embodied agent discussed in Section 3.1.5. The careful positioning of the sensors with respect to the robot's morphology, as required in a hard-wired feedback approach, is suggested by Pfeifer in [63]. A proper design of sensor- and actuator-array including the corresponding couplings can lead to a distributed, embodied active control structure as desired.

To implement this state-machine approach in the robot model and allow for application in the optimization process, a parametrization is required however. Here not only the trajectory, but also the timings and conditions for a state change must be considered in the parametrization. An example for a parametrized state-machine trajectory can be found in the BioBiped examples in Sections 8.3 and 8.4.

5 Design goals of robots interacting with the environment

In this chapter, typical goals for legged robots with highly elastic actuation are introduced and evaluated. According to the scope of this thesis, only goals that are relevant for legged robots with rich interactions with the environment are considered. The presented list of examples is not intended to be exhaustive, but strives to introduce a selection of relevant motion goals when considering dynamic locomotion.

In order to be able to systematically compare different configurations of passive and active control parameters of the considered robot, a mathematical formulation of the motion goals as objective functions is required. Within this chapter possibilities for measurement and assessment of the desired goals and for the respective application in simulation are presented. Some typical motion goals are applied in examples, which are discussed in Chapter 8. To transfer the principles from Chapter 3 to the presented design approach, several requirements regarding these principles must be considered in the definition of motion goals, as discussed in Setion 3.2.3.

In the discussed requirements derived from Pfeifer's and Bongard's principles it is stated, that all task and environment dependent constraints on the robot must be considered within the design goals. According to the requirements for the design of embodiment approach, the design goals must reflect all niche dependent implicit requirements defined by the ecological niche and all task dependent explicit requirements defined by the robot's tasks.

The goals presented in the following sections are based on motion features of humans and animals, since these define the threshold for dynamic motion capabilities of legged robots. The presented formalized goals enable to achieve these typical motion goals of dynamically moving agents. These goals include relevant motion criteria as for example performance, robustness, and versatility. Through these goals significant criteria can be considered in combination. In the future, it may be possible to consider further criteria like strength analysis.

During the optimization process, the goals are evaluated in simulation experiments to guarantee the consideration of all ingredients of the complete agent: embodiment, ecological niche, and information processes.

5.1 Performance of mobility

The performance of mobility describes the quality of goal accomplishment with respect to a specific motion task. Since every robot typically has an individual motion goal, the performance of mobility is defined differently for each robot. It has to be considered, that the list of possible tasks for robots, which interact with the environment is infinite. Therefore, only a selection of typical tasks is presented to illustrate the general approach on generating objective functions for performance criteria.

Typical tasks for legged mobile robots are related to a position change. When not stated differently, the position is defined as the position of the center of mass of the robot. When considering velocities or accelerations, the velocity and/or accelerations of the center of mass is decisive.

5.1.1 Reach desired position

Definition and applicability

Mobile robots are typically desired to reach a target position and orientation with respect to the terrain.

Measurement and assessment

The achievement of this goal can be measured, by checking the position and the orientation of the robot at the end of the simulation or at a specific time.

To allow for a convenient evaluation of this goal, the distance to the target position and the deviation to the target orientation is assessed respectively. Depending on the desired goal, different norms, as for example the euclidean distance can be applied to assess the distance.

Mathematical formulation

A possible mathematical representation of the objective, which considers the euclidean distance to the desired position is presented in Equation (5.1). To determine the configuration which is able to achieve this motion goal optimal, the distance between actual position $p(t_f) \in \mathbb{R}^3$ and target position $p_{\text{desired}} \in \mathbb{R}^3$ must be minimized. In this and all following equations, $Q \in \mathbb{R}$ represents the respective objective value of the function.

$$Q = |p_{\text{desired}} - p(t_f)|^2 \tag{5.1}$$

5.1.2 Reach desired velocity

Definition and applicability

Another typical goal for mobile robots, is to reach a desired speed at a specific time or position.

Measurement and assessment

Alternatively the target velocity can be desired on average within a specific range with respect to time or space. Also a maximum or minimum velocity can be a motion goal. The velocity of the robot is part of the dynamic simulation and can therefore be represented as series over time as result of the dynamic simulation.

Mathematical formulation

To illustrate the different kinds of velocity-related goals of a mobile robot, multiple exemplary goals are presented with their mathematical formulation.

$$Q =(v(t) - v_{\text{target}}) \tag{5.2}$$
$$Q =(v(t_x) - v_{\text{target}}) \quad \text{with} \quad p(t_x) = p_{\text{desired}} \tag{5.3}$$
$$Q =(\int_{t_\alpha}^{t_\beta} v(t)\text{dt})/(t_\beta - t_\alpha) - va(t)_{\text{target}}) \tag{5.4}$$
$$Q = \max_t(v(t)) \tag{5.5}$$

Hereby Equation (5.2) returns the difference of the actual velocity $v(t) \in \mathbb{R}^3$ to a target velocity $v_{\text{target}} \in \mathbb{R}^3$ at a specific time $t > 0$. In Equation (5.3) the difference to a target velocity at a specific position $p_{\text{desired}} \in \mathbb{R}^3$ is evaluated. Equation (5.4) returns the difference to a target average velocity $va(t)_{\text{target}} \in \mathbb{R}^3$ in the time range $t_\alpha > 0$ to $t_\beta > t_\alpha$. Equation (5.5) returns the maximum velocity. Typically Equations (5.2) to (5.4) are desired to be minimized, whereas Equation (5.5) is subject to maximization.

5.1.3 Perform desired gait

Definition and applicability

Humans and animals have different gaits in order to achieve energy efficient locomotion in multiple speeds. It is therefore desired to achieve a variety of gaits in robot locomotion as well. Since gaits are not uniquely defined, the determination of a gait in legged locomotion from dynamic motion data is a non-trivial task.

Measurement and assessment

There are typically different possibilities to define gaits:

- The **duty factor** $D > 0$ presented in Equation (5.6), describes the relation of flight phases to phases with ground contact during a gait cycle [10].

$$D = T_c/T \tag{5.6}$$

  In this equation, $T_c > 0$ is the ground contact time of all involved feet and $T > 0$ is the duration of one stride. This approach however can only be applied to distinguish gaits by means of the proportion of their flight-phase with respect to the stride length. Although a general assignment to typical gaits is not possible, this approach is suited to easily compare gaits.

- The **Froude number** Fr > 0 is a dimensionless speed, which describes the relation of centripedal forces to gravitational forces.

$$\text{Fr} = \frac{\text{centripedal force}}{\text{gravitational force}} = \frac{mv^2/l}{mg} = \frac{v^2}{gl} \tag{5.7}$$

  When assuming the center of mass of the robot moves on an arc trajectory, while a foot is in contact with the ground, the centripedal force can be calculated as mv^2/l. Hereby $m > 0$ depicts the mass of the robot, while $l > 0$ represents the distance between ground contact point and center of mass. In the walking scenario this approximately correlates with the length of the considered leg. With Fr ≥ 1 the centripedal forces exceed the gravitational forces. An arc-like movement is therefore no longer possible. A Froude number larger than 1 therefore theoretically requires the legged mobile agent to leave the ground during strides and introduce flight phases. Humans and animals however change their gait from walk to run and trot respectively, with a Froude number of Fr ~ 0.5 [36]. The change from trot to gallop in four legged agents is done at Fr ~ 2.5 [36].

- The **Q factor** is the ratio of conservative kinetic energy to non-conservative metabolic energy losses. It can also be used to describe the transition between walking and running. While in walking the Q factor is less or equal to 1, the Q factor in running is larger than 1 [31]. This approach however is more difficult to evaluate and requires additional information with respect to mere dynamic data results.

Owaki et al. combine the Froude number with special discriminating properties of the ground force trajectories to identify a two-legged running gait [61]: Only if the Froude number is larger than 1, and the ground force trajectory follows the desired path, the gait is identified as running gait. Likewise other approaches can be combined.

Mathematical formulation

Legged robots can be required to perform a specific gait or a gait change within the duration of the simulation. Target of the example in Equation (5.8) is the evaluation, if the robot is running (or trotting in four-legged locomotion respectively). The gait is measured with the Froude number in this example. While the objective returns 0, if the target gait of running (or trot) is achieved, it returns a larger value, if the gait is not achieved. Hereby the distance to the target gait with respect to the applied measurement is returned for more convenient optimization. The target objective is subject to minimization.

$$Q = \begin{cases} 0, & \text{if} \quad \mathrm{Fr} \geq 1 \\ (1 - \mathrm{Fr}), & \text{else} \end{cases} \tag{5.8}$$

5.1.4 Overcome target obstacles

Definition and applicability

When considering real world scenarios, a large quantity of obstacles is present. Another goal for mobile robots is therefore the ability to overcome specific obstacles like steps or ramps.

Measurement and assessment

To measure if a robot is able to overcome a target obstacle in simulation, the corresponding obstacle needs to be implemented in the simulation experiment as part of the environment. To assess if the robot is able to cross the obstacle with the current configuration, the position of the robot at the end of the simulation can be considered for example. If the robot is located behind the obstacle, the currently applied configuration suffices.

Mathematical formulation

The mathematical formulation for this approach is equal to Equation (5.1).

The goal to overcome an obstacle is very similar to the goal for robust locomotion, which will be presented in Section 5.3: both goals require to overcome irregularities. The measures for robustness discussed in Section 5.3 can also be applied in the here presented goal to overcome obstacles.

5.1.5 Reach desired jumping height

Definition and applicability

In some scenarios the jumping capability of a robot must be assessed. Especially when comparing robots with series elastic actuation to robots with stiff actuation it shows, that such with series elastic actuation have a more human-like performance regarding hopping.

Measurement and assessment

To evaluate the desired jumping height, the peaks of the position trajectory are analyzed regarding their height. A possible target when considering the jumping height is to achieve a maximum jumping height, or to maintain a constant peak height across multiple jumps. The maximum jumping height can easily be extracted from the position data. This objective is subject to maximization, of course. The goal of maintaining a constant jumping height requires a more sophisticated analysis of the position time series.

Mathematical formulation

The presented Equation (5.9) shows an example of how to approach this analysis. The distances of the jumping peaks to the desired height $\text{peak}_i^d > 0$ are added for every jump of the simulation. The auxiliary-function *peak* returns a list which contains all N local maximums of a function.

$$Q = \sum_{i=1}^{N} |\text{peak}_i - \text{peak}_i^d| \tag{5.9}$$

This objective summarizes the differences of the actually achieved jumping height to the desired jumping height and is therefore subject to minimization.

5.2 Versatility

Definition and applicability

Robots are in general desired to perform multiple motion goals. As discussed in Chapter 3, the requirement of versatility is an important part of an embodied intelligent agent. According to different established definitions of robots [88, 42] the versatility is even an inherent property of robots. A list of typical motion goals for legged mobile robots is presented in the preceded Section 5.1. The objective versatility has no distinct requirements but to achieve multiple of these objectives in sufficiently versatile locomotion scenarios. It moreover requires to perform multiple tasks with consistently good quality, while maintaining the integrity of the robot.

Measurement and assessment

To measure, if a robot or robot configuration is able to perform different tasks with sufficient quality, the different corresponding objectives have to be analyzed in simulation experiments. Typically this requires to perform multiple and sufficiently different experiments. The assessment of the individual tasks is executed according to the respective goals presented in Section 5.1. To conclude and select a configuration which fits all objectives is a non trivial task. The possible results and strategies to find a suitable design decision is discussed in detail in Chapter 7.

Mathematical formulation

As discussed, the objective of versatility is a composition of multiple performance goals. The mathematical formulation therefore corresponds to a set of performance criteria and a carefully selected set of experimental setups representing the variety of different locomotion scenarios and tasks. The composition in a multi-objective optimization problem over multiple (simulated) locomotion experiments is discussed in detail in Chapter 7.

5.3 Biological robustness

Definition and applicability

Usually robustness in control considers active dynamics only, whereas in this thesis active and passive dynamics and control properties are considered together. This motivates the consideration of biological definition of robustness.

In real world scenarios the robot is exposed to non perfect environments. The stabilization after contact situations with non expected disturbances is typically difficult however. To allow for the application in real world scenarios it is therefore required to render the robot robustly with respect to these disturbances. In the context of this thesis, a definition of biological robustness based on a publication of Kitano [45] is applied. He defines robustness as *[...] a property that allows a system to maintain its functions against internal and external perturbations*. These perturbations are limited to variations in position or time of the interaction. The magnitude of variation and forces is hereby task and robot dependent. The ability to withstand larger disturbances however, is desired.

Measurement and assessment

To measure robustness, multiple experiments are performed in simulation with slightly varied circumstances regarding interactions. The variation is hereby determined by the expected variance of the targeted real world scenarios. In [57], the robustness is evaluated in simulation by the application of forces, that push the robot forward and backward. The level of forces the robot can withstand without falling is the indicator of robustness in this approach. Plestan [67] additionally investigates the behavior of the robot with a change of the walking surface's height and elasticity to analyze robustness in simulation. The here applied approach to measure robustness is based on an approach by Kitano [46] however, which does not only include the actual variation of time and position, but also the expected probability of the disturbance of the interaction.

Mathematical formulation

Kitano presents in [46] a general mathematical formulation for the investigation of robustness.

$$R^S_{a,P} = \int_P \psi(p) D^S_a(p) dp \tag{5.10}$$

The robustness $R > 0$ of the system S with respect to a motion goal a against a set of perturbations P results according to Kitano's definition from the integral of the probability for a perturbation $\psi(p)$ times an evaluation function $D(p)$, with $p \in P$. The evaluation function determines, whether the system can maintain its function after the disturbance is applied. If the function cannot be fulfilled with perturbation p_n for example, then $D(p_n) = 0$.

The mathematical formulation of the objective of robustness used in the examples presented in this thesis is very similar to the one used by Kitano.

$$R^S_{a,P} = \int_P \psi(p) Q^S_a(p) dp \tag{5.11}$$

Instead of the evaluation function $D(p)$, an objective function Q to evaluate performance is applied.

A careful consideration of the robustness requires a suitable set of perturbations P. The resulting metric assesses robustness with respect to disturbances in time and position of interactions for a specific objective. It depends on the applied objective function, if the resulting metric is desired to be minimized or maximized. Examples for possible implementations of this objective are presented in Chapter 8.

5.4 Energy efficiency

Definition and applicability

A typical goal for autonomous mobile robots that are desired to perform in outdoor scenarios is a low energy consumption for motion tasks. The energy efficiency is therefore evaluated based on the external energy that is applied to the agent in order to achieve the desired motion. The considered class of elastically actuated robots has the ability to store and restore energy with the applied springs. A significant exploitation of elasticity is therefore target of this objective.

Measurement and assessment

The energy consumption can be measured by investigating the applied active control signals, including electronic feedback and electronic feed-forward control. These signals have to be integrated over the duration of the respective simulation to achieve the overall energy consumption. Alternatively the motor voltages or other motor input signals can be used for the evaluation of this goal.

Mathematical formulation

To calculate the energy consumption in the interval t_α to t_β, this equation can be applied as objective function:

$$Q = \int_{t_\alpha}^{t_\beta} \sum_{i=1}^{n_u} |S_i| \tag{5.12}$$

The sum of all n_u active control signals is hereby represented as S.

6 Parameters for robot design and control

As discussed in Chapter 4 the configuration of a robot is defined by the robot's structure and its set of parameters. The mechanical structure of the robot as well as the structure of the active control is generated within the design of the model presented in Chapter 4. The parameters are an important issue in the design of embodiment approach. Special requirements regarding the parameters are discussed within this chapter in detail. Typically there are different categories of parameters to determine the properties of the different structures:

- **Mechanical parameters** to describe the dimensions and physical properties of the robot's hardware.
- **Control parameters** are further distinguished with respect to the origin of the respective control signal:
  - **Feedback control parameters** are typically parameters to describe the tuning of common active control approaches, as for example PID control.
  - **Feed-forward control parameters** determine a parametrized control signal. The applied control signal is typically the target trajectory for position, velocity, or force-based control approaches.

These typical classes of parameters arise from the conventional sequential robot design methodology: The design of mechanical parameters is performed during hardware layout, while the control parameters are applied in a separate development step (see Section 2.3.1).

The new comprehensive design of embodiment approach includes the combined layout of active and passive control, and requires the consideration of all control-parameters during hardware development. A classification to the categories mentioned above is therefore no longer useful for the presented development approach. Instead a new approach to classify parameters is introduced, which is based on the variability of the respective parameter during operation of the robotic system: Versatile robotic systems require to adapt to current constraints given by the ecological niche or the task. Parameters therefore have to be classified based on their respective possibility to vary their control properties. This allows for a comprehensive layout of the considered set of parameters, while simultaneously guaranteeing to maintain the required versatility of the robotic system. The introduced new categories for parameter classification are presented and discussed in detail in the following sections.

Only few specific requirements arise from the principles of embodiment for the design of parameters. According to Section 3.2.4 both active and passive control parameters need to be considered. This includes task dependent and task independent parameters. Furthermore, the parameters need to be selected such that all defined goals are optimally achieved. This requirement is implicitly fulfilled by the application of an optimization. It must be ensured however to include all relevant parameters in the optimization process.

6.1 Constant parameters

A large proportion of the parameters involved in the robot's hardware or control is constant for various reasons. The actual reasons however imply constraints to the development process, and are therefore important to discuss in detail. In the following sections possible classes of constant parameters are presented.

6.1.1 Natural constants

Parameters that are given by the laws of physics are fix and cannot be varied. They cannot be included in the optimization process. A typical example for a natural constant which is relevant for the development of mechanics is gravity. Although the applied value $g = 9.81[m/s^2]$ is not constant due to its dependence on masses of the involved objects and their respective distance, it is considered as constant in relevant applications. Other relevant natural constants are for example material density, which contributes to define the correlation of geometry to inertia and mass, or surface properties, which determine the dynamical properties of contact situations.

6.1.2 Specific requirements

In contrast to the natural constants, parameters which are defined by specific requirements are not constant by the laws of physics. Specific requirements can be divided into several subgroups:

- **Technical requirements**: Parameters resulting from technical requirements are needed to secure the functionality or the mechanical strength of the robot. A typical example for a technical requirement is a damping parameter which results from the necessarily applied bearing.
- **Target constraints**: The constraints result from the requirements of the ecological niche or the specific task of the robot. A typical example for target constraints of a legged mobile robot is the kinematic structure, thus the topological arrangement of links and joints. Since the robot is required to be adapted to these, the target constraints are not considered variable during the optimization process.

In order to reduce the number of parameters for the optimization, as many items as possible should be included in the category of specific requirements. All parameters which are fixed, are not required to be considered in optimization. The resulting reduction of the problem dimensionality is highly desired in order to allow for a faster or more accurate computation of the optimal solution. An increase of the number of specific requirements can be achieved with different strategies:

- **Availability**: The availability of required hardware elements must be checked and only available elements are required to be considered. It is not required to perform continuous optimization with respect to a specific parameter, if only a discrete number of configurations for this parameter is available. Therefore the properties and accordingly the parameters of this considered element are reduced to the available discrete values. In a real hardware scenario it is possible to only have two types of springs in stock for example. In this example it is not required to consider a continuous range of spring coefficients, but it is sufficient to only consider the available ones.
- **Weighting**: Although the principle of the complete agent (see Section 3.1.2) states, that the agent always has to be considered in its entirety, this complete consideration is not always possible during the development process due to computational restrictions. The developing engineer must rank the importance of the involved parameters for the resulting performance regarding the desired goals. The engineer can then set a maximum number of parameters and select the used parameters for optimization based on the ranking. All parameters which are not included in the optimization are fixed

to a value, that can result from preliminary experiments or from the engineers expertise. Thus the design of embodiment approach can be scaled to computer systems with different computational power.

For a more detailed discussion on restrictions resulting from the optimization process, see Chapter 7.

6.2 Control parameters

Every parameter which is not fixed for any of the presented reasons can participate in the control of the system. This includes both active and passive control parameters. In the context of embodiment, the control parameters allow for the required adaption of the embodiment to the constraints as demanded by the principle of ecological balance discussed in Section 3.1.6. To guarantee the required comprehensive consideration of active and passive control (see Section 3.1.2), there is no differentiation between active and passive control parameters in the presented approach. Nevertheless, the existing control parameters are categorized into new classes, which reflect the ability of the respective control to vary its properties. In the following sections, these new categories to classify control parameters are presented. Since these parameters can be adapted during optimization, they are labeled variables.

6.2.1 Time independent variables

This class contains parameters, that cannot be varied after the initial adjustment based on the optimization results. All control elements with time independent variable have constant control properties. To find an optimal value for this class of parameters is especially difficult, since the properties of this control elements cannot be adapted to meet the different requirements of the considered goals. Instead, one unique optimal configuration is wanted to equally meet all defined constraints. This especially is relevant for the important requirement of versatility: Multiple motion goals typically result in multiple different optimal solutions for the considered parameters. A typical example for time independent variables is a spring stiffness of a series elastic actuator. The spring stiffness is usually considered constant. In an initial setup however, the spring coefficient can be adapted once. If no value can be found that sufficiently complies with the considered constraints, different strategies can be applied to still achieve an embodied agent with sufficient performance. These strategies are presented and discussed in Chapter 7.

6.2.2 Time dependent variables

Beside control elements with constant properties, there are control elements that can change their respective control properties during operation. This capability for adaption allows for an adaption to the requirements given by the different motion goals and therefore guarantees the requested versatility of the agent (see Section 3.1.9). Time dependent variables can adapt continuously, with respect to operation time, to optimally meet the current requirements. They typically can attain an arbitrary value within given boundaries. The speed in which the parameter can be adapted is given by the dynamics of the respective process that is used for adapting the control properties. Typically active control parameters can be adapted instantaneously, while passive control parameters can only be adapted with a delay. This delay is due to the dynamic properties of the actuator which performs the adaption process. A typical example for time dependent variables are target joint angle trajectories. These trajectories are not constant but vary over time to generate the desired motion behavior. The ability to adapt the control properties over time however requires the design of the corresponding active control trajectory. If the process to layout a trajectory to optimally adapt control parameters is done according to the principle of the complete agent (see Section 3.1.2) considering all interactions between embodiment, environment, and active control (information processing), the overall problem dimension is increased significantly. Moreover the increase of complexity of active control disagrees with the principle of cheap design (see Section 3.1.3).

The application of time dependent variables therefore is recommended only if no substitution with time independent or switchable variables is possible. However, especially when considering feed-forward control, typically no replacement to variable control elements can be found.

6.2.3 Switchable variables

Switchable variables describe time independent parameters with a number of discrete states among which can be selected during operation. As mentioned before, no difference is made between active and passive control parameters. The class of switchable variables therefore includes all types of variables that can switch their respective control properties among a discrete set of properties. Concerning passive control parameters, the shift can be accomplished by the application of additional actuators or even by a manual intervention. Active control parameters can of course also be implemented to be switchable. For both, passive and active control parameters, the switching process itself must be achievable in a sufficiently short period. In human walking the ground contact properties can be switched by changing the shoes for example. This corresponds to a change of applied feet in legged robots.

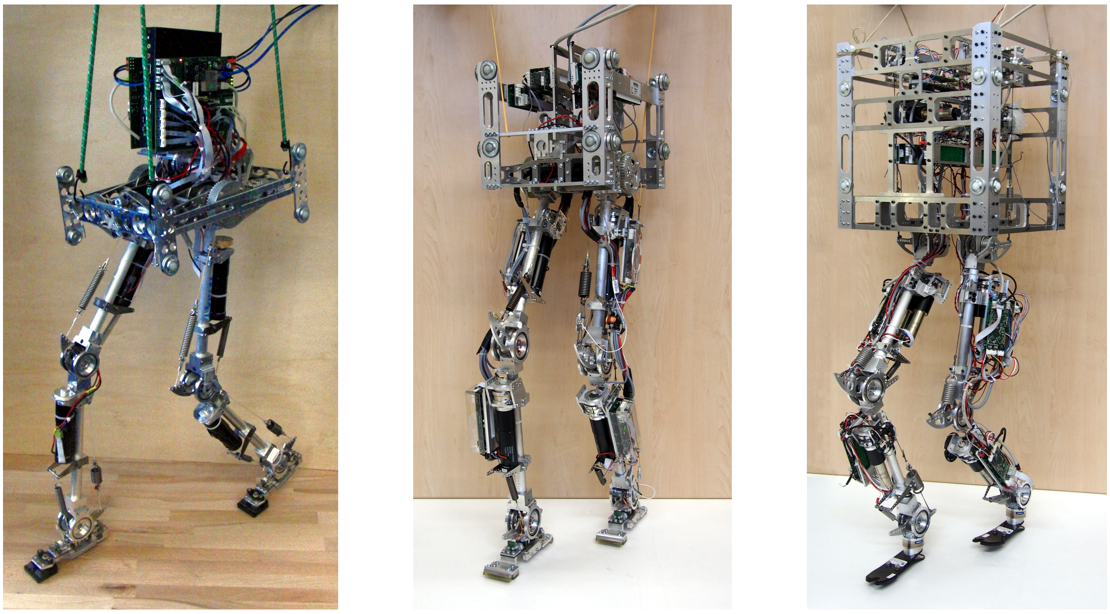
Typically switching between a small set of possible configurations to achieve the required passive control parameter is easier to realize from a technical perspective. But also considering the implementation of active control trajectories, the switchable parameter is easier to realize: In contrast to the more complex variable parameter trajectory, only discrete changes of the parameters to adapt to defined tasks are required. When considering the principle of cheap design (see Section 3.1.3), the application of switchable variables is preferable to time dependent variables: Although time dependent variables can increase the utilization of physical effects when applied to passive control elements, they always increase the complexity of the active control trajectory required for their respective adaption.

6.3 Parameters as key to time perspectives

The presented different types of parameters can be discussed regarding the time perspectives. The different time perspectives are considered relevant in the context of embodiment by Pfeifer in [62]. Although these time perspectives had a more important role in earlier versions of the principles to develop an embodied agent [65], the time scales need to be considered according to Pfeifer, as they are prerequisites for the emergence of intelligence.

Pfeifer's idea is based on older concepts from biology [84], that discuss biological organs as responsible for behavior. These organs however are not designed once and suffice every possible situation, but they perform and evolve in different time scales. According to Pfeifer *time scale integration is crucial when designing intelligent embodied agents* [62, p. 175, Section 5.11]. He deduced three different time scales:

- **The "here and now"**: An agent has to react on the conditions and constraints of the current situation. The embodiment and the active control must be designed to manage all relevant situations and disturbances.



(a) (b) (c)

Figure 6.1.: The comparison of the three BioBiped generations (a) BioBiped1 from 2010, (b) BioBiped2 from 2012, and (c) BioBiped3 from 2014 reveals its phylogenetic evolution. Several details were enhanced based on experiences to enable a better achievement of the desired motion goals.

Image source: own representation

- **The ontogenetic time scale**: An agent is required to manage certain tasks during its lifespan. The agent is adapted during operation to optimally meet the requirements given by the constraints. For that the agent is constantly adapting to improve its performance regarding possibly varying scenarios.

- **The phylogenetic time scale**: Between generations of agents certain improvements in embodiment and information processing emerge. During this evolution process the particular agent is adapted to optimally meet the constraints.

According to Pfeifer, improvements made in ontogenetic, as well as in phylogenetic time perspectives advance the capability of the individual agent to master its ecological niche and its tasks. A consideration of different time perspectives is therefore required to improve the performance of embodied agents. The suitable reaction to challenges in all time scales is made possible by active and passive control effects, involving motion and behavior control levels. The different time scales however can be matched to the presented development approach to some extent.

- Active and passive control are reacting in the "here and now" time perspective. Variable and switchable control properties allow for an optimal adaption to the current constraints. By the consideration of time dependent and switchable variables during the agent development, the agent suffices the requirement of the "here and now" time scale.

- In the lifespan of an agent, it is exposed to a set of several scenarios. All active and passive control parameters must be determined to suffice all requirements of the relevant scenarios. This is taken into account, by the simultaneous consideration of all goals of the agent in a multi-objective optimization process. The ontogenetic time perspective therefore is considered during the design of embodiment development process.

- Since typically individual robots and no populations of robots are developed, the consideration of robots on a phylogenetic time scale is difficult to consider in a robot development process. However, robot populations are implicitly considered in genetic optimization algorithms. Here a set of agents is compared with respect to their performance in the considered goals. This consideration of different robot configurations during genetic optimization can be mapped to the phylogenetic time scale.

  Often a parameter optimization is not sufficient and robots require structural improvements. Here typically manual improvement of the robot's structure is done by engineers. These improvements are based on experience and observations of the preceding generations of robots. This manual consideration of previous robot generations and the corresponding adaptions to the robot structure can also be considered as phylogenetic time scale. Figure 6.1 shows the three generations of the BioBiped robot for example. Based on experiences with simulation and real robot experiments the robot was enhanced to better achieve the desired motion goals.

The crucial requirement of considering time perspectives in agent development is therefore met in the presented development approach.

7 Optimization of embodiment

In the previous chapters the requirements to design an embodied agent were formalized. Moreover the different resulting steps of the design of embodiment approach were evaluated and discussed in detail. In this chapter these steps are used to create an optimization problem in order to determine the optimal passive and active control configuration regarding the desired behavior of the robot. The considered class of finite dimensional optimization problems is based on a **simulation of a dynamic robot model** and involves both **multiple different experiments**, as well as **multiple objectives**.

The optimization of dynamic systems through multi-body simulation is an established approach to find optimal hardware configurations [8, 20, 81]. Even when considering multiple objectives, established approaches to evaluate desirable parameters exist [9, 20, 21, 22]. As illustrated in Figure 2.5 and discussed in Chapters 2 and 3, the ingredients of such a simulation based optimization approach are, besides the optimization algorithm itself, modeling, criteria definition, and parameters. The optimization itself is preferentially performed with stochastic optimization approaches [22], as the risk of finding local solutions is reduced.

The application of multiple experiments in optimization problems is also considered in related publications. Typically multiple experiments in optimization are used to perform parameter identification. In [13] for example, least square regression is applied to optimally fit model behavior to observed behavior of a real robot which performs different motions in a series of experiments. To robustly identify the respective parameters disregarding measurement inaccuracies, sufficient information about the robot's dynamic behavior is required. In the cited publication the experiments are performed with real robots instead of dynamic simulation models to gain the desired insight in parameter properties. The combined application of multiple objectives and multiple experiments for multi-body dynamic simulation optimizations however is not addressed in related publications.

The presented design of embodiment uses a combined multi-body simulation based optimization approach with multiple experiments and multiple objectives. As discussed in Section 3.2.5 this combination results from the requirements which are derived from the principles to design an embodied agent:

- **Multiple objectives** are required to allow for the consideration of all desired goals of the robot. Only by considering multiple objectives, multiple motion goals and constraints can potentially be considered with equal priority.
- **Multiple experiments** are required to guarantee versatility with respect to the considered scenarios of the robot. By performing multiple relevant experiments which represent the considered scenarios, the robot's performance in these scenarios can be assessed. This assessment is required for a targeted optimization.

A multi-objective and multi-experiment optimization problem however, can be optimized with established multi-objective optimization approaches. Details and differences are presented in the upcoming sections.

A further requirement resulting from the principles to design an embodied agent is to simultaneously setup active and passive control parameters. This is achieved implicitly by considering the three constituents embodiment, interactions with the environment, and active control together in each simulation (see Section 3.1.1).

The following sections are not intended to present a detailed explanation of how to set up a general multi-objective optimization, since this is subject to several publications. Instead a discussion on the requirements given by the design of embodiment and possible approaches to address them is presented. In Section 7.1 therefore the formulation of the optimization problem regarding the special requirements is presented. The application of a multi-objective optimization typically results in a set of optimal solutions. It is however required to select one suitable solution to be applied to the resulting robot. In Section 7.2 evaluation strategies to proceed with such a set of multiple solutions are discussed.

7.1 Formulation of the optimization problem

A typical multi-objective optimization problem includes the objective functions, a sensitivity analysis, and the optimization algorithm [20]. A schematic of such an approach is depicted in Figure 2.5. In the following sections the setup of these components is discussed regarding the new design of embodiment concept. Due to the special influence of different types of parameters (see Chapter 6), the role of parameters and their corresponding constraints with respect to the optimization are also discussed in this section.

7.1.1 Parameters

During the optimization process, the particular properties of the different optimization parameters $p \in P$ must be considered. P typically equals a mixed set of real and integer values. By means of the classification of parameters to the categories presented in Chapter 6, a convenient consideration is possible. The assignment to the different classes is relevant for the further optimization process:

- **Constant parameters** are not included in the optimization as variables. Their values are predetermined by natural constants or design requirements of the robot.

- **Time independent variables** $p_{in} \in P_{in}$ which are constant during operation can only have one value that must remain equal for the operation in all different scenarios. A proper selection of these parameters is therefore crucial. With respect to the multi-objective optimization, this class of parameters must attain the same value in all optimal configurations. These parameters are explicitly subject to multiple objectives. In fact these parameters embody (besides the structure of embodiment and active control) the connection between the different considered goals. A reasonable setup of these parameters therefore is the key problem of the design of embodiment approach and central topic of the following Section 7.2.

- **Time dependent variables** $p_d \in P_d$ can arbitrarily change their values during operation. The optimal progression of this class of parameters over time can therefore be different for each objective. It is not necessary to consider these as multi-objective parameters.

- **Switchable variables** $p_s \in P_s$ can be adapted for each required scenario independently. Like time dependent variables they are not required to be considered as multi-objective parameters therefore.

It turns out, that only time independent variables P_{in} must be addressed with a multi-objective approach. All other parameters P_d and P_s can be optimized with a single-objective optimization algorithm. The present problem therefore can be considered as a combination of multi- and single-objective optimization. A possible solution to efficiently address this special property is presented in Section 7.1.4

7.1.2 Objective functions and constraints

Typically each motion goal is addressed in a separate problem formulation, which can be formulated as non-linear objective function $Q(p)\colon \mathrm{P} \to \mathbb{R}$, with P describing the whole parameter space, that is typically multi-dimensional (discrete or continuous), depending on the individual problem. Moreover sets of non-linear equality and inequality constraints must be considered during optimization. This problem can be formulated as non-linear program:

$$\max_{p} Q(p) \tag{7.1}$$

$$s.t. \quad g_i(p) \leq 0, \quad 1 \leq i \leq n_g \tag{7.2}$$

$$h_j(p) = 0, \quad 1 \leq j \leq n_h \tag{7.3}$$

$$p \in P$$

A solution p is valid, if it fulfills all constraints. A solution p is optimal, if it is valid and there is no other valid solution p^* with $Q(p^*) \leq Q(p)$. The mathematical problem formulation consists of an objective function shown in Equation (7.1), a set g_i of inequality constraints, and a set h_j of equality constraints shown in Equations (7.2) and (7.3) respectively, with n_g and n_h being the number of constraints. Equation (7.1) is a sufficient formulation even when considering minimization problems, since $\max Q(p) = -\min(-Q(p))$.

From the principles to design an embodied robot, special requirements regarding the problem formulation arise.

- To guarantee the versatility of the resulting robot, each goal of the robot must be considered in a distinct problem formulation.
- Each problem formulation can be based on a suitable number of simulation experiments. It is also possible to use results from a simulation experiment in multiple problem formulations.
- In the formulation of objective functions and constraints all discussed requirements to design an embodied agent are combined. Therefore it must be guaranteed, that each of these requirements is considered in the problem formulation:
  - **A model of all factors that are task and ecological niche independent**: This includes the structure of the robot embodiment, the structure of interactions with the environment, and the structure of active control elements (see Chapter 4).
  - **The assessment of the robot's behavior**: Depending on the behavior of the robot during the simulation experiments, the objective function returns a corresponding objective value. This value is used during the optimization to evaluate the optimal configuration (see Chapter 5).
  - **The definition of adjustable parameters**: Usually not all parameters can be varied likewise to adapt the robot's behavior (see Chapter 6).

Typically the desired motion goals are formulated as objective functions. The behavior of the robot in its environment can be formulated as set of constraints. In the applied multi-objective optimization the constraints are considered as penalty terms. Several penalty function approaches can be applied:

- **Penalty functions**: By the introduction of penalty functions, the separate constraint functions (Equations (7.2) and (7.3)) can be replaced. To guarantee that all the resulting objective values are valid, a penalty value is added to the objective value if a constraint is violated. Typically there are several strategies to apply a penalty function (outer penalty function, inner penalty function, barrier function, exact penalty function).

- **Elimination of constraints**: It is sometimes possible to reduce the number of constraints. This can be achieved for example by only considering the constraints, which are active in the desired solution.
- **Lagrange formulation**: If it is possible to reformulate the constraint optimization problem and introduce additional Lagrange variables, the problem can be approached as optimization problem without constraints. The problem is reduced to an objective function, since the constraints are included in this function. It must be considered, that the Lagrange approach requires gradient information.

7.1.3 Sensitivity analysis

Sensitivity analysis is a very important aspect of optimization processes in general, but especially in the presented design of embodiment approach. Due to the high complexity of the model and the objective function, these can be considered as black boxes: The relationship between input and output of the problem formulations are deterministic. Possible inaccuracies within the model or small deviations of the input signal can lead to large deviations of the output signal. To guarantee the quality of the model and therefore the results of the applied optimization an analysis of the robustness of the model is performed. Within this sensitivity analysis several aspects of the model can be checked. The analysis typically requires to perform many iterations at specially designed parameter configurations.

However there are no special requirements resulting from the design of embodiment approach for the sensitivity analysis. A more detailed discussion about sensitivity analysis can be found in [76] for example.

7.1.4 Selection of a suitable problem formulation and optimization algorithms

Due to the complexity of the present optimization problem, a careful analysis is required to identify and select suitable problem formulations and optimization algorithms. This section is intended to analyze requirements to the problem formulation and optimization. Based upon the identified constraints suitable algorithms are presented.

Three special requirements regarding the present problem influence the selection of a suitable optimization algorithm:

- The requirement to consider multiple objectives
- The requirement to consider multiple simulation experiments
- The impossibility to calculate gradient information in the particular simulation experiments

These requirements are addressed in the following paragraphs in more detail.

Multiple objectives

Multiple objectives must be considered to achieve the desired versatility of the robot. There are several approaches to handle multiple objectives in an optimization problem [24]:

- **Apply a scalarization strategy.** By converting the multiple objectives to a single objective established single objective algorithms can be applied. These strategies include the weighted sum of objectives, a separate consideration of the objectives with subsequent averaging, and ranking of the maximum of the objectives for example. Nevertheless the scalarization contains the risk to end at unfavored solutions: A solution generated by the combination of multiple objectives is potentially not optimal for any of the objectives, since it represents a tradeoff. When setting up robot hardware, it is desired to achieve robust hopping and robust jogging for example. The application of a scalarization strategy to generate a single objective could return a configuration, which neither allows the robot to hop, nor to jog. The scalarization strategies are therefore not suited in general for the design of embodiment approach.

- **Consider the set of Pareto optimal solutions.** By considering all Pareto-optimal solutions (see Definition 7.1), all relevant possibilities for an optimal configuration are considered. Instead of a single solution, a set of optimal solutions is generated. The calculation of Pareto-optimal solutions however requires sophisticated optimization algorithms, as for example the Nemhauser-Ullmann algorithm [58].

Definition 7.1 (Pareto-optimal)**.**

A Pareto-optimal solution is a configuration, which cannot improve one of its objectives, without worsening another objective. p_1 is a Pareto optimum of a set P with n objectives $q_i, i = 1, ..., n$, if P does not include another set p_2 with

$$\begin{aligned} \forall\, i = 1, ..., n \quad & q_i(p_2) \leq q_i(p_1) \\ \exists\, j \quad \text{with} \quad & q_j(p_2) < q_j(p_1) \end{aligned}$$

when considering a minimization problem. A Pareto-optimal solution therefore is at least equal in all objectives and better in at least one objective.

By utilizing the combined structure of the present multi- and single-objective problem, established single-objective optimization approaches can be applied to the multi-objective problem to find the Pareto-optimal set of solutions. The problem can be considered as two-tier optimization:

- Goal of the **outer optimization** is to find a configuration of time independent parameters $p_{in} \in P_{in}$ (see Section 7.1.1, such that each motion goal can be achieved optimally. It must be considered, that only time independent parameters P_{in} are optimized in the outer optimization. The inner optimization provides, that the sets of switchable parameters P_s and time dependent variables P_d are optimal for the considered P_{in}. For each considered goal a separate outer optimization is required.

- Goal of the **inner optimization** is to find a set of optimal variables P_s and P_d for a given set P_{in}. It is therefore typically required to perform multiple inner optimizations.

For each value of the outer optimization it is required to perform an inner optimization. The proposed nesting allows for the consideration of the different properties of parameters as required. While the inner optimization can address all parameters except time independent ones, the outer optimization can only adapt time independent variables to achieve the optimal solution. An optimal configuration of the time independent parameters can be found, by comparing only optimal configurations regarding the other involved parameters. These two tiers of optimization have different requirements though:

- In order to find the set of Pareto-optimal solutions, the results of the outer optimizations of the different goals must be comparable regarding Pareto-optimality. It is therefore required to gain a objective function for every of n goals, which is only dependent on the time independent parameters P_{in}. This function can be generated by applying surrogate function based approaches. A possible sophisticated optimization approach which is based on surrogate functions is presented in [32]. Alternatively a surrogate function can be achieved by interpolation of a discrete set of considered configurations (see examples in Sections 8.3 and 8.4).
- The inner optimizations must return one optimal configuration for the variable parameters P_d and P_s regarding a given set of P_{in} for each goal separately. There are therefore no special requirements regarding the multi-objective decision making.

The optimal configuration regarding all considered goals can be evaluated conveniently by comparing the function values for each configuration and each goal. A more detailed discussion on the selection of suitable configurations from optimization results is presented in the following Section 7.2.

Multiple simulation experiments

Multiple simulation experiments must be considered within the optimization. This requirement can easily be achieved by considering each objective independently. For every objective a number of simulation experiments can be performed. It is however possible to use the results from one simulation experiment for multiple objectives (see example in Section 8.3). To reduce calculation time however, the number of simulation experiments should be held as low as possible. Nevertheless, the application of multiple simulation experiments has no special requirements regarding the optimization algorithm.

Gradient information

Typically it is difficult to calculate gradient information from the considered specific objectives and constraints. This holds for both the inner and outer optimization problem.

- Model properties are often not continuously differentiable. This holds especially in legged mobile locomotion, since discontinuities as for example contacts are typically a key feature of the considered class of robots.
- The numerical calculation of gradient information from complex motion dynamic models requires high computational effort.
- The objective function can include discontinuities.
- The objective function can include numerical inaccuracies.
- Especially when considering the outer optimization, the evaluation of gradient information is difficult. Each function value of the outer optimization function, requires the analysis of an inner optimization process. The correlations are therefore not easy to identify.

It is therefore advisable to apply gradient-free (blackbox) optimization approaches.

Optimization algorithm

The analysis of requirements results in the application of different optimization algorithms for the inner and outer optimization problem:

- Based on the previous analysis of the optimization problem, the outer optimization problem is ideally approached with a gradient-free surrogate function based optimization approach. It must also be considered, that every evaluation of a function value requires an inner optimization. Therefore an optimization algorithm with only few function evaluations is desirable. Typical approaches are response surface methods, radial basis functions, or design and analysis of computer experiments (DACE) [32]. Approaches based on interpolation are typically also sufficient.

- Typically the inner optimization problem requires a gradient-free optimization approach. To prevent local optima the application of random walk optimization approaches as for example genetic algorithms is advisable. But also surrogate function based approaches or pattern search approaches can be applied. If gradient information is available however, the application of algorithms which utilize gradient information should be preferred. If furthermore an analytic solution is available, this solution should be preferred.

7.2 Discussion of the results of multi-objective optimization

As discussed before, there are several approaches to solve a multi-objective optimization problem. When not ranking the considered multiple goals and forming a combined solution, each goal returns its respective objective value. Typically the considered solution of a multi-objective optimization problem is therefore not unique. Instead a set of optimal solutions is generated by the optimization algorithm. Typically however it is required to decide on the proceeding with multiple solutions regarding the construction of the robot hardware. This raises the requirement to perform an analysis of the results. This analysis is required in order to find the most suitable solution from the set of optimal solutions.

The following sections will present and discuss typical results when considering an exemplary problem with two single-dimensional objectives. All presented examples are subject to maximization. The presented examples can be applied to allow for an application of the discussed approach to higher dimensional problems. The examples presented in the following sections are illustrated with graphs, in which the objective value Q (ordinate) is plotted to the parameter value P_{in} (abscissa). The two different goals are depicted hereby in different colors. Depending on the applied approach for solving the outer optimization problem, the combined multi- and single-objective optimization approach discussed in the preceding section, generates only a set of discrete solutions regarding the parameters P_{in}. For convenience the graphs presented in this section however depict a continuous function regarding P_{in}.

7.2.1 Multiple optimal solutions

It is possible, that there is no coherence between one or more parameters and the considered objectives. In Figure 7.1 the objective values for both criteria are constant for all considered parameter values of P_{in}. In this special case, both considered multi-objective criteria have no coherence with respect to the considered goals. The value of P_{in} can be chosen arbitrarily within the regarded boundaries since all resulting objective values are equally optimal. To identify one unique optimal value for the considered parameter P_{in} however, additional objectives must be evaluated. A constant coherence of considered parameter and objective typically indicates, that the respective parameter does not influence the considered objective. In this case the objective is not suited to identify an optimal value for the considered parameter and can be neglected.

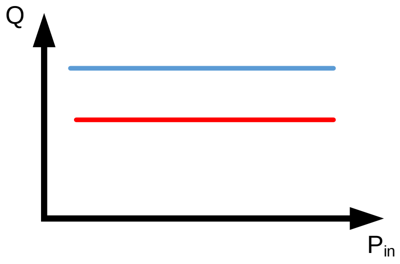


Figure 7.1.: The parameter does not influence the considered objective Q. Therefore all configurations of P_{in} are optimal.

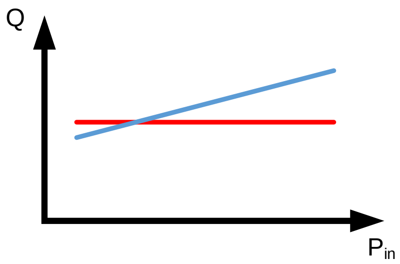
Image source: own representation

7.2.2 Unique optimal value

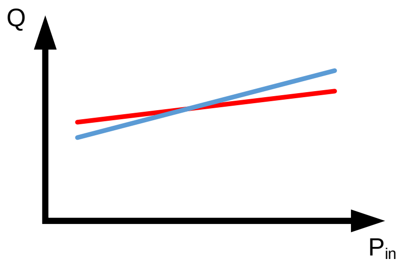
Ideally the optimization results in one unique optimal solution for the considered parameters.

In the example displayed in Figure 7.2a, the optimal configuration of P_{in} only depends on the objective depicted in blue. A higher value of P_{in} results in a higher value of the objective. P_{in} however has no influence on the other objective, which is depicted in red. The optimal configuration is therefore unique.

Figure 7.2b shows an example, in which both considered objectives are influenced uniformly by the plotted parameter. In both objectives the objective values increase with increasing parameter value. The optimal value for both objectives are at the upper boundary of the considered parameter. This allows for a straightforward selection of a suitable value for the considered parameter P_{in}. Again the optimal configuration is unique.



(a) The parameter influences one objective (blue). The other objective is not affected.



(b) Both objective values improve with increasing value of P_{in}.

Figure 7.2.: One unique optimal configuration of P_{in} exists. This is achieved by either uniform behavior of the considered objectives (see Fig. 7.2b), or by the incidence, that only one objective is influenced by the considered parameter (see Fig. 7.2a).

Image source: own representation

Since the optimal value for P_{in} is at the upper boundary in both considered examples, an expansion of the boundaries should be considered if possible however. This way a possible global optimum can be found.

7.2.3 Ambiguous solution

Often however the optimal configuration is not unique and a more sophisticated evaluation of the results of the optimization is required.

All graphs depicted in Figure 7.3 do not have a unique solution for the parameter P_{in} when considering the respective objectives. The optimal configurations for each considered objective differ: it is not possible to find one optimal configuration for P_{in} which is optimal for every considered objective.

In these ambiguous cases, the set of reasonable solutions must be detected. To decide which configuration P_{in} is best suited, different decision making approaches can be applied [24]:

- Ranking the sum of objectives
- Ranking objectives separately and average the ranks
- Ranking the maximum of the objectives
- Pareto-ranking

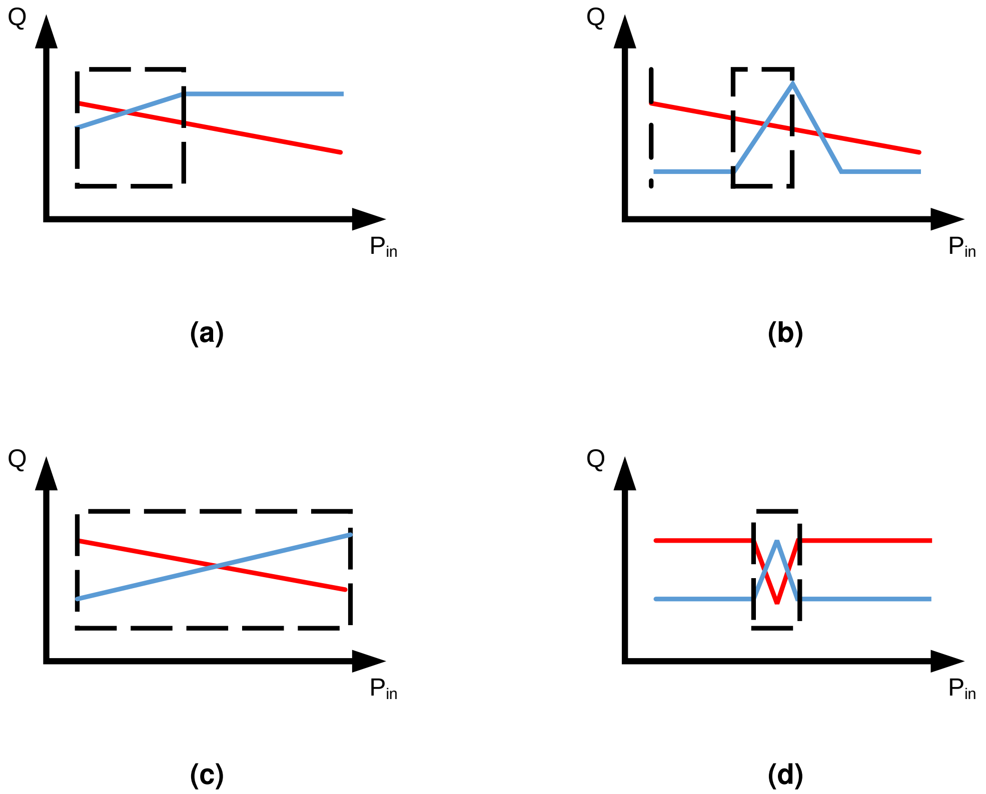


Figure 7.3.: All depicted examples have no unique solution. The respective Pareto-optimal subset of P_{in} is emphasized with a dotted box.

Image source: own representation

However, the first three listed scalarizing approaches are just examples of specific Pareto-optimal configurations. The set of Pareto-optimal solutions does include all admissible solutions of the considered objectives and therefore each ranked combination. To prevent the exclusion of the best suited solution by selecting unsuitable ranking approaches, the Pareto-ranking is applied instead. A definition of Pareto-optimality is presented in Definition 7.1.

For convenience the Pareto-optimal solutions are emphasized in the graphs depicted in Figure 7.3: All configurations of P_{in} within the marked areas are Pareto optimal. Only configurations in the marked area are reasonable to select for application in the robot: Configurations outside of the the marked area are worse regarding at least one objective. From the detected set of Pareto-optimal solutions, one solution must be selected for application in the considered robot. Since all Pareto-optimal solutions are equally good with respect to the definition of Pareto-optimality, an additional metric must be introduced to select the respective configuration. Typical approaches to do so are listed in the following. The list is sorted by increasing complexity of the respective measure. A more complex technique requires more time to compute and more engineering expertise to implement.

1. **Weight Pareto-optimal solutions** If it is possible to rank one objective more important than another, a ranking can be introduced. It must be considered, that the ranking only comprises the set of Pareto-optimal solutions. Consider that different ranking strategies can be applied (see Section 7.1.4).

2. **Introduce a threshold** In cases where a minimum performance is desired, a threshold can be introduced to one or more objective. Within the solutions that are above the threshold regarding the considered objective(s), the optimal solution is selected based only on the remaining objective(s).

3. **Introduce sensitivity information** It is always desirable to end in a stable solution: Small changes in the input parameters are desired to produce only slight changes of the considered objective function value. This is especially relevant when considering inaccuracies of the applied model with respect to the real (desired) robot. A more robust solution is therefore sometimes to prefer over better performance, because it is easier to achieve in the real robot.

4. **Introduce additional objectives** If the present objectives do produce a set of equally good solutions, which can not be ranked by any of the above techniques, it can be useful to introduce further objectives.

5. **Adapt boundaries** If no reasonable good solution can be achieved by the application of the above techniques, an adaption of the parameter boundaries can potentially improve the solutions. It is possible, that a more suitable result is detected beyond the defined boundaries.

6. **Adapt type of parameter (P_{in} or P_s/P_d)** By allowing for the time independent variables to be switchable or even time dependent variables, the performance will likely improve and a more suitable configuration can be selected. It must be considered however, that a change in the type of parameter probably changes the structure of the embodiment. The robot must be adapted, such that formerly time independent parameters can be adapted to the new type. Although this technique is highly appreciated since the performance is much likely increased for each considered objective, it can be difficult to implement the required adaptions to the robot structure. In the context of legged mobile robots with highly elastic actuation, different optimal solutions for multiple objectives could result for example in the application of elastic elements with variable spring coefficients.

7. **Introduce additional parameters for optimization** It is also possible, that the system's performance is reduced by having specific parameters fixed. Adding some additional formerly fixed

parameters to the optimization as time independent parameters can help to find a more suitable solution. It must be considered, that this approach increases the complexity of the overall optimization problem and therefore increases the computation time.

8. **Adapt embodiment and/or active control structure** An adaption of the robot structure or the structure of the active control leads to different results of the objective functions. Adapting these structures however is a fundamental change of the robot's embodiment and requires a new execution of the optimization.

8 Example problems and applications

In the preceding chapters the design of embodiment approach to develop and layout an embodied legged robot is presented and discussed in detail. It is ensured during the discussion, that the principles to design an embodied agent discussed in Chapter 3 are projected to the sophisticated development concept. Each relevant principle finds its corresponding representation within the several steps of the design of embodiment approach. To show that the presented approach can indeed be applied to develop an embodied agent, four relevant examples are discussed in the following sections.

To illustrate the applicability of the design of embodiment approach for the design and layout of legged mobile robots, the upcoming examples are intended to show these issues:

- The robot resulting from the development process can be considered as an optimally embodied agent with respect to the detected relevant requirements presented in Table 3.2. The examples are analyzed with respect to these requirements (if applicable).
- The resulting embodied robot can take most advantage of the utilization of physical effects. The specific advantage can include increased versatility, energy efficiency, robustness, and/or performance. To evaluate the specific advantage a comparison with traditionally designed robots is performed.

To be able to focus on each aspect of the design of embodiment approach, the examples are designed to have different levels of complexity. While each example investigates the central aspect to simultaneously set up passive and active control parameters of a robot, the particular examples are focused on individual steps of the approach. The four discussed examples are:

1. **Abstract swinging mass**: An elastically actuated mass with one DOF is desired to swing with a target amplitude. Two different hardware configurations are hereby considered in terms of different masses to account for different dynamical properties. Both active and passive control parameters need to adapt to the considered masses. This example is relevant in the context of the presented design of embodiment approach for legged mobile robots, since it investigates the natural frequency in oscillatory motions.

2. **Throwing arm**: An elastically actuated robotic arm with one rotational DOF is desired to throw a point mass. In this example two divergent objectives are evaluated: in one experiment the point mass is desired to robustly hit a certain target with respect to uncertainties in time and position. In a second experiment the point mass is desired to be thrown at maximum distance. This example is relevant regarding the development of legged robots, as it simultaneously investigates multiple motion goals that are important in robust locomotion: performance, robustness, and versatility. Moreover the robot used in this example is equipped with a series elastic actuator, which is also used in the BioBiped robot [73]. The example is furthermore intended to show, that the design of embodiment approach can efficiently set up parameters of a series elastic actuator.

3. **1D hopping of BioBiped2 robot**: In the third example the design and layout of the elastically actuated two-legged mobile robot BioBiped2 is evaluated. The robot is desired to perform a hopping motion. During this motion the robot torso is constraint to a single degree of freedom.

4. **2D walking and jogging of BioBiped2 robot**: In the most complex example the BioBiped2 robot is investigated again. In this example the robot is desired to perform two different gaits: walking and jogging. The robot is hereby constraint to two degrees of freedom in the sagittal plane.

Due to space restrictions the following samples will provide not every of the steps in equal level of detail. Moreover in the examples of the two-legged robot, the step of modeling is reduced to a sole presentation of the applied model. A complete illustration of the modeling process is not in the scope of this thesis.

8.1 Abstract swinging mass

Oscillating periodic motions are a key ingredient in dynamic legged locomotion. Typically legs swing forward and backward in order to achieve a robust energy efficient forward motion of the respective agent. By the application of series elastic actuators, the motion energy can be stored and reused to reduce the required energy effort however. With applied elasticity, the actuator is only required to induce a low amount of energy into the system to overcome energy losses caused by physical interactions. The challenge in this scenario is to set up the elastic elements of the applied series elastic actuator together with the actuation to minimize the energy effort while achieving the desired motion.

Often it is desired to achieve different gaits in locomotion to specifically react on task or environment dependent conditions. It is however difficult to set up hardware and control components to achieve these required different gaits with high energy efficiency. In order to investigate these key properties of legged locomotion, the following issues are investigated in the first example:

- Setup of passive and active control
- Achieve two different energy efficient “gaits”

Implementation of example

In order to investigate oscillating motions with different natural frequencies, an abstract example of a two-mass oscillator is considered. The system is actuated by an applied parametrized force. It is desired to identify optimal parameters for this applied force, as well as optimal coefficients for the used springs.

The system is desired to oscillate at a given amplitude with high energy efficiency. Although the interaction with the environment is reduced to an elastic connection of one mass with the surroundings, this abstract example is relevant regarding the development of an embodied legged robot due to several reasons:

- The example requires an oscillating motion. This kind of motion is very relevant in legged locomotion. Moreover the considered oscillation is desired to be energetically efficient. Just as in a legged robot, it is therefore required to find and utilize the natural frequency of the system.
- Both active and passive control parameters can be adapted. As in legged locomotion the coordination of these different types of control is crucial to achieve efficient motion.
- The example investigates the setup of a system with different objectives. Just as in legged locomotion with different gaits, an efficient solution to achieve two possibly different frequencies in oscillation for consistent hardware is desired.

Therefore the robotic system of a two-mass oscillator is considered. The setup of the one-dimensional system is illustrated in Figure 8.1. Link 1 with mass m_1 is connected to the environment with spring 1, which has a linear spring coefficient k_1 and a linear damping coefficient of d_1. The equilibrium length of spring 1 is x_{10}. Link 2 with mass m_2 is connected to link 1 via spring 2, which has a linear spring coefficient k_2 and a linear damping coefficient d_2. The equilibrium length of spring 2 is x_{20}. While link 1 can be actuated by a force F [N], link 2 is moving accordingly, while passively controlled by the embodiment of the considered system.

The goal of the design of embodiment is to find optimal control parameters for the active control trajectory F and the passive control parameters k_1 and k_2 to achieve energetically efficient motions of link 2. To allow for a realistic solution, the spring coefficients must have a minimum value of 0.5 [N/m]. While link 2 is desired to oscillate in a given amplitude of $\delta = 0.2$ [m], the mass of link 2 is varied between two experiments in order to cause different natural frequencies. In a first experiment the $m_2 = 1$ [kg] and in a second experiment $m_2 = 2$ [kg].

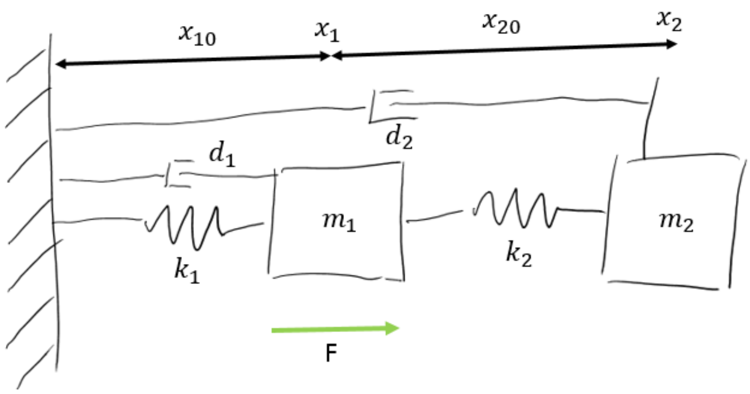


Figure 8.1.: The image shows a sketch of the setup for the swinging mass example. Involved parameters are the masses m_1, m_2, the spring coefficients k_1, k_2, the damping coefficients d_1, d_2, the equilibrium lengths x_{10}, x_{20}, the equilibrium positions x_1, x_2, and the applied force F. Although the image depicts a spacial expansion of the involved masses, they are considered as point masses.

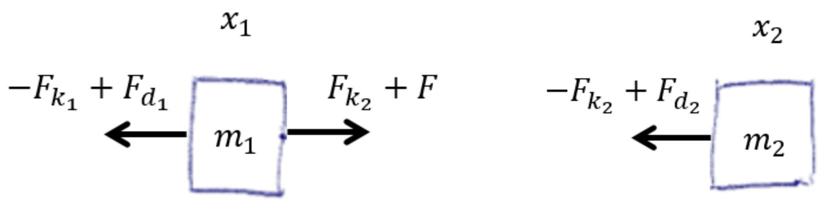
Image source: own representation

In the following sections, the design of embodiment approach is applied to the example. While each step is discussed in detail, a special focus is on the modeling of robot, environment, and active control. The achieved result is compared with a corresponding traditionally designed system. Furthermore the result is analyzed regarding the requirements of an embodied agent discussed in Chapter 3.

8.1.1 Modeling robot, environment, and active control

As discussed in Chapter 4, the modeling of robot, environment, and active control consists of two steps: (1) the determination of a suitable structure to potentially meet the given objectives, and (2) the implementation of a mathematical model of this structure. The robot structure and the structure of the interaction with the environment however are already implicitly included in the task definition. This reduces the task of the determination of structures to find a suitable structure for the active control. For convenience the structures of the three constituents are explicitly formulated:

- **Structure of the robot**: Two masses m_1 and m_2 with a translational DOF are connected with a spring with coefficients k_2 and d_2. The spring is damped with respect to the environment. A formulation as equation of motion can be established by generating a free body diagram of the involved links (see Figs. 8.2a and 8.2b). The free body diagram of mass 1 already includes the point of origin of the interaction with the environment.



(a) Free body diagram of link m_1 **(b)** Free body diagram of link m_2

Figure 8.2.: The illustrations show the respective free body diagrams of the the involved links of the swinging mass example.

Image source: own representation

When including the spring and damping coefficients the following forces result:

$$F_{k_1} = k_1(x_1 - x_{10}) \quad (8.1)$$
$$F_{k_2} = k_2((x_2 - x_1) - x_{20}) \quad (8.2)$$
$$F_{d_1} = d_1 \cdot \dot{x}_1 \quad (8.3)$$
$$F_{d_2} = d_2 \cdot \dot{x}_2 \quad (8.4)$$

The damping is modeled as viscous damping with proportional dependency with respect to velocity.

- **Structure of the interactions with the environment**: The interaction with the environment in this example is a linear elastic connection to a fixed frame. Moreover the masses are proportionally damped with respect to their velocity with respect to the fixed frame. These connections are modeled in Equations (8.1), (8.3), and (8.4).
- **Structure of the active control**: According to Section 4.3 the structure of active control must allow for the induction of the natural frequency of oscillating systems. This can be achieved by the application of a sine wave signal. To achieve the desired swinging behavior, the sine wave must be designed such that the frequency and amplitude can be adapted during optimization. An adaption of the phase shift however is not required, since mass 1 is the only actuated object in the example and no coordination to other actuated objects is required therefore. The applied structure of active control for this example is:

$$F = a \cdot \sin(f \cdot t) \quad (8.5)$$

All three constituents are combined in a single set of differential equations:

$$\begin{aligned} m_1\ddot{x}_1 &= -k_1(x_1 - x_{10}) + k_2((x_2 - x_1) - x_{20}) - d_1\dot{x}_1 + a\sin(f \cdot t) \\ &= x_1(-k_1 - k_2) + \dot{x}_1(-d_1) + x_2(k_2) + k_1x_{10} - k_2x_{20} + a\sin(f \cdot t) \end{aligned} \quad (8.6)$$

$$\begin{aligned} m_2\ddot{x}_2 &= -k_2((x_2 - x_1) - x_{20}) - d_2\dot{x}_2 \\ &= x_1(k_2) + x_2(-k_2) + \dot{x}_2(-d_2) + k_2(x_{20}) \end{aligned} \quad (8.7)$$

To allow for a consideration of the equation of motion as a set of ordinary differential equations of first order, the involved motion variables are substituted:

$$
\begin{aligned}
x_1 &= y_1 \\
\dot{x}_1 &= y_2 \\
x_2 &= y_3 \\
\dot{x}_2 &= y_4
\end{aligned}
$$

By applying the substitution, a set of ordinary differential equations of first order is generated:

$$
\begin{pmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \\ \dot{y}_4 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ \frac{-k_1-k_2}{m_1}+\frac{k_2}{m_1} & -\frac{d_1}{m_1} & +\frac{k_2}{m_1} & 0 \\ 0 & 0 & 0 & 1 \\ \frac{k_2}{m_2} & 0 & -\frac{k_2}{m_2} & -\frac{d_2}{m_2} \end{pmatrix} \cdot \begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{k_1 x_{10}}{m_1} - \frac{k_2 x_{20}}{m_1} + \frac{a \sin(f \cdot t)}{m_1} \\ 0 \\ \frac{k_2 x_{20}}{m_2} \end{pmatrix} \tag{8.8}
$$

This set of equations can be used to describe the motion behavior of the considered system. Besides the presented mathematical formulation (8.8), there are other techniques to simulate and predict the motion behavior of a system. Figure 8.3 for example shows an overview of the implementation of the swinging mass example in the MATLAB® Simulink® SimMechanics™ generation 2 toolbox. Instead of formulating mathematical coherencies, the model is set up graphically using symbolic blocks to describe links, joints, and forces. The actual mathematical description of the robot's dynamics is performed by algorithms, which cannot be accessed by the user. Within the following sections the mathematical formulation presented in Equation (8.8) is used however.

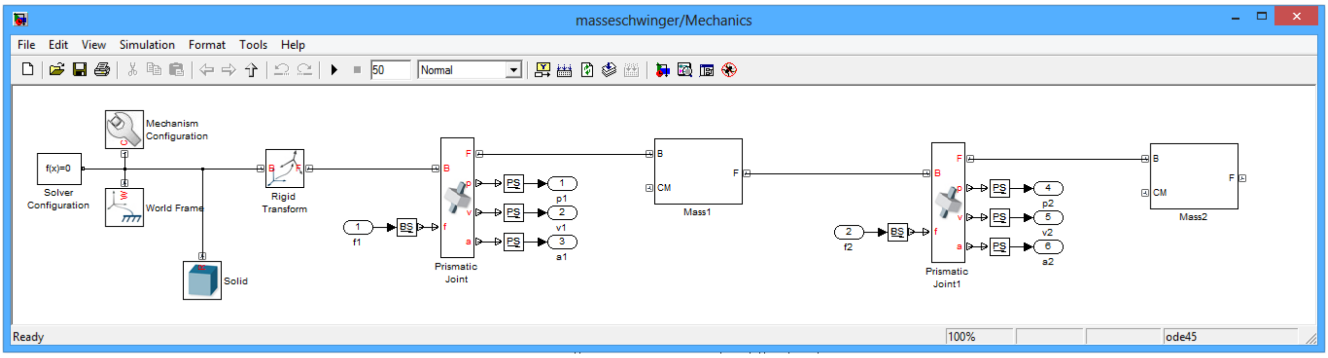


Figure 8.3.: The picture depicts an overview of the symbolic implementation of the dynamic behavior of the swinging mass in MATLAB® Simulink® SimMechanics™.

Image source: own representation

8.1.2 Design goals

The goals of the considered robot system as defined in the definition of task, are to achieve oscillating motions of link 2 with two different masses $m_2 = 0.5$ [kg] and $m_2 = 2$ [kg] in a separate experiment for each mass. The desired one dimensional oscillation has the amplitude $\delta = 0.2$ [m]. The according problem formulations are therefore:

- **Problem formulation 1**: achieve a settled induced oscillation with mass $m_2 = 0.5$ [kg] with an amplitude of $\delta = 0.2$ [m] while minimizing the applied energy effort.

- **Problem formulation 2**: achieve a settled induced oscillation with mass $m_2 = 2$ [kg] with an amplitude of $\delta = 0.2$ [m] while minimizing the applied energy effort.

It is therefore desired to minimize the applied energy, while achieving the desired motion in each experiment. As discussed in Chapter 7, the optimization problem is divided into inner and outer optimization. In this example the inner optimization is applied to find a suitable set of parameters for the amplitude and angular frequency of the parametrized force F. The set of spring coefficients k_1 and k_2 is kept constant for each iteration of the inner optimization. The inner optimization problem can be formulated as objective function with nonlinear constraints:

$$\begin{aligned} \min_{a,f \in \mathbb{R}} Q &= a \cdot \sin(f \cdot t) \quad \text{with} \quad t \in [0, 2\pi] \\ s.t. \quad h(a, f, \delta) &= 0 \end{aligned} \tag{8.9}$$

The nonlinear equality constraint $h(a, f)$ includes a sophisticated assessment of the differential Equation of motion (8.8). This assessment is performed in two steps:

1. A settled period of the oscillating link 2 must be detected from the experiment results. This is achieved in the present example by evaluating and comparing the peaks of two neighboring periods. If these considered peaks are suitably close (if they differ by only 0.1% in the example), the period can be considered as settled.
2. The equality constraint function $h(a, f)$ returns the squared difference of the detected settled peaks and the desired amplitude.

8.1.3 Parameters for robot design and control

As discussed in Chapter 6, all parameters used in the simulation experiments must be assigned to either one of the following groups:

- **Constant parameters**: Besides given natural constants this includes parameters which are fixed due to technical requirements or design requirements:
  - mass $m_1 = 1$ [kg]
  - Mass m_2 has different properties in scenario 1 and 2. In scenario 1 $m_2 = 0.5$ [kg], while in scenario 2 $m_2 = 2$ [kg].
  - damping coefficients $d_1 = 1$ [N· s/m] and $d_2 = 1$ [N· s/m]
  - equilibrium lengths $x_{10} = 0.1$ [m] and $x_{20} = 0.1$ [m]

  As mass 2 in this example shows, the properties of a constant parameter can differ in-between the considered scenarios. The different applied masses are subject to the requirements and therefore not included in the optimization.

- **Time dependent and switchable variables**: This includes the active control parameters which are used to describe the applied parametrized force.
  - amplitude $a \in P_d$
  - angular frequency $f \in P_d$

In the presented example it is sufficient to consider the active control parameters as switchable: They are constant for each considered experiment.

- **Time independent variables**: Passive control parameters are typically time independent. They cannot adapt their properties during operation and must be selected such that optimal operation is possible in all considered scenarios. In the present example this includes the passive control elements.
  - spring coefficients k_1 and $k_2 \in P_{in}$

  It is desired to find one optimal configuration for the spring coefficients, which is optimally suited for both considered scenarios. Furthermore the resulting spring coefficient must be larger then 0.5 [N/m].

8.1.4 Optimization of embodiment

The inner optimization as described in Section 8.1.2 is performed with the genetic algorithm of the MATLAB optimization toolbox. The optimization settings are set as follows:

- Population size: 40
- Maximum generations: 100
- Function tolerance: 1e-14
- Nonlinear constraint tolerance: 1e-6
- Scaling function: rank
- Selection function: stochastic uniform
- Elite count: 2
- Crossover fraction: 0.8
- Boundaries of amplitude: 0.01 – 4
- Boundaries of frequency: 0.01 – 4

The optimization was performed on an intel CORE i7 (2.67 GHz), 4GB RAM computer. The duration of each inner optimization process was between approx. 200 [s] and 3000 [s].

The outer optimization involves an evaluation of multiple inner optimizations. To systematically analyze the resulting behavior regarding the considered set of parameters, an interpolation approach is applied. Hereby only a limited number of inner optimizations is performed, while interpolating the values in-between.

In order to specify the parameter constraints and potentially reduce the problem dimension a preliminary optimization was performed. In this first outer optimization an equidistant grid of $4 \cdot 4$ inner optimizations was evaluated to get information on the overall system behavior. Figure 8.4 depicts the resulting required energy effort in [J/period] of this first outer optimization run with the boundaries of 0.5 - 4 [N/m] for each considered spring coefficient. Here the left figure shows the results for the first problem formulation with $m_2 = 0.5$ [kg], while the right figure shows the results of the second problem formulation with $m_2 = 2$ [kg]. A preliminary visual analysis shows, that the difference regarding the

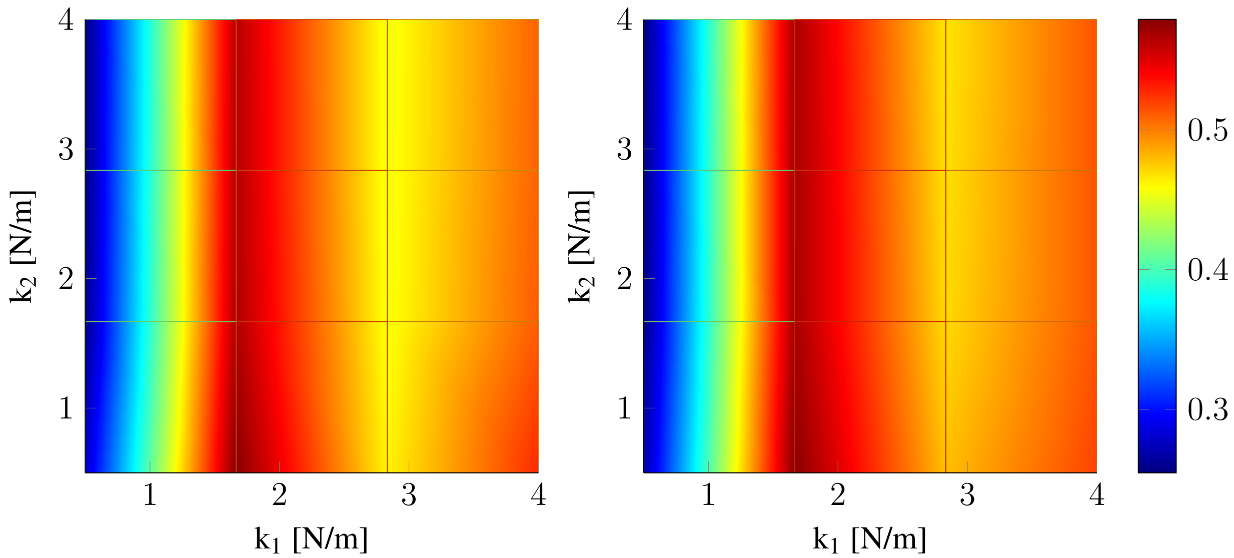


Figure 8.4.: Resulting minimal energy requirements for the desired motion regarding the considered spring coefficients k_1 and k_2. The left figure shows the resulting energy in [J/period] for problem formulation 1 with $m_2 = 0.5$ [kg], while the right figure shows the resulting energy for problem formulation 2 with $m_2 = 2$ [kg]. The minimal energy effort regarding the parameters for amplitude and frequency for each considered configuration is indicated with colors. The grid indicates the evaluated discrete configurations. The energy is only dependent on spring coefficient k_1.

Image source: own representation

two considered problem formulations is marginal. It must be considered, that only 16 configurations are evaluated for each goal. They are indicated by the grid: only configurations on crossings are evaluated. Colors in-between are interpolated for convenience.

The analysis of the achieved data shows, that the results are to a major proportion depending on the spring coefficient k_1. The influence of the spring coefficient k_2 can therefore be ignored and the respective spring coefficient be chosen arbitrarily.

A second outer optimization run therefore only evaluates the optimal configurations for discrete configurations of spring coefficient k_1. The spring coefficient k_2 is kept constant with a value of $k_2 = 2$[N/m] during all inner optimizations. In a less abstract scenario the availability or a new design goal, as for example the expenses of the applied springs, could have been applied to find a suitable spring. Here this value for k_2 is chosen arbitrarily. While the boundaries are the same as in the two-dimensional array, a finer grid of configurations for k_1 is applied. Figure 8.5 shows the results of the two considered problem formulations. Again the small deviation between the two considered problem formulations becomes visible.

8.1.5 Classification of results

The parameters a and f are switchable variables, while the spring coefficients are time independent. It is therefore required to find an optimal configuration of the time independent variables k_1 and k_2. The results show however, that the spring coefficient k_2 has only marginal influence regarding the energy consumption in the desired settled oscillation motion. The spring coefficient k_2 can therefore arbitrarily be chosen within the considered range of 0.5 to 4 [N/m]. As a more fine grained analysis of the remaining

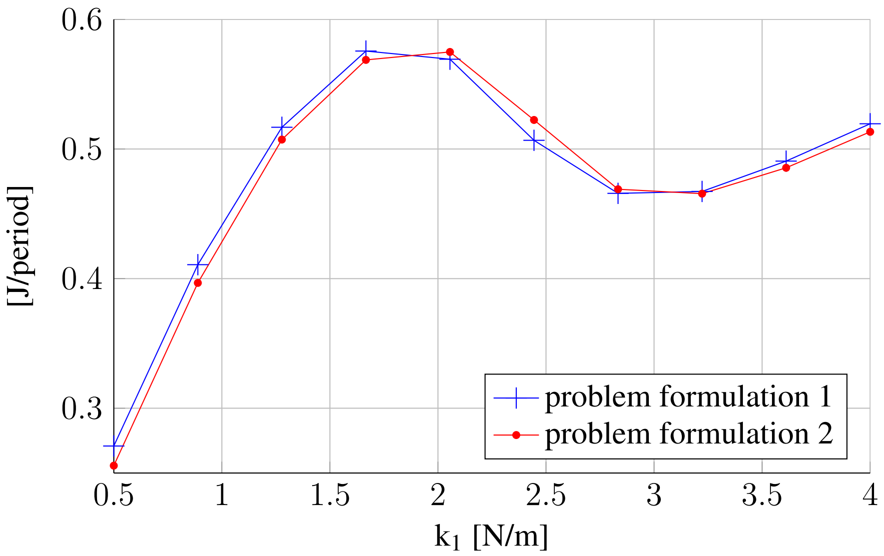


Figure 8.5.: Resulting minimal energy requirements for the desired motion regarding only the considered spring coefficients k_1. It must be considered, that only marked configurations are evaluated. Lines in-between are interpolated.

Image source: own representation

spring coefficient k_1 reveals, both objectives have an optimum at the lower range of the considered interval for $k_1 = 0.5$ [N/m].

The optimal configurations of the parameters a and f depend on the choice of the parameters k_1, and k_2 and on the considered goal. Possible optimal configurations for $k_2 = 2$ [N/m] are listed in Table 8.1.

	problem formulation 1 ($m_2 = 0.5$ [kg])	problem formulation 2 ($m_2 = 2$ [kg])
amplitude a [m]	0.1312	0.1318
angular frequency f [s^{-1}]	0.1086	0.1017
spring coefficient k_1 [N/m]	0.5	0.5
spring coefficient k_2 [N/m]	2	2
energy effort [J/period]	0.2708	0.2557

Table 8.1.: The table lists possible resulting values for the swinging mass example discussed in Section 8.1. The active control parameters are very similar to achieve the desired motion of each goal.

8.1.6 Comparison with a conventionally designed robot

To show the advantages of the new design of embodiment approach, a sequential approach as example for a typical conventional approach to set up the control is discussed for comparison in the following. Sequential approaches to layout and design control and hardware parameters do not consider possible interdependencies between active control and physical reactions systematically however.

In the presented approach, which follows the iterative design approach discussed in Section 2.3.1, passive control parameters are selected first by considering the system behavior. Active control parameters are evaluated in a second step by an optimization approach.

- **Step 1: setup of passive control**: In contrast to the approach discussed in Section 2.3.1, the passive control parameters are not identified in several iterations, but are calculated from the equations of motion. Due to the low complexity of the present example, this can be done with plausible approximation.

  The magnification factor describes the connection of input and output amplitude of an oscillating system in settled oscillation. In order to identify the optimal spring coefficients for the applied springs, the magnification factor of the system must be evaluated as a function of the spring coefficients. A higher magnification factor indicates a more energy efficient configuration of spring coefficients, because the input amplitude is amplified to a greater extent. To calculate the magnification factor the equation of motion must be considered.

  The dynamic behavior of the system is described as:

$$\begin{aligned} M\ddot{x} + D\dot{x} + Kx &= g && (8.10) \\ \text{with} \quad K &= \begin{bmatrix} k1 + k2 & -k2 \\ -k2 & k2 \end{bmatrix} && (8.11) \\ M &= \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} && (8.12) \end{aligned}$$

  Hereby K is the stiffness matrix, D the damping matrix, and M the mass matrix. To allow for a modal decoupling, the damping matrix D is approximated as Rayleigh damping:

$$D = \beta K \tag{8.13}$$

  The Rayleigh damping factor β is set to 0.1 in this example. The vector x describes positions of the involved bodies, while the vector g describes outer excitation forces. By assuming

$$\begin{aligned} x(t) &= \hat{x}(\omega)e^{i\omega t} && (8.14) \\ g(t) &= \hat{g}(\omega)e^{i\omega t} && (8.15) \end{aligned}$$

  and

$$(-\omega^2 M + i\omega D + K)\hat{x} = \hat{g} \tag{8.16}$$

  the dynamic stiffness matrix can be written as:

$$K_{ds}(\omega) = -\omega^2 M + i\omega D + K. \tag{8.17}$$

  Inverting the dynamic stiffness results in the frequency response matrix. To evaluate the maximal magnification factor, a force is applied to the considered system and the frequency response is evaluated. The optimal magnification factor can be found by maximizing the magnification factor:

$$\begin{aligned} u &= \max_f K_{ds}^{-1} \cdot g && (8.18) \\ \text{with} \quad g &= \begin{bmatrix} 1 \\ 0 \end{bmatrix} && (8.19) \end{aligned}$$

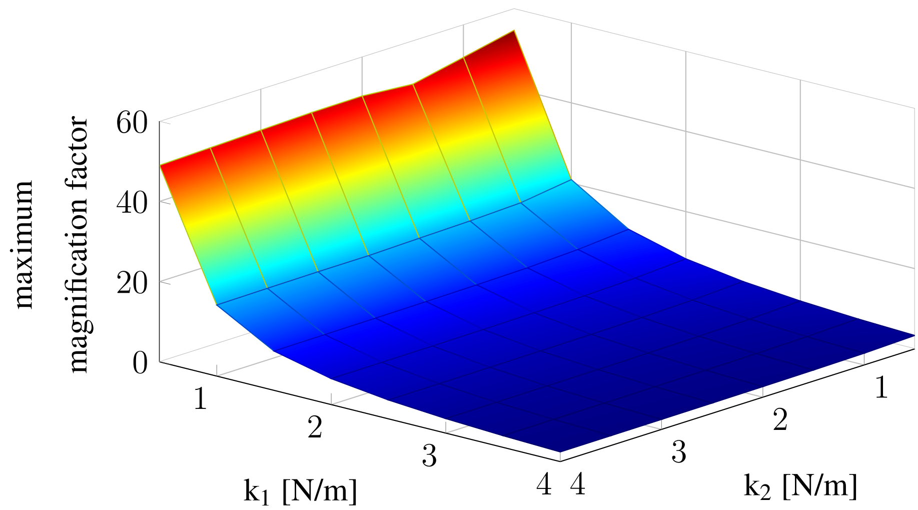


Figure 8.6.: Maximum magnification factor of each configuration [k_1, k_2] for problem formulation 1. The magnification factor is calculated with a simplified equation of motion. Problem formulation 2 results in a similar configuration.

Image source: own representation

To find the optimal configuration of spring coefficients, the maximum magnification factor 8.18 is calculated for possible configurations of k_1 and k_2. The results for problem formulation 1 are displayed in Figure 8.6. As can be seen in the figure, the lowest spring stiffness coefficient for k_1 results in the highest maximum magnification factor. Problem formulation 2, which is not displayed, results in a similar configuration: again the maximal magnification factor is achieved for the minimal spring stiffness k_1. The coefficient for k_2 however has no influence on the magnification factor and can therefore be chosen arbitrarily for both problem formulations. It must be considered however, that the magnification factor is only valid for the approximated system with Rayleigh damping. Based on the results the coefficients can be selected:

$$k_1 = 0.5 \quad (8.20)$$

$$k_2 = 2 \quad (8.21)$$

The value for k_2 is again chosen arbitrarily.

- **Step 2: setup of active control**: As before the system is excited by a parametrized force F (see Equation 8.5). To identify the optimal active control parameters for amplitude and frequency, an optimization is performed. This optimization is based on Equations 8.8, which describe the dynamic behavior of the system. Target of the optimization is to find a configuration of amplitude and frequency which generates an amplitude of $\delta = 0.2[m]$ in settled oscillation for mass 2. The optimization is performed with the genetic algorithm of the MATLAB optimization toolbox, using the same settings as used for the design of embodiment approach. The resulting amplitude and frequency are equal to the results achieved with the design of embodiment approach.

It turns out, that the iterative consideration of passive and active control elements generates the same results as the design of embodiment approach in this specific example. The results are listed in Table 8.1. It must be considered however, that the required optimization of the conventional approach corresponds to one inner optimization of the design of embodiment approach. When considering only the optimization time, the conventional approach is drastically faster in this example therefore. While both the iterative approach and the design of embodiment approach are capable to identify the presented suitable solution, advantages of the design of embodiment approach can be recognized:

- In the presented example the analytic evaluation of the magnification factor which is simplified by decoupling the system of differential equations. This applied approximation potentially generates incorrect results however. Moreover in more complex systems the analytic evaluation is typically not feasible. Alternatively the robot hardware can be designed using the proposed iterative improvement described in Section 2.3.1.

- Although seemingly straight forward, the presented conventional approach is more complex and requires more in depth knowledge regarding the considered robot system and motion goals than the design of embodiment approach. While in the design of embodiment approach it is sufficient to minimize the energy effort to achieve an energy efficient system, the conventional approach requires a more sophisticated consideration of the problem formulation. To consider the elastic elements independently from the actuation, the calculation of the magnification factor is required. This is however a complex problem when performed analytically and only possible in systems with low complexity. Scalability can not be guaranteed in the conventional approach.

8.1.7 Evaluation of requirements for embodiment

To show, that the resulting configuration of the example construction can be considered as optimal embodied agent, a detailed examination based on the principles to design an embodied agent discussed in Chapter 3 is performed. In the following list, the resulting configuration of the swinging mass example is evaluated with respect to every principle with high or medium relevance as defined in Section 3.2. The stated summaries of the principles are taken from Table 3.2.

- **Three constituents:** *The requirements in form of ecological niche and desired tasks of an agent, need to be considered in agent development.*
  The ecological niche regarding the motion properties of the system is represented by the equation of motion. The desired motion goals are defined as problem formulations for a comprehensive optimization process. In the optimization process both the ecological niche, and the motion goals are evaluated simultaneously to achieve the optimal configuration of the agent.

- **Complete agent:** *Both the interactions between embodiment and environment (passive control), as well as the interactions between information processing and environment (active control) need to be considered in agent development.*
  Four parameters were evaluated in the example: The amplitude and frequency of the applied oscillating force, and the spring coefficients of the two applied elastic elements. While the amplitude and frequency of the applied force are active control parameters, the spring coefficients are passive control parameters. Therefore both active and passive control parameters are considered.

- **Cheap design:** *Passive control elements should be preferred over active control.*
  The resulting system involves passive control elements in form of elastic elements. Moreover these have optimized properties with respect to the desired goal. While the effect of passive control parameters is maximized, the active control is reduced to minimum effort to achieve the desired goals.

- **Sensory-motor coordination:** *An appropriate setup and coupling of sensors and actuators can increase the performance of the agent, while reducing the active control effort. Furthermore reafference and sensor fusion can increase the amount of available information.*
  The example does not contain sensors. Therefore this principle cannot be examined.

- **Ecological balance 1:** *Balance the complexity of sensor, motor, and information process.*
  This example neither includes sensors, nor motors. Therefore this principle cannot be examined.

- **Ecological balance 2:** *Balance the task distribution between active and passive control (while preferring passive control as suggested in the principle of cheap design) by the application of complex kinematic structures, elasticity, damping, and compliance.*
  The motion is achieved by exciting the elastic system in a suitable frequency, such that the input force is amplified and the desired motion is achieved. The configuration of all involved parameters is selected to minimize the applied energy effort. With respect to this requirement the motion task is distributed between excitation force and passive control elements while maximizing the contribution of passive control elements.

- **Parallel processes:** *Tasks should be performed distributed, but loosely coupled via the embodiment and the interactions with the environment.*
  In this example the resulting motion can only be achieved in the given configuration. Although the motion tasks are not distributed, since only one motion task is considered simultaneously, the embodiment and the interactions with the environment are utilized to achieve the desired motion.

- **Value:** *Define values for different goals of the agent.*
  The design of embodiment approach utilizes a model-based optimization to achieve the desired configuration. For this optimization the motion goals are defined as problem formulation. In this context values are defined: A lower energy effort is ranked with a higher value in this example.

- **Versatility:** *Prefer passive control over active control while maintaining the required versatility of the agent defined by ecological niche and tasks.*
  All desired goals can optimally be achieved with the resulting configuration of passive control parameters. By the adaption of the active control parameters, the required variation to achieve each of the desired goals can be reached. Moreover in this specific example the optimal configurations of the considered passive control elements is equal for each goal. Therefore the individual optimal results can be achieved for each problem formulation.

The examination of every principle with medium or high relevance for the design of legged mobile robots reveals, that all applicable principles are addressed in this example. The design of embodiment approach is therefore suitable to optimally set up the considered passive and active control parameters in this example in order to achieve an optimally embodied agent.

8.1.8 Discussion

In this first example the design of a two-mass oscillator with respect to two different problem formulations is presented. It is desired to set up predefined active and passive control parameters while maintaining the versatility of the system to efficiently achieve two different motion goals. Besides the application of series elastic actuators the example examines oscillatory motions which both are relevant in legged locomotion. The conduction of every step of the design of embodiment concept is discussed in detail.

Moreover the results are put in context by comparison to results achieved with a conventional approach. The final evaluation shows, that the resulting system can be considered as optimal embodied agent with respect to the principles to design an embodied agent by Pfeifer and Bongard [62] presented in Chapter 3.

The comparison to the conventional approach reveals, that the design of embodiment approach is capable to identify the same configuration as the conventional sequential approach. Moreover less in-depth understanding regarding the system's dynamic properties is required in the design of embodiment approach. This is especially important when considering more complex problems as can be seen in the upcoming example problems. The problem formulation of the design of embodiment approach is a straight forward list of all desired motion goals, whereas the conventional approach requires an in-depth understanding of both the considered system, and the desired motion goals. In the conventional approach of the presented example the energy efficiency was not achieved by the intuitive approach of minimizing the applied energy in the first step, but by performing a frequency band analysis to identify the optimal magnification factor. Besides being an indirect and non-intuitive approach to set up the considered system, this approach is much more complicated and cannot be transferred to more complex problems: Even in the presented simple example an approximation of the applied damping must be included to allow for the analytic calculation of the required dynamic stiffness.

The intuitive approach of the design of embodiment approach is in the end more time efficient even in this simple example, by reducing the work load of the respective engineer. The calculation is shifted to the computer.

8.2 Throwing arm

Typically one stride in legged locomotion can be divided into the contact and the flight phase. The different properties of these parts of a stride characterize the overall locomotion of an agent:

- During the contact phase, forces are exchanged between ground and agent. As long as the contact is established, passive and active control elements can influence the agent's overall motion.
- The flight phase can be considered as ballistic throw resulting from the control actions performed during contact phase (as done for example in the SLIP model [69]). Only small influence to the dynamic behavior is typically achieved during the flight phase.

Therefore it is crucial to perform suitable control actions during contact phases in legged locomotion. In order to analyze the capability of the design of embodiment approach to handle periodic contacts, the second example therefore is desired to address the following motion goals:

- The agent must be capable to achieve **high-performance** motions. In legged locomotion this is typically coincident with fast locomotion speed. By tuning passive and active control together, the resulting performance is desired to be maximized.
- The achieved motion must be **robust** with respect to variations in time and space. In real world scenarios the time and position of transitions between the two phases depends on unknown conditions and typically cannot be predicted accurately. Despite these disturbances it is crucial to reach a target region regarding position, velocity, and acceleration during the flight phase to maintain stability. The agent must therefore be laid out robustly to overcome disturbances while maintaining sufficient accuracy.

In summary the second example must be designed to investigate the capabilities of the design of embodiment approach to layout a system with the following requirements:

- The considered motion must contain a contact and a flight phase.
- Passive and active control must be set up to achieve two motion goals:
  - Achieve robustness with respect to variations in time and space
  - Maximize performance (locomotion velocity)

Implementation of example

In the second example all these requirements are considered. Instead of a legged robot however, the design of a throwing arm is evaluated. This way a very similar mechanical structure to an established walking model (SLIP model [69]) can be considered, while avoiding the complex mechanics of a touchdown event (see Section 4.2). A focus on the design of embodiment regarding the presented requirements, which are highly relevant in legged locomotion is therefore possible. A more complex contact model which includes impacts is applied in the subsequent examples of a two-legged robot in Sections 8.3 and 8.4.

With respect to the stated requirements, the throwing motion of the arm is considered as contact phase. During this phase the object is in contact with the robotic arm. The flight of the object can be considered as the desired ballistic flight phase. The robotic arm has a single DOF and is actuated by a series elastic actuator (see Figure 4.2). The object is considered as point mass. During the design of embodiment process, the spring coefficient of the series elastic actuator and the parameters of a parametrized actuation trajectory are laid out. To include the stated requirements, the following goals are desired to achieve:

- **Achieve robustness:** Despite an added disturbance the object is desired to hit a target region.
- **Maximize performance:** Speed in locomotion is gained by increasing the stepping frequency and/or increasing the step size. Here only the throwing distance is considered, which is corresponding to the step size. The passive and active control parameters must be laid out, to achieve the maximum throwing distance.

A third implicit goal is the consideration of versatility. The passive control of the robotic arm must be set up consistently to achieve both fundamentally different goals. A schematic view of the arm is depicted in Figure 8.7.

The active control must be designed, such that a prestress, of the applied series elastic actuator can be utilized to improve the performance. It is therefore required to accelerate the motor backwards at first to preload the spring with potential energy. In the following forward motion not only the actuator, but also the stored energy can be utilized to accelerate the point mass. This forward motion of the motor with additional support of the preloaded spring can potentially result in high performance.

8.2.1 Modeling robot, environment, and active control

The dynamic behavior of the considered system is divided into two phases: the contact and the flight phase. Since these phases have fundamentally different dynamic properties, they are modeled in different equations of motion. In the following paragraphs the formulation of each phase is presented in detail. It must be considered that both the constraints of the ecological niche and the interactions with the environment are considered within the mathematical formulations of contact and flight phase. Subsequently the formulation of the applied active control structure is presented. With the active control all three constituents of the first principle to design and embodied agent (see Section 3.1.1) are considered.

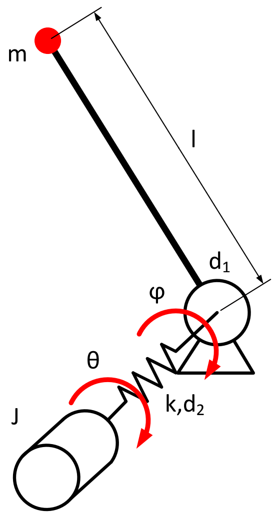


Figure 8.7.: 3D-schematic of the considered robotic arm with one DOF. The actuator with Inertia J and motor angle θ shown in front is connected to the arm via an elastic element. The elastic element has a spring coefficient k, and damping d_2. The arm itself has a joint damping d_1, length l and the point mass m on its end. φ describes the current angle of the arm. Zero positions for θ and φ are in straight upward position.

Image source: own representation

Modeling the contact phase

In the structure of the presented example, the elastic element has a spring coefficient k and a spring damping $d_2 = 1$ [Nms]. The motor angle is modeled as θ, and the joint angle as φ. Zero positions for both angles are in straight upward position. The arm is without mass and has length $l = 0.3$ [m]. The attached object is considered as point mass with $m = 0.5$ [kg]. The motor inertia is $J = 0.033$ [kgm^2]. The rotational DOF is mounted at $x = 0$ with a height of $y = 1.5$ [m]. The DOF receives a damping of $d_1 = 1$ [Nms].

A mathematical representation of the dynamic behavior of the arm excluding the motor behavior is formulated in Equation (8.22). The dynamic behavior of the motor is formulated in Equation (8.23). Actuator and robotic arm are implemented correspondingly to the series elastic actuator concept. They are coupled by an elastic element with spring coefficient k and viscous spring damping d_2. The applied motor torque is indicated with T.

$$\ddot{\varphi} \cdot m \cdot l^2 = g \cdot l \cdot m \cdot \sin(\varphi) - (d_1 \cdot \dot{\varphi}) - k \cdot (\varphi - \theta) - d_2 \cdot (\dot{\varphi} - \dot{\theta}) \quad (8.22)$$

$$\ddot{\theta} \cdot J = k \cdot (\varphi - \theta) + d_2 \cdot (\dot{\varphi} - \dot{\theta}) - T \quad (8.23)$$

Modeling the flight phase

The flight phase is modeled as ballistic throw without aerodynamic properties.

$$\ddot{x} \cdot m = 0 \quad (8.24)$$

$$\ddot{y} \cdot m = -g \cdot m \quad (8.25)$$

Initial conditions are derived from the equation of motion of the arm: Position and velocity of the mass at the time of release are considered as starting conditions of the throw. Due to the simplicity of the equations, the flight path of the object can be calculated analytically.

Modeling the active control structure

As discussed before, the active control structure must allow for a direction change to achieve a preloading of the applied series elastic actuator. Therefore the applied motor torque T is described with a set of three parameters: The first parameter T_1 describes the initial torque and T_2 describes the torque after change in direction. The parameter α_t describes at what angle the change of direction is performed. Although the motor changes direction, the arm is exposed to inertia and utilizes the momentum. Thereby energy can be stored in the spring and released later to increase the performance. A further active control parameter is the angle of release α_r. As soon as the robotic arm meets the desired angle of release α_r in forward motion, the object is released. The current position and velocity of the object are then transferred to the ballistic flight Equations (8.24) and (8.25).

8.2.2 Design goals

As discussed before, two robot motion goals are desired:

- **Problem formulation 1**: achieve high robustness with respect to variations in time and position in hitting a certain target.
- **Problem formulation 2**: achieve high performance regarding the maximum throwing distance while again considering perturbations.

In the following paragraphs the design and implementation of according objectives is discussed.

Achieve robustness

The resulting throw should be robust against slight variations with respect to the time of release and the position of release. To evaluate robustness, a variation of the definition of Kitano is applied as discussed in Chapter 5 (see Equation (5.11)).

As in Kitano's definition, a suitable set of perturbations P is applied. In this case the set of perturbations includes variations in time as well as in position of release. The applied perturbations result from the combination of variations in time $\Delta_t = [-0.004, -0.002, 0, 0.002, 0.004]$ [s] and position of release $\Delta_p = [-0.01, 0, 0.01]$ [m]. The variation of the position of release adapts the arm length of the robot. In total the set of perturbations therefore contains 15 different starting conditions. In this example, the probability for a perturbation $\psi(p)$ is equal for all considered perturbations.

Despite the perturbations, the robot is desired to robustly achieve its goals. One desired goal is to achieve a desired state after the flight phase ends to maintain stability and have suitable starting conditions for the following step. This goal is evaluated by investigating the accuracy of the examined throw under influence of the applied perturbations. The object is therefore desired to hit a certain target at $x = 2.37$ [m] and $y = 1.73$ [m][1]. The according objective function given in Equation (8.26) penalizes the quadratic distance to the target when hitting the plane with $x = x_{target}$.

$$Q_1 = \Delta_y^2 \tag{8.26}$$

By considering the deviations to the target, the objective function must be minimized.

A smaller robustness value indicates a better robustness in this case: if the object hits the target with distance $\Delta_y = 0$ for every considered perturbation $p \in P$, the respective configuration can be considered

[1] The position of the target is based on the position of the bullseye in darts according to the German Electronic Darts Sports Club (DEDSV).

as robust against these perturbations. The resulting robustness coefficient $R_{1,P}$ is therefore desired to be minimized. The inner problem for this goal can therefore be formulated as:

$$\min_{T_1,T_2,\alpha_t,\alpha_r} R_{1,P} \quad = \quad \sum_P \Delta_y^2 \quad \text{with} \quad x = x_{target} \tag{8.27}$$

Maximize performance

A further objective function that is typically required in robots that interact with the environment is performance. To investigate this requirement, the robot arm is targeted to throw at maximum distance. The objective function given in Equation (8.28) evaluates the horizontal distance from base to projectile when it hits the ground plane $y = 0$.

$$Q_2 = x \tag{8.28}$$

Again a robust solution is desired however. Since disturbances typically affect motion goals with rich interactions with the environment, the maximum throwing distance is desired to be achieved despite slight variations in the position and time of release. Therefore again the definition of robustness of Kitano is applied, using the same set of perturbations as in the problem formulation of robustness. Target of the optimization is to maximize the average throwing distance of the object, with respect to all considered perturbations. A possible mathematical formulation for the second goal is therefore:

$$\max_{T_1,T_2,\alpha_t,\alpha_r} R_{2,P} \quad = \quad \sum_P x \quad \text{with} \quad y = 0 \tag{8.29}$$

Achieve versatility

The requirement of versatility is implicitly implemented by the application of multiple criteria. A potential resulting configuration which is capable to achieve the different goals optimally can be considered as sufficiently versatile in this example.

8.2.3 Parameters for robot design and control

The used parameters must be assigned to either one of the groups of parameters defined in Chapter 6.

- **Constant parameters**: Besides natural constants this includes parameters which are fixed due to technical requirements or design requirements:
  - gravity $g = 9.81$ [m/s^2]
  - mass $m = 0.5$ [kg]
  - damping $d_1 = 1$ [N$\cdot$ s/m] and $d_2 = 1$ [N$\cdot$ s/m]
  - motor inertia $J = 0.033$ [kg$\cdot$m^2]
  - arm length $l = 0.3$ [m]
- **Time dependent and switchable variables**: This includes the active control parameters which are used to describe the applied parametrized torque T.
  - initial torque T_1 [Nm] $\in P_d$
  - torque after direction change T_2 [Nm] $\in P_d$
  - angle of switch between torques and change of direction α_t [rad] $\in P_d$

– angle of release α_r [rad] $\in P_d$

Here these parameters are considered as switchable variables with individual constant properties for each objective.

- **Time independent variables**: In this example only the spring coefficient of the applied series elastic actuator is considered as time independent variable.
  – spring coefficient k [N $\cdot$ m/rad] $\in P_{in}$

8.2.4 Optimization of embodiment

As discussed in Chapter 7, the optimization is divided into outer and inner optimization.

Inner optimization

Each inner optimization is performed with the genetic algorithm of the MATLAB optimization toolbox. The following settings were used:

- Population size: 40
- Maximum generations: 100
- Function tolerance: 1e-8
- Scaling function: rank
- Selection function: stochastic uniform
- Elite count: 2
- Crossover fraction: 0.8
- Boundaries of torque T_1: (-100) – (-1) [Nm]
- Boundaries of torque T_2: 1 – 100 [Nm]
- Boundaries of angle of torque change α_t: $-\pi/2$ – 0 [rad]
- Boundaries of angle of release α_r: $-\pi/2$ – 0.5 [rad]

The optimization was performed on an intel CORE i7 (2.67 GHz), 4GB RAM computer. Each inner optimization took 1200 seconds in average.

Outer optimization

Each objective is considered in a separate step in the outer optimization.

1. In the first step, the objective to maximize robustness in context with accuracy is considered only. To evaluate this robustness with respect to the time dependent passive control parameter k, a set of inner optimizations is performed with fixed k for $k = [0.1, ..., 10]$. In this optimization run 10 values for k are considered. Figure 8.8 depicts the resulting minimum quadratic average distance to the target position with respect to the involved perturbations which are required to investigate robustness.

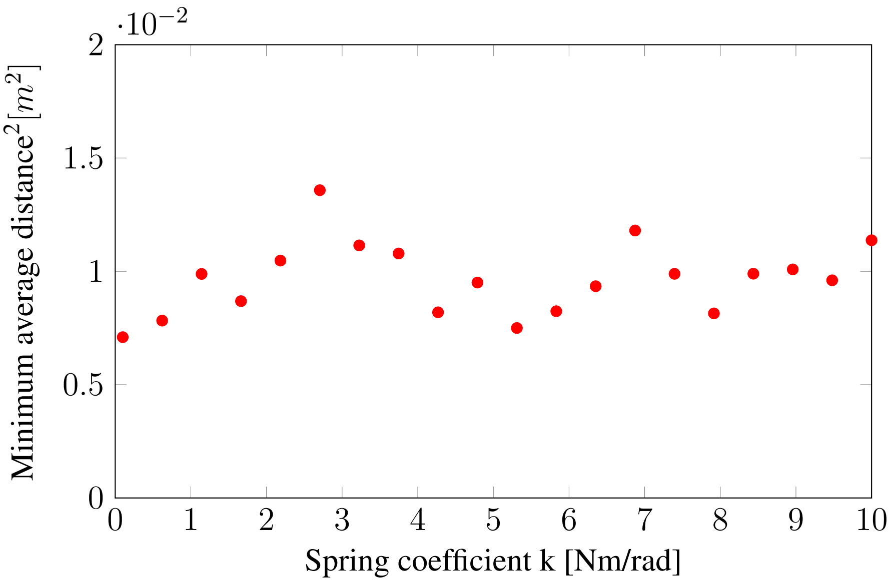


Figure 8.8.: In this plot the optimal result for each considered spring coefficient is depicted regarding the simulation experiment to optimize robustness. Each result represents the minimum quadratic average distance to the target position with respect to the involved set of perturbations.

Image source: own representation

Although a minimum can be recognized within the investigated set, no distinct gradient is visible: the minimum quadratic average distance is oscillating. When considering all collected data, a potential outcome can be, to consider all examined spring coefficients as capable to achieve a sufficient result. Another approach can be to only consider the minimum quadratic average distance smaller than a threshold. In this example, all evaluated spring coefficients are considered sufficient for the goal to robustly hit a certain target with desired accuracy.

2. In a second step the maximum throwing distance is considered. Since the evaluation of the first step showed, that all considered spring coefficients are equally good to fulfill the desired goal, the spring coefficient is only dependent on the required maximum throwing distance.

   It is therefore sufficient to perform one optimization which includes not only the time dependent parameters T_1, T_2, α_r, and α_t, but also the spring coefficient k. The results of this optimization are listed in Table 8.2.

	Q_1	Q_2	T_1	T_2	α_t	α_r	k
Configuration 1	**0.01**	3.83	-97.5	86.6	-0.91	-0.7	5.42
Configuration 2	0.43	**5.02**	-100	100	$-\pi/2$	-0.79	5.42

Table 8.2.: The table lists results for the throwing arm example. Configuration 1 achieves a minimal value for the first objective Q_1: the quadratic average distance to the desired goal. Configuration 2 achieves a maximal value for the second objective Q_2: the maximum throwing distance.

8.2.5 Classification of results

To achieve the respective motion goals different configurations regarding the active control of the system are required. The systematic consideration of the passive control parameters allows for the application of

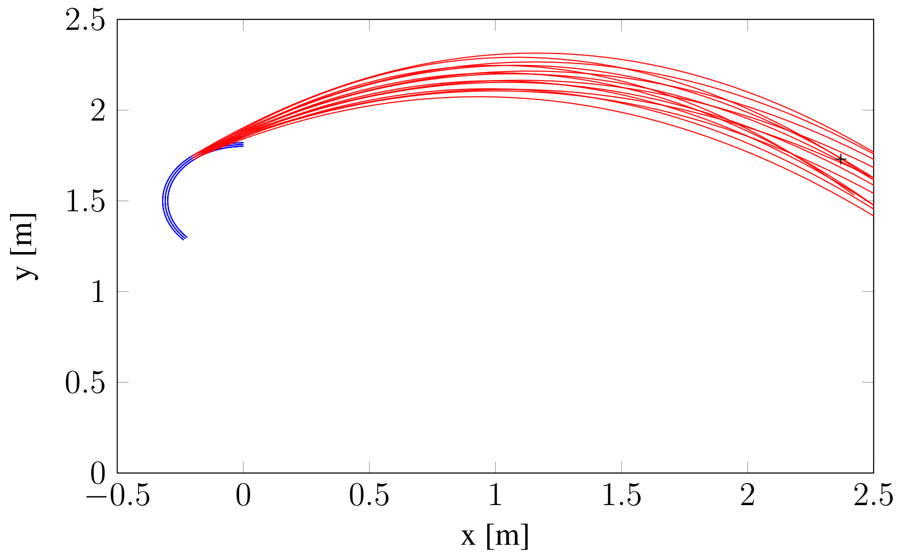


Figure 8.9.: The figure shows the set of trajectories which result from the optimal configuration with respect to the robustness goal. The blue curves hereby depict the trajectory of the mass while in contact with the arm. Note that each applied perturbation that varies position results in a different arm length. The red curves depict the respective flight paths that result from the optimal configuration for the considered parameters and the applied set of perturbations. The target is depicted as black plus.

Image source: own representation

one optimal solution for the spring coefficient, such that every goal can be achieved optimally. Figure 8.9 depicts the resulting trajectories for each considered perturbation when applying the optimal configuration regarding the goal to maximize robustness. The trajectory of the arm is depicted in blue, while the flight path of the object is depicted in red. The different considered flight paths hit the target marked as black plus or are at least within a sufficiently small area around the target.

Figure 8.10 shows the trajectories which result from the application of the configuration that is optimal to achieve the performance goal. The ground at $y = 0[m]$ is hit at $x = 5.02[m]$ in average with the optimal configuration.

8.2.6 Comparison with a conventionally designed robot

To set up the active and passive control parameters of the considered system is a complex problem. It is however addressed in several publications [12, 25, 90]. In these approaches typically the dynamic equations are analytically evaluated to identify correspondences between elasticity or damping and the achieved velocity, as for example in [25]. While the scope of these examinations is to show the increase of performance through series elastic actuators [90], or the ability to substitute conventional stiff actuators with smaller series elastic actuators [30], the presented approaches are not suited for the setup of embodied agents.

A key requirement as discussed in Section 3.1.9, is the design of passive control parameters, such that the required versatility is maintained. Therefore it is not sufficient to setup any time independent parameter of the robot without the consideration of all desired motion goals. Approaches found in related literature however are only capable to identify optimal configurations regarding all considered parameters for a single objective and are therefore not suited here.

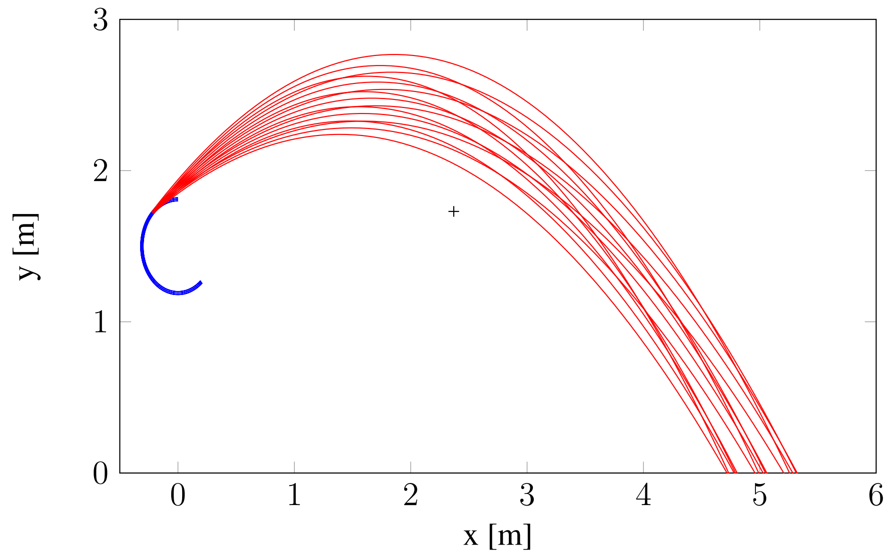


Figure 8.10.: The figure shows the set of trajectories which result from the optimal configuration with respect to the performance goal. The blue curves hereby depict the trajectory of the mass while in contact with the arm. The red curves depict the respective flight paths that result from the optimal configuration for the considered parameters and the applied set of perturbations. The black plus indicates the target of the robustness goal. It is displayed for convenience.

Image source: own representation

Moreover complex nonlinear dynamic problems as the present do often not offer an analytic solution. In these cases it is therefore not possible to analytically identify the required correspondences between passive and active control parameters. An approach to make use of the (approximated) analytic solution is presented in Section 8.1.6.

The present example displays a more complex problem, due to the applied hybrid differential equation of contact and flight phase and the involved non-linearity and can therefore not be solved analytically. Thus instead of applying an analytic approach, the iterative development process as applied in [18] is used. Like the approach used in [16], this process is sequential:

1. At first the system is considered rigid. Instead of a series elastic actuator, a stiff actuator is applied. The active control parameters are optimized with respect to each desired motion goal. For this optimization process, the same optimization parameters as presented in Section 8.2.4 are applied.

   Table 8.3 shows the resulting active control parameters regarding the two motion goals: rigid 1 are the results for the robustness objective, and rigid 2 for the performance objective. It must be considered, that the rigid system is only capable to throw a maximum distance of 1.34 [m]. To nevertheless be capable to hit the target at $x = 2.37[m]$ and $y = 1.73[m]$, the upper limit of T_2 was raised to 400 [Nm]. Furthermore it must be considered, that the result of this rigid setup is independent of the torque T_1: no energy can be stored in the spring, therefore no wind up motion is required in this scenario. The values for T_1 are rather resulting from a set time constraint, which limits the simulation of the arm motion to 2.5 seconds. To bring the arm in time to the in position to start the forward throwing motion, a sufficient torque must be applied.

2. In the second step, the elastic element is applied to the system. By means of a further optimization with the same settings as before, the optimal value for the elastic element is evaluated. Results are shown in Table 8.3 as elastic 1 and 2 for the respective motion goals. Again it must be considered,

that the applied torque T_2 in the robustness objective is higher than the defined limit. Nevertheless one can recognize an increase in robustness with respect to accuracy through the application of an elastic element.

To evaluate the maximum throwing distance additional expert's knowledge is integrated in the active control. Instead of applying the optimized results for the active control parameters, these are adapted manually using expertise: by the application of maximum torques T_1 and T_2, and by setting the minimum angle for a change of direction α_t, the resulting velocity can be optimized. The resulting throwing distance with optimized stiffness coefficient k is close to the result achieved with the design of embodiment approach.

In summary it must be considered, that it is not possible to set up the control parameters for the example system for the goal to robustly hit a certain target without violating the defined parameter boundaries with the sequential approach.

In contrast to the conventional approach presented in Section 8.1.6, this approach does not require the analytic solution of a complex differential equation. Interim results reveal, that a sequential approach is not suitable for the present problem. Although therefore the boundaries are adapted in favor of the discussed conventional approach, and some parameters are manually adapted to improve the solution, the result achieved with the design of embodiment approach is better (see Table 8.3).

Furthermore this approach generates a solution, in which the time independent parameter k is different for each considered motion goal. Another development step is therefore required to determine the final result for the spring coefficient k. As discussed in Section 7.2 many strategies to proceed with divergent results in multi-objective optimization are possible. Typical approaches that can be applied without alternating the structure of the presented system are confined to ranking the solutions: the more important motion goal defines the respective value for k. This however leads to a decrease in motion performance for either one of the considered motion goals. A weighting of the results, as for example averaging over the resulting values is however not recommended, as it generates configurations in which none of the considered motion goals can be performed with sufficient quality.

	Q_1	Q_2	T_1	T_2	α_t	α_r	k
Rigid 1	**0.03**	3.59	-81.64	**347.89**	-0.71	-0.87	-
Rigid 2	45.22	**1.34**	-78.97	100	-0.85	-0.76	-
Elastic 1	**0.01**	3.55	-81.64	**347.89**	-0.71	-0.87	191.92
Elastic 2	0.63	**4.97**	*-100*	*100*	$-\pi/2$	-0.76	6.02

Table 8.3.: The table lists results for the conventional approach to the throwing arm example. Rigid 1 and 2 show the optimal configuration for a system with rigid actuation instead of a series elastic actuation for each considered goal respectively. Elastic 1 and 2 show the final results with additionally evaluated elastic element. It must be considered, that the torque T_2 in the solution of the robustness goals are 3.5 times higher then the upper limit for optimization. This increase is necessary to be able to hit the target at all. Furthermore the active control parameters T_1, T_2, and α_t are selected manually in the elastic performance objective by the application of expert's knowledge.

8.2.7 Evaluation of requirements for embodiment

As discussed in Section 8.1.7 regarding the first example, the resulting configuration of the second example is also considered with respect to the principles for the design of an embodied agent by Bongard and Pfeifer [62].

The resulting configuration of the throwing arm example is evaluated with respect to every principle with high or medium relevance as defined in Section 3.2. The stated summaries of the principles are taken from Table 3.2.

- **Three constituents:** *The requirements in form of ecological niche and desired tasks of an agent, need to be considered in agent development.*
  The set of hybrid differential equations to describe the behavior of the robotic arm describes the ecological niche of the robot. The respective goals are formed as objective functions for a model-based optimization process.
- **Complete agent:** *Both the interactions between embodiment and environment (passive control), as well as the interactions between information processing and environment (active control) need to be considered in agent development.*
  The considered design process involves the setup of four active control parameters T_1, T_2, α_t, and α_r, and one passive control parameter k.
- **Cheap design:** *Passive control elements should be preferred over active control.*
  The given structure of the example problem allows only for the application of one passive control element, which has been optimized to optimally achieve the desired goals. The comparison to a sequential design discussed in Section 8.2.6 reveals, that a rigid system has less performance.
- **Sensory-motor coordination:** *An appropriate setup and coupling of sensors and actuators can increase the performance of the agent, while reducing the active control effort. Furthermore reafference and sensor fusion can increase the amount of available information.*
  This example neither includes sensors, nor motors. Therefore this principle cannot be examined.
- **Ecological balance 1:** *Balance the complexity of sensor, motor, and information process.*
  This example neither includes sensors, nor motors. Therefore this principle cannot be examined.
- **Ecological balance 2:** *Balance the task distribution between active and passive control (while preferring passive control as suggested in the principle of cheap design) by the application of complex kinematic structures, elasticity, damping, and compliance.*
  The optimal solution for both objectives involves a wind up motion to store energy in the elastic element of the series elastic actuator. By the distribution of tasks to active and passive control an increase in performance and robustness is achieved.
- **Parallel processes:** *Tasks should be performed distributed, but loosely coupled via the embodiment and the interactions with the environment.*
  The design of the robot's structure allows for a consideration of the influence of environment effects.
- **Value:** *Define values for different goals of the agent.*
  The performed optimization is based on a systematic assessment of the considered configurations with respect to the defined motion goals. The definition of values is therefore firmly established within the presented design of embodiment approach.

- **Versatility:** *Prefer passive control over active control while maintaining the required versatility of the agent defined by ecological niche and tasks.*
  The design of embodiment allows for the design of time-independent passive control elements by a special consideration of the different classes of parameters. Although the resulting configuration includes a constant passive control parameter k which is equal for both objectives, no restrictions regarding the achieved results per se are visible.

All relevant principles that can be applied in this example are considered in the resulting design of the robot. The resulting robot can therefore be considered as an embodied agent.

8.2.8 Discussion

In the presented example, a one-DOF robot arm with series elastic actuation is desired to achieve two different motion goals: achieve robustness while maintaining accuracy, and achieve high performance. Although considering a throwing arm, important properties which are required in a legged mobile scenario are investigated: The interplay between contact and flight phase in walking is represented by throwing an object with a robot arm. Control actions can only be performed during the contact phase. While the flight phase cannot be influenced by the control in this example, it is nevertheless as in legged locomotion important for the resulting motion.

Another reference to the legged mobile scenario is the selection of objectives in this example: One important factor in locomotion is the robustness with respect to disturbances in time and space. This example therefore considers the robustness of the throw when trying to hit a specific target. Moreover the example considers the maximum performance of the robot arm, by investigating the maximum throwing distance.

By the simultaneous setup of passive and active control parameters, optimal configurations were detected. These configurations are selected such that the time independent parameters, which are typically as in this case the passive control parameters, are equal for all configurations. The optimal configuration therefore only differ in the active control parameters. Active control parameters however can easily be adapted without additional actuation. This synergy of passive control actions wherever possible and active control actions wherever needed guarantees the desired properties of an embodied agent.

To put the results which are achieved with the design of embodiment approach in context, an alternative conventional approach with sequential layout of active and passive control elements is performed. In a first development step, the active control parameters are optimized for a system with rigid actuation. The results of this optimization reveal, that more energy is required to achieve results with similar performance. In the second development step the passive control parameter is optimized, while maintaining the already selected active control parameters. A comparison of these results with the results achieved with the design of embodiment approach shows, that although the sequential set up generates valid configurations, they are inferior. The simultaneous approach guarantees to consider all possible synergies between active and passive control.

Furthermore the conventional sequential approach generates one configuration for each considered motion goal, which are different regarding the time independent parameter. With the results achieved by the conventional approach, it is therefore not possible to achieve optimal results for each motion goal by adapting the active control parameters only. The resulting configuration of the design of embodiment approach however guarantees the versatility of the agent by generating configurations which only differ in active control parameters.

This example shows, that the design of embodiment approach, although it is simple to implement, generates high quality results for the design and set up of the considered motion problems.

8.3 1D hopping with the two-legged elastic musculo-skeletal robot BioBiped2

In this and the following example the design of embodiment approach is applied to the BioBiped 2 robot, which is presented in detail in [73]. The BioBiped 2 robot shown in Figures 6.1b and 8.11 is a bio-inspired two-legged musculo-skeletal robot with series elastic actuation. The musculo-skeletal structure hereby refers to the rigid kinematic construction with antagonistic actuation by means of tendons with elastic properties. Therefore not only the two-legged structure of the robot is bio-inspired, but also the principles of actuation.

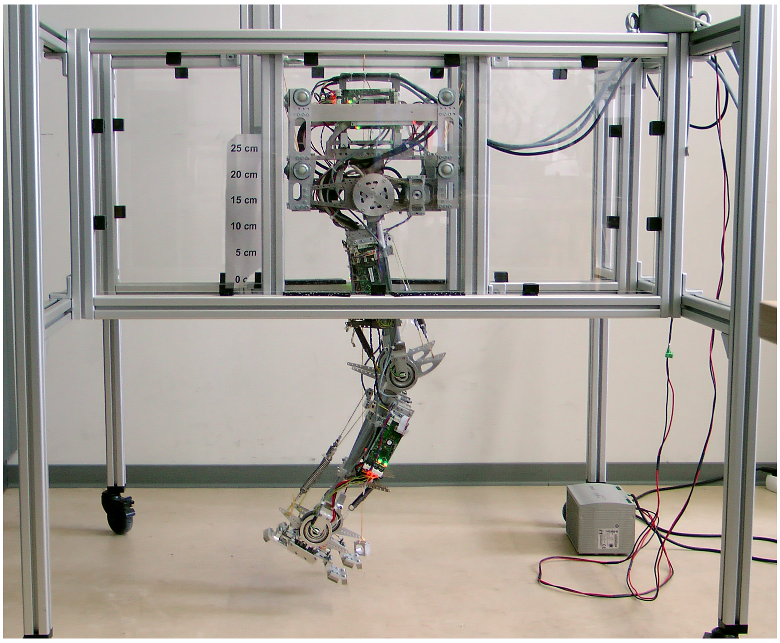


Figure 8.11.: The BioBiped 2 robot is constrained to a single translational DOF by the supporting frame.
Image source: own representation

The BioBiped 2 robot is part of the BioBiped project funded by the Deutsche Forschungsgemeinschaft under grant number STR 533/7-1. One goal of the project is to achieve human-like three dimensional running, walking, and standing with a robot. To achieve this target, technical specifications arising from the human were applied in the construction of the robot. A schematic view of the robot's structure is depicted in Figure 4.1b. The BioBiped2 robot comprises two legs and a small proportion of the torso. Corresponding to the human leg, the robot has the three pitch joints hip, knee, and ankle in each leg. The knee and ankle joints can be extended actively by a series elastic actuator for each joint. The flexion of knee and ankle is performed passively by an elastic element without actuation. The hip can be moved actively in both directions by means of a series elastic actuator.

In order to achieve stable locomotion of the robot in real world environments, multiple intermediate steps have been reached and/or are planned with the real robot in experiments. The 1D synchronous hopping motion, which is one of the already performed experiments is approached in this example from the perspective of embodiment.

The considered example is based on experiments which have been performed with the real BioBiped2 robot. In the example the BioBiped2 is desired to perform a leg-synchronous hopping motion. For this experiment the trunk of the robot is fixed in a frame, which only allows a one-dimensional up-and-down-motion. The legs of the robot can be actuated according to the capabilities of the robot without further restrictions. Previous experiments on the real robot revealed, that it is difficult to suitably adjust the spring coefficients to perform as robust passive control parameters in real world experiments. The adjustment renders difficult because of the high dynamical complexity of the robot hardware. Moreover the interplay between active and passive control parameters is difficult to investigate systematically in real world experiments. The goal of the design of embodiment approach in this example is therefore to detect the optimal configuration for selected passive and active control parameters to optimally achieve the required hopping motion.

Since the design of the complex mechanics of a two-legged robot is explicitly included in this example, it is relevant by definition in the design of a two-legged robot. It is furthermore relevant for achieving dynamic locomotion for three main reasons:

- The applied joint angle trajectories are similar to the eventually desired running or jogging motion.
- As in running or jogging, the interactions with the environment are reduced to forefoot contacts with the ground.
- The hopping motion includes both contact and flight phases in periodic alternation. This fundamental property is a key characteristic in dynamic running and jogging.

In contrast to the theoretical examples approached in the preceding sections, this and the following example consider the dimensioning of a real robot system. Since typical conventional approaches are not well suited to address a system with such complexity, the presented example is not compared to other approaches. To nevertheless illustrate the significance of the results, the 1D hopping example is compared with results achieved in real hardware experiments.

Implementation of example

In this example a detailed simulation model of the BioBiped2 robot is considered. To achieve the desired motion, the robot is required to achieve two motion goals:

- The achieved synchronous hopping must have sufficient quality. A possible approach to define the subjective target of hopping quality mathematically is discussed in Section 8.3.2.
- The sagittal ground contact forces must be minimal. The desired up-and-down hopping motion requires ground reaction forces to work in the same direction. Ground reaction forces that work to the front and back are not contributing to the desired motion and are therefore to be minimized.

To allow for an objective consideration of the hopping quality a metric is introduced. This metric is evaluated in detail in the formulation of the design goals in Section 8.3.2. Since the robot is desired to perform a 1D hopping motion, all energy that is applied in upward direction during ground contact is considered as high value. Energy which is applied in sagittal direction however is considered as adverse and must therefore be minimized.

Required dimensions and coefficients of the robot model correspond to the respective values of the real robot. A list of applied dimensions and coefficients is listed in the definition of the model in Section 8.3.1. The variables which are desired to be considered in the presented optimization are selected based on experiences made on the real robot. The robot is actuated with a state machine control approach, that includes two different states: a retracted state and an extended state. Based on additional information from ground contact sensors, the target joint configuration is switched between these states. Furthermore the elastic elements in knee and ankle are desired to be optimized. The different parameters are discussed in more detail in Section 8.3.3.

8.3.1 Modeling robot, environment, and active control

The modeling of robot, environment, and active control structure is approached corresponding to the elaboration presented in Chapter 4. First a suitable kinematic structure of the robot is selected which potentially meets the the given objectives for each constituent. In the second step a mathematical representation for the model of robot, environment, and active control structure is evaluated. However, as in the preceding examples, the robot structure is part of the target constraints. The robot structure corresponds to the structure of the BioBiped2 robot. In the following the structures of the three constituents are explicitly formulated:

- **Structure of the robot:** The considered BioBiped2 robot is a two legged robot with series elastic actuation. Since synchronous hopping is desired, it is sufficient to only consider one leg and half of the trunk in the simulation. The leg of the robot consists of three segments: thigh, shank, and foot. Together with the trunk this results in a chain of four rigid links. These links are connected by rotational joints. The structure of the robot as used in the simulation model is depicted in Figures 4.1b 4.1c, and 8.11.

  As depicted in Figure 4.1c the joints of the BioBiped2 robot are actuated by series elastic actuators. The respective motors are located in the link above the respective joint. The actuators in knee and ankle however are only applied to extend the joints. The antagonistic retraction motion is performed by passive elastic elements without actuation.

  As discussed in the throwing arm example in Section 8.2, a walking motion typically involves a ground contact phase and a flight phase. To take account of this hybrid character of the considered hopping motion, the model of the motion dynamics is also divided into flight phase and ground contact phase. A change between these phases is triggered by either touching (impact) or leaving (liftoff) the ground. To prevent singularities or a penetration of the ground by the heel, the foot is equipped with two point contacts: at the forefoot and at the heel.

  The mathematical representation can be applied to calculate the robot's motion, including position, velocity, and acceleration from the applied forces. Due to the high complexity the resulting set of differential equations is located in the appendix of this thesis. A detailed derivation and modeling of the used equations is presented in [27][2].

- **Structure of the interactions with the environment:** The interactions with the environment are reduced to gravity, ground contacts, and a 1D up-and-down constraint of the upper body of the robot. The mounting of the upper body represents a reduction of the respective degrees of freedom to a 1D translational movement coaxial to the gravity vector. Neither damping nor elasticity nor further effects are applied to the mounting.

  The ground contact however is a more complex interaction with the environment. It is required for the structure of this interaction to allow several basic properties that can also be investigated in real world contacts:

  - The penetration of the ground by the foot must be prevented.

[2] The author wishes to thank Johannes Geisler for providing the BioBiped model.

- The ground contact must allow for the application of stiction.
- Forces in the two dimensions of the sagittal plane must be measurable.
- Sufficient damping must be included in the ground contact to achieve realistic resulting forces.

These requirements are considered in the presented example by the application of a spring-damper based ground contact with linear spring and linear but direction dependent damping coefficients.

The ground contact is modeled with two equations:

$$m \cdot \ddot{x}(t) = -d_x \cdot \dot{x}(t) - k_x \cdot (x(t) - x_{\text{contact}}) \quad (8.30)$$
$$m \cdot \ddot{y}(t) = -d_y \cdot (\min(0, \dot{y}(t))) - k_y \cdot y(t) \quad (8.31)$$

It must be considered, that the y axis is pointing downwards. These equations allow for a suitable consideration of the stated requirements. The penetration of the ground is approached by the application of an elastic force, which is proportional to the penetration depth. The coefficient of this elastic force is k_y. Damping in y-dimension is implemented to be direction dependent. Only motions that are directed downwards are damped with linear damping coefficient d_y. Upward motions are not damped to prevent the respective foot from sticking to the ground. Furthermore the ground contact allows for the application of stiction. The x-coordinate of the ground contact is stored as $x_{\text{contact}})$. A possible deviation from the contact position is reduced by the application of an elastic force with linear coefficient k_x. Velocities in x-direction are reduced by means of viscous damping with a linear coefficient d_x.

- **Structure of the active control:** The active control structure is based on the one which is used for the real BioBiped2 robot. A state machine based approach as presented in Section 4.3.4 is used in the present example. For each joint which is involved in the considered motion, two states are considered:
  - retraction state
  - extension state

  These states are triggered by the events ground contact and liftoff. As soon as the ground contact is established, the extension state is set as target joint configuration. The retraction is triggered with the liftoff.

  To apply the target joint configuration to the robot joints, a PD-feedback-controller is used. The PD-controller calculates and applies the required force to actuate each joint individually.

8.3.2 Design goals

The resulting configuration of the robot is desired to achieve two motion goals:

- **Problem formulation 1**: achieve optimal hopping quality in synchronous hopping with 1D-confinement
- **Problem formulation 2**: minimize transferred ground contact energy in sagittal direction

These motion goals are discussed in more detail in the following paragraphs.

Achieve optimal hopping quality

The hopping quality is analyzed by investigating a series of 14 to 20 hops. In order to concentrate on hops with settled oscillation, only the last 10 hops are considered. An optimal hopping of the robot is desired to fulfill several requirements:

- The motion is desired to be consistent over a number of hops. This motion goal is evaluated by considering the mean hopping height of 10 hops regarding the hip.
- The foot must leave the ground. In order to avoid noise the minimal jumping height is 0.03 [m]. Jumps with less peak height are not considered as jumps. A penalty for each jump with less jumping height is applied to the objective value therefore.
- The air time must be large. The air time is equivalent to $(1 - \text{duty factor})$ (see Section 5.1.3).
- It is desired to achieve a target hopping height of the feet. This target hopping height is set to 0.09 [m], since this height can be achieved by the real robot in hopping experiments. The squared difference to this target height is applied as penalty value.
- In order to achieve a stable periodic jumping motion, the upward distance of the hip in a flight phase is desired to be maximized. Maximizing the upward motion while disregarding the flight phase can result in a distinctive up-and-down motion while sticking to the ground. When maximizing the flight phases only however, jumps with low height difference could be preferred.

These requirements are summarized in one objective function which is subject to minimization:

$$\begin{aligned} Q_1 = & - & (\textstyle\sum \text{peak}_i^{\text{hip}})/i + \sum(\text{peak}_i^{\text{foot}} < 0.03) \\ & - & (1 - (\textstyle\sum \text{duty factor}_i)/i) + \sum(\text{peak}_i^{\text{foot}} - 0.09)^2 \end{aligned} \tag{8.32}$$

Assuming that every considered jump is above the minimal height of 0.03 [m] and the peak height is at least close to the desired 0.09 [m], the objective value is less then zero.

Minimize sagittal ground contact energy

The ground reaction force contributes to the flight path of the robot to a great extent. In the considered example the robot is desired to perform an upward motion without lateral or saggital acceleration. By the consideration of the robot in the saggital plane only, no lateral forces occur in this example however. It is therefore desired to minimize the integral of the saggital ground contact forces $\text{GCF}^{\text{saggital}}$. This requirement can be formulated as objective function:

$$Q_2 = \int \text{GCF}^{\text{saggital}} \text{dt} \tag{8.33}$$

The results are normalized by considering the average value of hops eight to ten of the considered ten hops.

8.3.3 Parameters for robot design and control

This example is intended to show the capabilities of the design of embodiment approach, by considering a set of parameters for optimization, which is difficult to determine optimally with conventional approaches. The set of parameters is selected based on experiences with the real robot in hardware experiments.

Technical parameters are based on CAD data of the BioBiped robot. The target angles in retraction state of knee and hip are set to a constant value based on preliminary simulation experiments.

Parameters for damping and friction are included in the simulation model. However they are not considered as design parameters in the optimization, since they can neither be measured nor adapted easily in current robot hardware. Also elasticity in the actuation is more relevant for the motion types and motion goals considered.

- **Constant parameters**:
  - lengths of foot: 0.105 [m], shank: 0.33 [m], and thigh: 0.33 [m]
  - center of gravity of foot: 0.0525 [m], shank: 0.195 [m], thigh: 0.195 [m], and upper body: x=0.0012 [m], y=0.0566 [m]
  - lever arm for spring attachment for BF/knee: 0.076 [m]
  - lever arm for spring attachment for VAS/knee: 0.076 [m]
  - lever arm for spring attachment for TA/foot: 0.074 [m]
  - lever arm for spring attachment for SOL/foot: 0.074 [m]
  - mass of foot: 0.878 [kg], shank: 2.028 [kg], thigh: 2.028 [kg], and upper body: 2.55 [kg]
  - moment of inertia of foot: $908.283 \cdot 10^{-6}$ [kg $\cdot$ m^2], shank: $7590.626 \cdot 10^{-6}$ [kg $\cdot$ m^2], and thigh: $8527.31 \cdot 10^{-6}$ [kg $\cdot$ m^2]
  - spring coefficient of the series elastic actuator of the hip: 250 [N/m]
  - joint damping of ankle: 0.25 [Nm s], knee: 0.25 [Nm s], and hip: 0.25 [Nm s]
  - ground stiffness: 20000 [N/m]
  - ground damping: 30 [N s/m]
  - initial dropping height: 0.15 [m]
  - target angle in retraction state of knee and hip: 1 [rad]

- **Time dependent and switchable parameters**:
  - P-gain of joint control: $P \in P_d$
  - D-gain of joint control: $D \in P_d$
  - target angle in retraction state of ankle: $\tau_{A0} \in P_d$
  - target angle in extension state of ankle: τ_{A1}, knee: τ_{K1}, and hip: $\tau_{H1} \in P_d$

- **Time independent parameters**:
  - spring coefficient of knee extensor (VAS): k_{VAS} [N/m] $\in P_{in}$
  - spring coefficient of ankle extensor (SOL): k_{SOL} [N/m] $\in P_{in}$
  - spring coefficient of knee and ankle flexor (BF and TA): k_F [N/m] $\in P_{in}$

It must be considered, that the spring coefficients of knee and ankle flexor are considered in one common variable k_F. Experiments with the real robot showed, that the application of springs with equal stiffness for both flexors is a suitable approach. Moreover this way the optimization parameters can be reduced.

Damping parameters are not considered to be adaptable both in this and the upcoming example discussed in Section 8.4. Although they can easily be adapted in simulation, a measurement and adjustment on the real robot cannot be realized easily. Possible results concerning the damping can therefore not be applied to the BioBiped2 for real-world experiments.

8.3.4 Optimization of embodiment

For the integration of the model the ode23s solver is applied.

- **Inner optimization**: As in the preceding examples the inner optimizations were performed with the genetic algorithm of the MATLAB optimization toolbox. The optimization settings are set as follows:
  - population size: 80
  - maximum generations: 100
  - scaling function: rank
  - selection function: stochastic uniform
  - elite count: 2
  - crossover fraction: 0.8
  - stall generation limit: 40
  - boundaries of P-gain: 20 – 400
  - boundaries of D-gain: 0 – 20
  - boundaries of target angle in retraction state of ankle τ_{A0}: 0 – 1
  - boundaries of target angle in extension state of ankle τ_{A1}: 1 – π
  - boundaries of target angle in extension state of knee τ_{K1}: 0 – 1
  - boundaries of target angle in extension state of ankle τ_{H1}: 0 – 1

  The optimization was performed on an intel CORE i7 (2.67 GHz), 4GB RAM computer. The duration of each inner optimization process was between approx. 1 [h] and 3 [h].

- **Outer optimization**: The optimal hopping quality based on the problem formulation discussed in Section 8.3.2 is evaluated for each relevant configuration of spring coefficients for soleus (SOL), vastus (VAS), and the antagonist springs biceps femoris (BF) and tibialis anterior (TA) (see Figure 4.1). To identify the optimal configuration of springs the the two motion goals are approached in separate steps.
  1. In the first step the hopping quality is examined only. To reduce the problem size, only available and reasonable spring configurations for the application in the real robot are considered. These springs include:
     - spring coefficients SOL: 6700, 7900, 10000, 13000 [N/m]
     - spring coefficients VAS: 10000, 13000, 15400, 17900 [N/m]
     - spring coefficients BF and TA: 2000, 4100, 5800 [N/m]

The consideration of every possible combination results in 48 different configurations. For each of these combinations an inner optimization is performed with the settings described above.

2. The second problem formulation is approached by only considering optimal configurations regarding the first problem formulation. Instead of applying another optimization algorithm, the optimal results regarding the active control parameters for each spring coefficient configuration are considered. This way the 48 different configurations are ordered based on their performance regarding the second motion goal. It is moreover guaranteed, that only optimal hopping configurations are considered.

8.3.5 Classification of results

The results regarding the two motion goals are depicted in Figure 8.12. Hereby plots 8.12a, 8.12c, and 8.12e depict the optimal hopping quality for each investigated configuration of time independent parameters, while plots 8.12b, 8.12d, and 8.12f depict the respective saggital ground reaction energy in [Js]. Both motion goals are subject to minimization, rendering dark blue regions in the graphs as optimal solutions. Every investigated configuration is marked with a black dot. Pareto-optimal configurations are highlighted with a red dot.

The analysis reveals, that antagonist springs with a low coefficient of 2000 [N/m] result in jumps with low hopping quality regarding the presented metric (see Figure 8.12a). When applying the Nemhauser-Ullmann algorithm [58] to the 48 investigated points, the set of Pareto-optimal solutions can be achieved. The seven Pareto-optimal configurations are listed in Table 8.4. The respective active control parameters for the Pareto-optimal solutions are presented in Table 8.5.

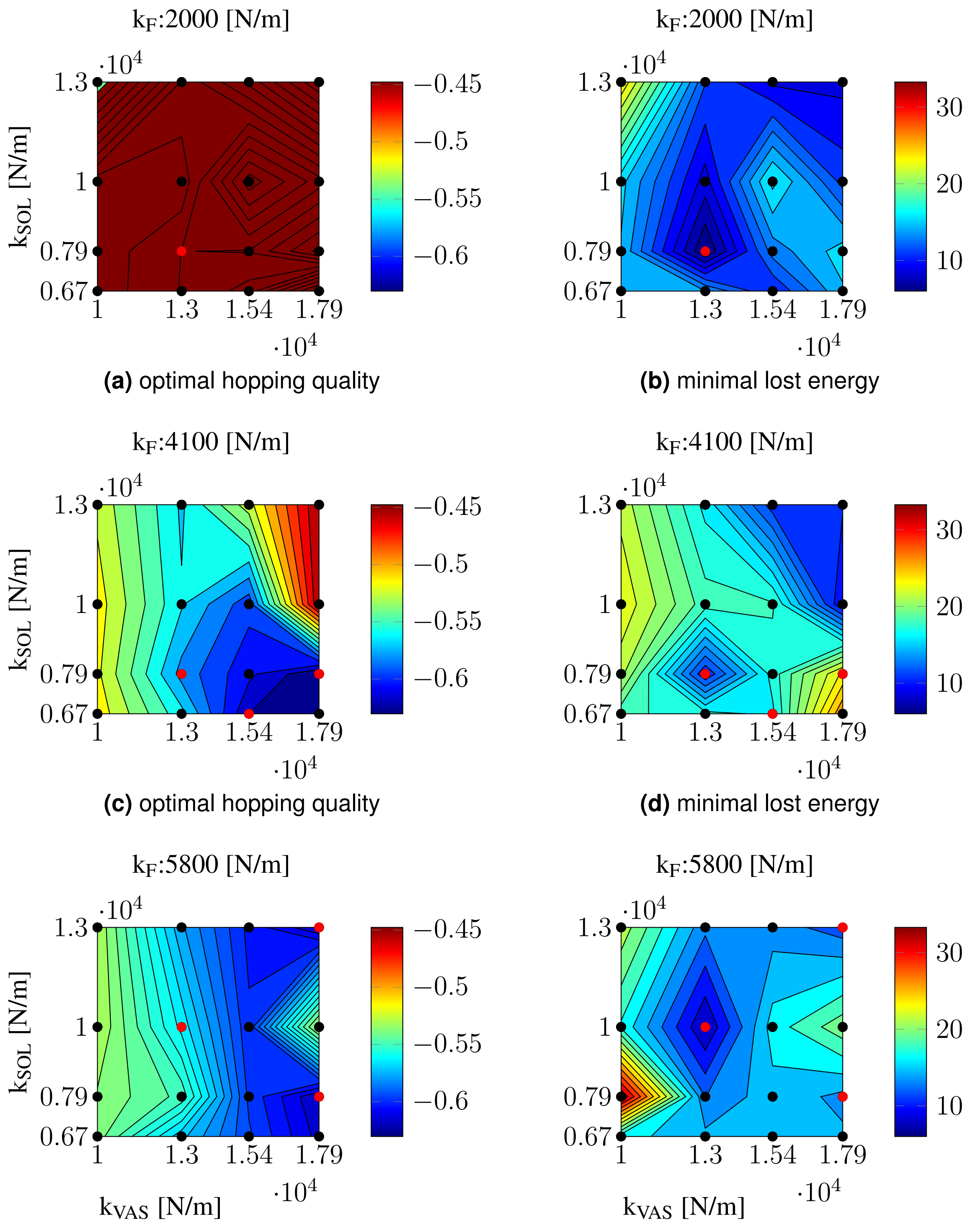
	Q_1	Q_2 [Js]	k_{VAS} [N/m]	k_{SOL} [N/m]	k_F [N/m]
1	-0.6304	23.3747	17900	7900	4100
2	-0.6190	16.5611	15400	6700	4100
3	-0.6167	13.9564	17900	7900	5800
4	-0.6167	11.9250	17900	13000	5800
5	-0.5775	10.5913	13000	7900	4100
6	-0.5637	8.1198	13000	10000	5800
7	4.5919	5.9952	13000	7900	2000

Table 8.4.: The table lists all Pareto-optimal configurations of the investigated solutions regarding the two problem formulations.

The hopping trajectories over time of all seven Pareto-optimal configurations with optimal time-independent control parameters are plotted in Figure 8.13. The plotted trajectories include the hip height in the upper region of the graph, and the height of the foot tip, in the lower region. The trajectories of the optimal configuration regarding problem formulation 1 are highlighted in blue, while the optimal trajectories of problem formulation 2 are highlighted in red.

It is visible, that the optimal trajectory regarding problem formulation 1 is consistent after a short period of transient oscillation. Furthermore a high duty factor is achieved as desired. However, with a height of 0.13 [m] the jumping height does not meet the desired 0.09 [m].

The optimal trajectory regarding problem formulation 2 however is not very consistent. For both the hip height, and the height of the foot tip no distinct consistent oscillating behavior can be recognized over



(a) optimal hopping quality **(b)** minimal lost energy

(c) optimal hopping quality **(d)** minimal lost energy

(e) optimal hopping quality **(f)** minimal lost energy

Figure 8.12.: The graphs show the resulting optimal hopping quality and the minimal saggital ground reaction energy for each investigated spring configuration. Plots 8.12a, 8.12c, and 8.12e hereby depict the hopping quality for the different antagonist spring coefficients 2000 [N/m], 4100 [N/m], and 5800 [N/m]. Plots 8.12b, 8.12d, and 8.12f depict the minimal saggital ground reaction energy of the different antagonist springs respectively. The ground reaction energy is depicted in [Js] Evaluated configurations are marked as black dots. Pareto-optimal solutions are highlighted with red dots.

Image source: own representation

	P-gain	D-gain	τ_{A0}	τ_{A1}	τ_{K1}	τ_{H1}
1	371.5279	0.8709	0.0182	2.6053	0.1662	0.0650
2	391.9881	0.1002	0.1807	2.5158	0.0204	0.1514
3	304.3960	0.0856	0.1040	2.0723	0.0064	0.2783
4	327.0578	0.1693	0.0437	1.7670	0.1706	0.5654
5	328.0974	0.3319	0.1595	3.0375	0.1990	0.9369
6	313.4455	0.4931	0.7090	1.8359	0.1324	0.4277
7	369.3233	0.6324	0.0293	2.6924	0.1834	0.1242

Table 8.5.: The table lists the active control parameters for the Pareto-optimal configurations.

the investigated series of hops. When comparing the presented results based on the trajectories and on the values listed in Table 8.4, the configuration number seven, which is plotted in red in Figure 8.13, is not sufficient. Although the saggital ground reaction energy is optimal, the configuration is not considered for further evaluation.

Regarding the remaining configurations 1 – 6, no general optimal solution can be named. Each of the solutions is Pareto-optimal. Therefore additional information or objectives are required for further decision.

A possible further objective to layout the passive control of the robot is addressed in the following example in Section 8.4.

8.3.6 Evaluation of requirements for embodiment

In the present example the dimensioning of selected passive and active control parameters of an existing robot is evaluated. The following list evaluates the principles by Bongard and Pfeifer in order to show, that the resulting robot with according active and passive control configurations can be considered as embodied agent.

- **Three constituents:** *The requirements in form of ecological niche and desired tasks of an agent, need to be considered in agent development*
  All three constituents are considered in the dimensioning of the active and passive control parameters. The explicit consideration of interactions with the environment and motion goals in the development approach guarantees a targeted dimensioning of the relevant parameters.

- **Complete agent:** *Both the interactions between embodiment and environment (passive control), as well as the interactions between information processing and environment (active control) need to be considered in agent development.*
  Although only a few parameters are considered in the dimensioning process, both active and passive control parameters are included. The complete agent principle is therefore regarded in the dimensioning of the BioBiped.

- **Cheap design:** *Passive control elements should be preferred over active control.*
  The structure of the robot is given by the example description. Therefore no explicit preference for one or another type of control parameters could be influenced in the example. The equal consideration of passive and active control elements however allows for a selection of suitable parameters to optimally achieve the desired motion goals.

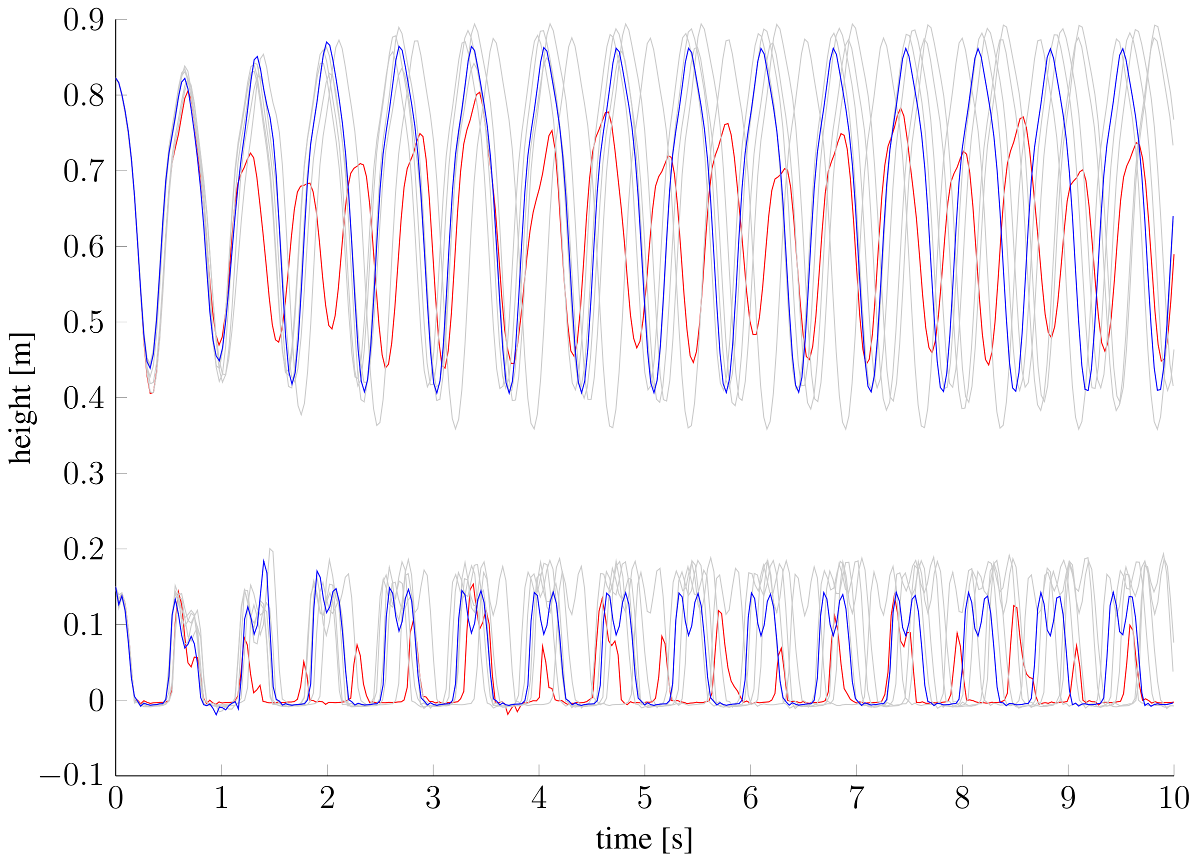


Figure 8.13.: Hopping trajectories of the Pareto-optimal solutions of the 1D hopping example. The upper trajectory depicts the position of the hip joint over time and the lower trajectory the position of the foot-tip. The optimal trajectory when only considering problem formulation 1 is depicted in blue, while the optimal solution when only considering problem formulation 2 is depicted in red. Further Pareto-optimal solutions are shown in grey.

Image source: own representation

- **Sensory-motor coordination:** *An appropriate setup and coupling of sensors and actuators can increase the performance of the agent, while reducing the active control effort. Furthermore reafference and sensor fusion can increase the amount of available information.*
  No actuators or sensors are considered in the presented example. Nevertheless the applied energy can be used to dimension the respective actuators.

- **Ecological balance 1:** *Balance the complexity of sensor, motor, and information process.*
  This example neither includes sensors, nor motors. Therefore this principle cannot be examined.

- **Ecological balance 2:** *Balance the task distribution between active and passive control (while preferring passive control as suggested in the principle of cheap design) by the application of complex kinematic structures, elasticity, damping, and compliance.*
  The characteristics of the applied series elastic actuation allows for a balancing of active and passive control elements.

- **Parallel processes:** *Tasks should be performed distributed, but loosely coupled via the embodiment and the interactions with the environment.*

The robot structure allows a task distribution between active and passive control, not only by the elastic coupling of actuator and link, but also by the arrangement of the kinematic structure.

- **Value:** *Define values for different goals of the agent.*
  By systematically evaluating the desired motion goals in the applied optimization algorithm, the configuration with the highest value regarding the motion goals is selected. The definition of values is firmly established within the design of embodiment approach.

- **Versatility:** *Prefer passive control over active control while maintaining the required versatility of the agent defined by ecological niche and tasks.*
  By the consideration of two motion goals a set of Pareto-optimal solutions is found. This set of solutions guarantees the versatility of the resulting robot.

As can be extracted from this list, all relevant principles are considered in the resulting robot. The resulting robot can therefore be considered as embodied agent.

8.3.7 Evaluation of results in real world robot experiment

To further evaluate the quality of the results, two hardware experiments with the BioBiped2 robot are conducted. The target of the experiments is to achieve one-dimensional hopping with different passive control settings and to compare the achieved hopping quality based on the motion goals defined in Section 8.3.2. A comparison of the sagittal ground reaction forces is not possible, since the achieved forces cannot be measured in the present setting. The comparison therefore is reduced to the first objective only.

In the first experiment a passive control configuration is applied, which is based on the experiences with the hardware. The configuration results from two years of working with the hardware. Hereby the applied springs have been selected by considering the quality and robustness of the respectively conducted experiments. Furthermore the configuration is based on technical insight and estimations. The hardware configuration is shown in Table 8.6 as experiment 1. The configurations only differ in the spring stiffness of the applied vastus, as can be seen in Table 8.6 and in Figure 8.12. For the second experiment the optimal result regarding the hopping quality of the design of embodiment approach is chosen.

Experiment	k_{VAS} [N/m]	k_{SOL} [N/m]	k_F [N/m]
1	15400	7900	4100
2	17900	7900	4100

Table 8.6.: The table shows the applied passive control configuration for the conducted hardware experiments.

Although the simulation model which is used for the design of embodiment approach is very accurate, there are small differences and uncertainties. The most relevant uncertainty for this set of experiments are the damping and friction coefficients. These have been estimated conservatively for the simulation model.

As in the simulation, the robot is controlled by a set of target angles, which are triggered by the interaction with the environment. As soon as a ground contact or a lift off is detected, the target angle changes. Due to technical limitations, the results for the active control (see Table 8.5) cannot be applied to the robot however. The robot is not controlled by a target angle configuration τ as in the simulation model, but by a target motor configuration ϑ. Therefore the target configuration cannot be applied directly. Moreover the dynamic behavior of the applied motor is not included in the optimization model. The resulting motions are therefore different regarding the dynamic behavior. Finally to protect the hardware, the applied velocities and torques are limited.

In order to nevertheless achieve a robust hopping motion with high jumping height, an active control configuration which has been tested with the passive control configuration of experiment 1 is applied to the robot. The target motor angles for ankle (ϑ_{A0} and ϑ_{A1}), knee (ϑ_{K0} and ϑ_{K1}), and hip (ϑ_{H0} and ϑ_{H1}) are shown in Table 8.7. As before, the index 0 indicates the retraction state, while the index 1 indicates the extension state.

ϑ_{A0}	ϑ_{A1}	ϑ_{K0}	ϑ_{K1}	ϑ_{H0}	ϑ_{H1}
-2	-14	110	10	160	40

Table 8.7.: The table shows the applied target motor angles for both conducted hardware experiments in [deg].

For this experiment the BioBiped2 robot is mounted to a frame to reduce the DOF of the torso to the desired translational up-and-down motion. Figure 8.11 displays the setting of the experiment and shows the constraining mechanism of the robot. The robot starts in retraction state and with initial foot tip height of 0.15 [m].

To evaluate the objective value, different motion data is required:

- The duty factor is calculated based on the ground reaction force measured in the left foot tip. Due to noisy data, the analysis of the duty factor is performed manually.
- The height of the foot tip is measured by a high speed camera. The resulting peak heights are achieved by visual analysis of the video data.
- The height difference of the hip is measured with an accelerometer.

As discussed in the definition of the hopping quality objective in Section 8.3.2, the objective value is calculated by combining these features (see Equation (8.32)).

Results of experiment 1

For the evaluation of the results three hops out of 32 consecutive hops are manually selected. These hops are performed in a row and are selected based on their uniformity. Motion data which is relevant to calculate the objective value of the hopping quality is listed in Table 8.8.

Inserting the values in Equation (8.32) generates the hopping quality value of $Q_{E1} = -0.098 + 0 - (1-0.442)+0.00692 = -0.64908$. It must be considered however, that here only 3 hops are considered instead of 10 as in the simulation experiment. When extrapolating the respective data, an objective value of $\hat{Q}_{E1} = -0.098 + 0 - (1 - 0.442) + 0.02306 = -0.63294$ results.

Results of experiment 2

In this experiment again three hops of a consecutive series of 15 hops are evaluated. Again these hops are selected manually based on their uniformity. As in the first experiment, the relevant motion data is displayed in Table 8.9.

When inserting the values in Equation (8.32) the hopping quality is generated. For the second experiment with the configuration based on the design of embodiment approach, this value is $Q_{E2} =$

Hop No.	contact phase [ms]	stride length [ms]	duty factor	$\text{peak}^{\text{foot}}$ [m]	$(\text{peak}^{\text{foot}} - 0.09)^2$	Δ^{hip} [m]
24	131	308	0.425	0.044	0.002116	0.099
25	139	313	0.444	0.042	0.002304	0.094
26	147	322	0.456	0.040	0.0025	0.102
∅			0.442	0.042		0.098

Table 8.8.: The table shows the duration of contact phase and stride length of the considered hops of hardware experiment 1. Furthermore the calculated duty factor, the peak foot tip height, and the maximum height difference of the hip during the flight phase is displayed.

Hop No.	contact phase [ms]	stride length [ms]	duty factor	$\text{peak}^{\text{foot}}$ [m]	$(\text{peak}^{\text{foot}} - 0.09)^2$	Δ^{hip} [m]
8	135	358	0.377	0.062	0.000784	0.065
9	135	366	0.369	0.069	0.000441	0.062
10	128	344	0.372	0.060	0.0009	0.060
∅			0.373	0.064		0.062

Table 8.9.: Congruent with Table 8.8 this table shows the duration of contact phase and stride length of the considered hops of hardware experiment 2. Again also the calculated duty factor, the peak foot tip height, and the maximum height difference of the hip during the flight phase is displayed.

$-0.062 + 0 - (1 - 0.373) + 0.002125 = -0.68688$. To consider that in the real experiment only three instead of ten hops as in the simulation experiment are included the data must be extrapolated. The resulting value is $\hat{Q}_{E2} = -0.062 + 0 - (1 - 0.373) + 0.00708 = -0.68192$.

Discussion of the results of the hardware experiment

In a set of two experiments two passive control configurations have been compared regarding their resulting hopping quality. The first configuration is based on two years of experience with the BioBiped2 robot and has been chosen to robustly achieve high hopping heights. The second configuration corresponds to the results of the design of embodiment approach. Here the optimal configuration for the resulting hopping height has been chosen. For both experiments a state machine based active control was applied. To circumvent differences and inaccuracies between the simulation model and the real robot however, established active control parameters have been used. These control parameters are known to generate robust hopping for the configuration, which was used for experiment 1.

The evaluation of the captured motion data of the two considered configurations reveals, that the configuration, which is based on the design of embodiment approach is better when comparing the hopping quality. The evaluation moreover shows, that the difference regarding the hopping quality of the two considered configurations is 7.2%.

When comparing the results of the hardware experiments with the results of the simulation, differences regarding the hopping quality values can be recognized. Table 8.10 lists the results of each considered experiment in simulation and real hardware experiment. While the hardware experiment shows an improvement of 7.2% for the configuration used in experiment 2, the simulation only shows an improvement of 4.1 %.

These differences result from the conservatively chosen damping and friction parameters, which are applied in the simulation model for the joints and for the ground contact. The comparison shows, that despite small deviations resulting from model uncertainties, the design of embodiment approach can be successfully applied.

Experiment	simulation result	hardware result
1	-0.6047	-0.63294
2	-0.6304	-0.68192
Improvement	4.1 %	7.2 %

Table 8.10.: This table shows the simulation results and hardware results for the hopping quality of both considered experiments. In the last row the improvement from experiment 1 to experiment 2 is depicted.

8.3.8 Discussion

In this section the dimensioning of passive control parameters is presented using the example of the BioBiped2 humanoid robot. For this example the robot is desired to perform a one-dimensional hopping motion. This hopping motion is subject to two motion goals: The hopping must achieve a desired hopping quality, considering hopping height, duty factor, and uniformity, while the achieved ground reaction energy in saggital direction must be minimal.

Experience with the real robot hardware shows, that finding the optimal configuration of the springs, which are applied in the series elastic actuators, is a difficult process. To find a suitable configuration of these control parameters a long series of experiments was performed. Nevertheless it is not guaranteed, that the resulting configuration of this manual and time-consuming process is optimal with respect to the desired motion goals. An analytic approach to find the optimal configuration is not applicable for this example however.

In the presented example, this dimensioning process is performed with the design of embodiment approach. Each step of the design of embodiment approach is applied to the example problem: The robot and its constraints are modeled in detail as mathematical representation. This model allows for the evaluation of the robot's motion by applying forces or target angles with a corresponding feedback control. In the next step the motion goals are formalized to evaluate the quality of a configuration. Furthermore parameters, which are desired to be optimized and their respective properties are discussed. The subsequent optimization combines these design steps and generates a detailed insight regarding the quality of each considered passive control configuration.

By assessing 48 different hardware configurations and applying a threshold regarding the desired hopping quality a set of six Pareto-optimal solutions was identified. These results can be ranked by either of the applied objectives and a suitable configuration can be selected. It must be considered, that each of the achieved results is of equal optimality in the definition of Pareto. A unique solution can be achieved by applying additional objectives for example.

The evaluation regarding the requirements of embodiment shows, that the resulting robot configuration corresponds to the principles to design an embodied agent by Bongard and Pfeifer. The design of embodiment approach is therefore suitable for the dimensioning of active and passive control parameters of elastically actuated humanoid robots.

The conclusive comparison of the achieved results with a real hardware experiment furthermore shows, that the design of embodiment approach is suited to design and set up passive control parameters for real world robots. The configuration which is optimal according the design of embodiment approach regarding the desired motion goal, turned out to be better than the established and conventionally determined configuration.

8.4 2D locomotion of the two legged elastic musculo-skeletal robot BioBiped2

Ultimately the presented design of embodiment approach is intended to optimize the design and setup for the locomotion of bio-inspired compliant legged robots. Therefore the design of embodiment approach is applied to evaluate the optimal configurations of the BioBiped2 robot for a walking and running motion in this concluding example. The BioBiped2 robot, which is discussed in detail in Section 8.3, is depicted in Figures 6.1b and 8.11. As in the previous example, the design of embodiment approach is applied to come to design decisions regarding the passive control elements.

The BioBiped2 robot is desired to perform fast running on flat terrain. Furthermore the robot is desired to perform an efficient walking gait. Therefore it is necessary to find the optimal configurations of active and passive control parameters to achieve these motion goals. In the following sections the application of the design of embodiment approach is presented.

As in the preceding examples the resulting configuration is discussed based on the requirements for an embodied agent presented in Chapter 3. In contrast to the preceding examples however, no comparison to established design approaches or to real hardware experiments is performed. The design and setup of active and passive control parameters to achieve fast running and efficient walking in a two-legged robot is a complex problem, which cannot be addressed systematically with established approaches. The dimensioning of respective parameters in the BioBiped2 robot is performed by manual adjustment based on expert knowledge and experiences. Since the real BioBiped2 robot is up to date not operational for in-plane locomotion, no experiences regarding the control parameters exist.

The application of the design of embodiment approach to this complex problem is intended to prove, that even complex problems can be addressed with this new approach. Moreover the received results can be used as initial set of parameters for a possible hardware-in-the-loop evaluation to achieve a walking and running motion of the BioBiped2 robot.

8.4.1 Modeling robot, environment, and active control

For this example the Matlab Simulink SimMechanics model of the BioBiped robot, which was developed by Radkhah in [72], is used[3]. This model can be considered as very accurate representation of the robot's dynamic behavior. In contrast to the model used in the previous example, Matlab and the SimMechanics toolbox allows for an easy adaption of the model to the considered constraints. Moreover the model has been tested and validated with experiment results from hardware tests [72].

To allow for the application of the model in the considered scenario, the model must be expanded by a state machine for active control, as discussed in Section 4.3.4. In the following, a brief assignment of the model to the defined categories is presented. This assignment is complemented by an introduction to the applied state machine. A more detailed introduction to the robot model can be found in [72].

- **Structure of the robot:** The structure of the robot is modeled as chain of rigid links and joints. As displayed in Figure 4.1c, each leg includes three links (thigh, shank, and foot) and three joints (hip, knee, and ankle). The legs are mounted via the hip joint to the torso. As presented above, the actuation is performed by serial elastic actuators. These are mounted in order to mimic the dynamic

3 The author wishes to thank Dr.-Ing. Katayon Radkhah for providing the BioBiped model.

properties of the most important muscles in human legs. In contrast to the human, the robot can only actively actuate the extension of knee and ankle, since only vastus (VAS) and soleus (SOL) are actuated. The retraction is passively performed by attached springs with constant properties.

It must be considered, that the simulation model does not include joint-angle constraints for the ankle joints. This difference to the real robot is addressed by the problem formulations however.

The voltages of the applied motors are limited to 18 [V]. This value has proven in experiments with the real robot to be sufficient for rapid hopping motions.

- **Structure of the interactions with the environment:** Besides gravity the robot is affected by two types of interactions with the environment:
  - The robot is mounted, such that the torso can only move in the saggital plane. This means, that the degrees of freedom of the torso are reduced to up-and-down, and forward-and-backward motions.
  - In order to achieve a legged motion, the robot must be capable to perform ground contacts. As in the example in Section 8.3, each foot has two contact points: one at the tip, and the other at the heel. To calculate the required forces, the Hunt-Crossley model is applied [51].

  In contrast to the example in Section 8.3, no friction is assumed for the translational movement of the torso.

- **Structure of the active control:** To address the formulated requirements to develop an embodiment agent, the active control structure is based on a state machine. This state machine is added to the existing BioBiped model, by implementing a new Simulink block and adapting the respective program for operation.

  Whenever a ground contact is established (touch down), or finished (lift off), a new set of target motor angles for every involved joint is set. The structure of the implemented state machine is depicted in Figure 8.14.

  In order to allow the application of the same state machine for jogging and for walking motions, the state change can not only be initiated by a triggering event, but by a trigger state (ground contact or flight phase). This way it is possible to skip states in the progress. In this example only the states, which are marked in grey in Figure 8.14 are applied in gaits without flying phase. The unconventional implementation of the state machine generates complex active control decisions by reflex-like parallel processes, which are coupled by interactions with the environment (see Section 3.1.7).

  The respective target motor positions (extend, retract, and prepare) for each joint are subject to optimization in the inner optimization.

8.4.2 Design goals

The target robot configuration is desired to be optimal with respect to two motion goals:

- **Problem formulation 1**: achieve a fast jogging motion
- **Problem formulation 2**: achieve energy efficient walking

The two problem formulations are discussed in detail in the following paragraphs:

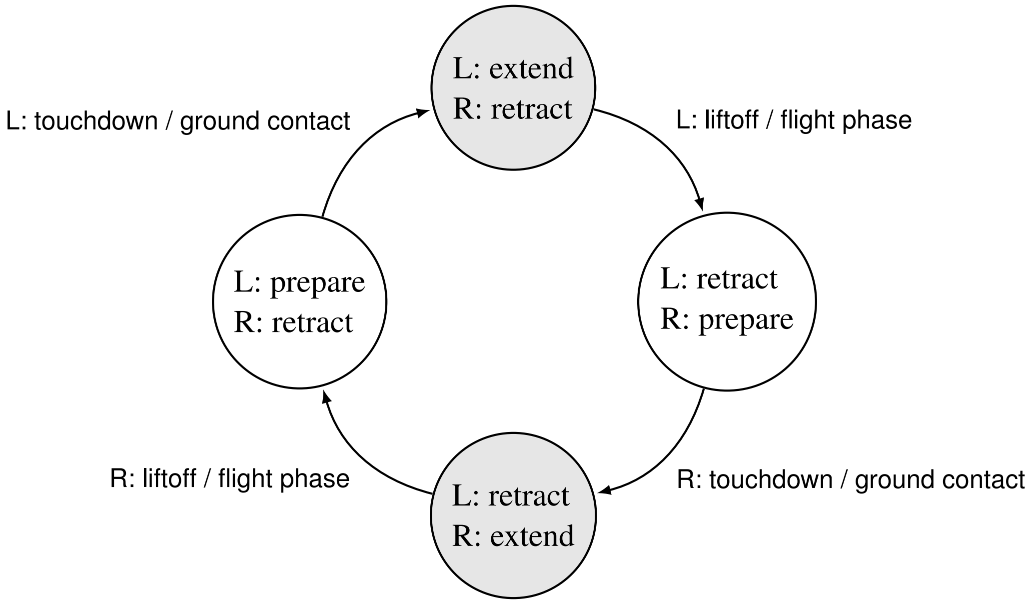


Figure 8.14.: The graph displays the structure of the state machine, which is applied in the present example. Overall there are four states, which are triggered by the flight phase or contact phase of either of the two feet. The state machine returns the respective target motor position for all involved joints (hip, knee, and ankle) for both legs.

Image source: own representation

Achieve a fast jogging motion

The robot is desired to achieve a fast forward motion with flight phases in-between the alternating ground contacts. The robot starts with no initial velocity at a height of 1 [m], regarding the center of mass of the torso. At start the left leg is in retraction state, while the right leg is in prepare state. The initial joint velocity is zero for each joint.

To evaluate the velocity, the achieved distance Δ_x at the end of a time period of six seconds is assessed. In this problem formulation the robot is desired to perform a fast jogging motion with flight phases. Therefore it is also necessary to reward flight phases in the problem formulation. This can be achieved by considering the duty factor. To prevent the robot from moving in the opposite direction, a penalty term is introduced.

$$Q_1 = \begin{cases} -10 \cdot \Delta_x + \text{duty factor} \cdot 10, & \text{if } \Delta_x < 0 \\ -\Delta_x + \text{duty factor} \cdot 10, & \text{else} \end{cases} \tag{8.34}$$

The objective is subject to minimization.

Finally it must be considered, that the used model does not include joint-angle constraints in the ankle. To prevent the optimization from generating solutions which violate the joint-angle constraints of the real world robot, another penalty term is introduced in the problem formulation. If the ankle joint-angle is below -2 [rad] or above 2 [rad] at any time of the simulation, a penalty value of 30 is added to the result.

Achieve energy efficient walking

For the second motion goal, the robot is desired to perform a walking gait. Walking is typically characterized by the lack of flight phases and a low energy consumption. For this experiment the robot starts with an initial velocity of 0.5 [m/s] with a height of 0.72 [m], regarding the center of mass of the torso. As for the jogging motion, the initial configuration of the left leg is the retraction state, while the initial configuration of the right leg is the prepare state. Again the initial joint velocity is zero for each joint.

Besides a low energy effort and minimal airtime, a threshold must be achieved. This minimum distance is set to 5 [m] in 6 seconds for this example. If the minimal distance is not reached or the robot is falling, which is identified by a low torso position, a penalty term is introduced.

$$Q_2 = \begin{cases} 1000 * (5 - \Delta_x) + E + T_f, & \text{if } \Delta_x < 5 \\ 10000 + E + T_f, & \text{if torso}_z < 0.2 \\ E + T_f, & \text{else} \end{cases} \tag{8.35}$$

The time of flight T_f in this equation is the number of milliseconds without ground contact of at least one foot. The energy E is the overall motor power in [W] calculated by motor velocity times torque for each motor.

As in the objective function of the jogging criteria, the ankle angle-joint constraint is also achieved by the implementation of another penalty term.

8.4.3 Parameters for robot design and control

Due to space restrictions, the list of constant parameters is not presented here. A complete list can be found wihtin the context of [72].

As in the previous example the damping and friction coefficients are considered in the simulation. They are however not considered in the optimization process, since they can neither be measured nor adapted easily in current robot hardware.

The following list will focus on the parameters, which are considered during the optimization processes.

- **Time dependent and switchable parameters**:
  - target angle in retraction state of ankle τ_{A0}, knee τ_{K0}, and hip τ_{H0} [rad] $\in P_d$
  - target angle in preparation state of ankle τ_{A1}, knee τ_{K1}, and hip τ_{H1} [rad] $\in P_d$
  - target angle in extension state of ankle τ_{A2}, knee τ_{K2}, and hip τ_{H2} [rad] $\in P_d$
- **Time independent parameters**:
  - spring coefficient of knee extensor (VAS) k_{VAS} [N/m] $\in P_{in}$
  - spring coefficient of ankle extensor (SOL) k_{SOL} [N/m] $\in P_{in}$
  - spring coefficient of knee and ankle flexor (BF and TA) k_F [N/m] $\in P_{in}$

8.4.4 Optimization of embodiment

For the integration of the model the ode23s solver is applied.

- **Inner optimization**: The inner optimizations were performed with the genetic algorithm of the MATLAB optimization toolbox. The optimization settings are set as follows:
  - population size: 20

- maximum generations: 60
- scaling function: rank
- selection function: stochastic uniform
- elite count: 2
- crossover fraction: 0.8
- stall generation limit: 8

The boundaries of the active control parameters are listed in Table 8.11. The optimization was performed on an intel CORE i7 (2.67 GHz), 4GB RAM computer. The duration of each inner optimization process was between approx. 2 [h] and 3 [h]. The boundaries are chosen based on the motion capabilities of the BioBiped2 robot. To furthermore exclude undesired motions, the hip motor angle range is reduced.

	retract		prepare		extend	
	min	max	min	max	min	max
ankle	-4	0	-4	0	-4	0
knee	2	6	2	6	2	6
hip	-0.2	1.2	-0.2	1	-0.4	1

Table 8.11.: Here the applied boundaries of the active control elements are listed in [rad].

- **Outer optimization**: To find the optimal configuration for each considered motion goal, two series of outer optimizations are performed. In each series of optimizations the following spring coefficients are considered. The results of the optimization process are desired to be applied in the real world hardware. Therefore additional constraints resulting from limited installation space, hardware strength and limited availability apply. The set of investigated spring coefficients is accordingly reduced, based on the results of the previous example discussed in Section 8.3.
  - spring coefficients SOL: 7900, 10000, 13000 [N/m]
  - spring coefficients VAS: 13000, 15400, 17900 [N/m]
  - spring coefficients BF and TA: 4100, 5800 [N/m]

  Overall this results in 18 combinations for each problem formulation.

  For each of these combinations an inner optimization is performed with the settings described above.

8.4.5 Classification of results

The optimal objective values for each considered configuration are depicted in Figure 8.15. Figures 8.15a and 8.15b show the optimal values for problem formulation one: jogging, while Figures 8.15c and 8.15d show the optimal values for problem formulation 2: walking. To more conveniently visualize the three considered dimensions of parameters (k_{VAS}, k_{SOL}, and k_F), each plot shows a constant parameters for k_F.

Configurations which are evaluated in the simulation are marked with a black dot. Configurations which are Pareto-optimal are marked with a red dot. Both objectives are subject to minimization, therefore in every plot a smaller value is better. Table 8.12 shows the according objective values and passive control configurations of the four Pareto-optimal solutions. Tables 8.13 and 8.14 furthermore list the respective active control parameters of the Pareto-optimal configurations for either jogging or walking.

Finally the jogging and walking motion with respective optimal passive and active control configuration are presented as sequence of frames (see Figures 8.16 and 8.17). The frames are taken from an animation of the resulting motions. For the visualization, the animation tool from [72] is applied. The complete animations of jogging[1] and walking[2] can be found online.

The analysis of these optimal configurations (number 1 for jogging and number 4 for walking in Table 8.12) depicted in Figures 8.16 and 8.17 reveals, that each desired motion goal requires a different passive control configuration. For jogging the knee actuator must be equipped with a stiffer elastic element, while the ankle and both antagonists require a softer spring. For walking a softer knee actuator elasticity is preferred, while the ankle and antagonists are equipped with stiffer springs. The two desired motion goals therefore do not have a unique solution regarding the configuration of the passive control elements.

	Q_1	Q_2	k_{VAS} [N/m]	k_{SOL} [N/m]	k_F [N/m]
1	-10.4730	386.6014	15400	7900	4100
2	-10.0912	348.9239	17900	7900	4100
3	-9.1303	331.1323	17900	10000	5800
4	-7.4631	310.8973	13000	10000	5800

Table 8.12.: The table lists all Pareto-optimal configurations of the investigated solutions regarding the two problem formulations jogging (Q_1) and walking (Q_2).

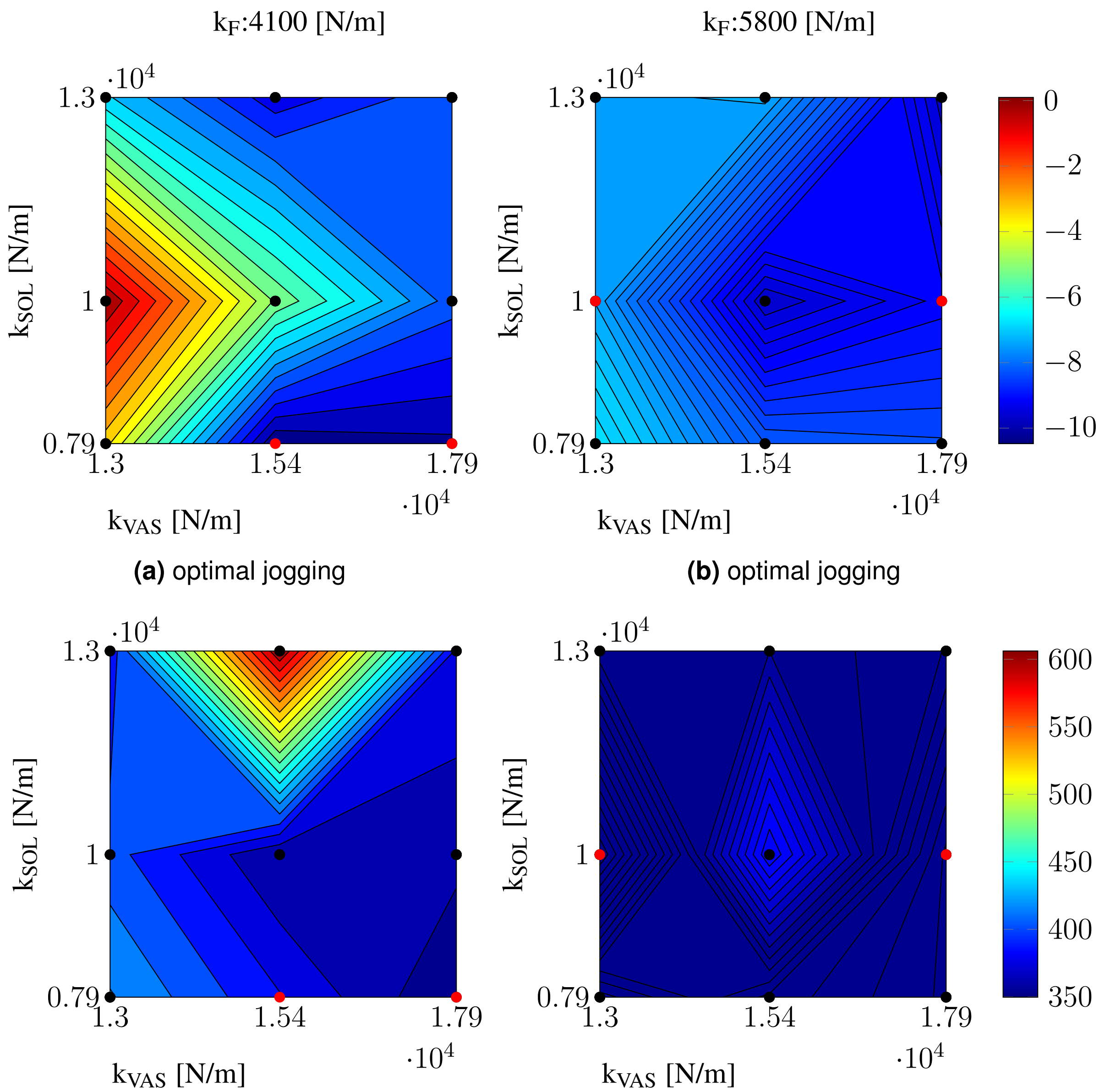
	τ_{A0}	τ_{A1}	τ_{A2}	τ_{K0}	τ_{K1}	τ_{K2}	τ_{H0}	τ_{H1}	τ_{H2}
1	-1.9	-0.097	-2.0406	2.9113	2.9875	4.6395	0	0.6092	-0.0136
2	-1.9	-0.097	-2.0355	2.9114	2.925	4.7333	0	0.6092	0.0399
3	-0.6791	-0.4403	-2.72	2.72	4.3928	5.8283	0.093	0.4191	-0.0553
4	-2.7229	-0.4562	-3.0371	3.0738	3.7586	5.7855	0.0376	0.7795	-0.0131

Table 8.13.: The table lists the target motor angles in [rad] for a jogging motion of the Pareto-optimal passive control configurations.

	τ_{A0}	τ_{A1}	τ_{A2}	τ_{K0}	τ_{K1}	τ_{K2}	τ_{H0}	τ_{H1}	τ_{H2}
1	-1.6657	-0.3736	-0.9601	4.3684	3.7722	3.8805	0.0317	0.9389	0.5483
2	-1.6644	-0.8757	-0.9361	4.3533	3.7722	3.7189	0.0333	0.9103	0.5442
3	-1.463	-0.8757	-0.9376	4.3806	3.8542	3.7745	0.04649	0.8827	0.6258
4	-1.5372	-0.9975	-0.9348	4.3533	3.7722	3.7212	0.07884	0.8857	0.649

Table 8.14.: The table lists the target motor angles in [rad] for a walking motion of the Pareto-optimal passive control configurations.

[1] `http://youtu.be/GfJiyzFVm_w`
[2] `http://youtu.be/0XHmlTrj2FU`



(a) optimal jogging

(b) optimal jogging

(c) optimal walking

(d) optimal walking

Figure 8.15.: These plots depict the optimal objective value for each considered spring configuration. Figures 8.15a and 8.15b show the optimal values for jogging, according to Equation (8.34). Figures 8.15c and 8.15d show the optimal objective values for walking, based on Equation (8.35). Evaluated configurations are marked with a black dot, while Pareto-optimal configurations are marked with a red dot.

Image source: own representation

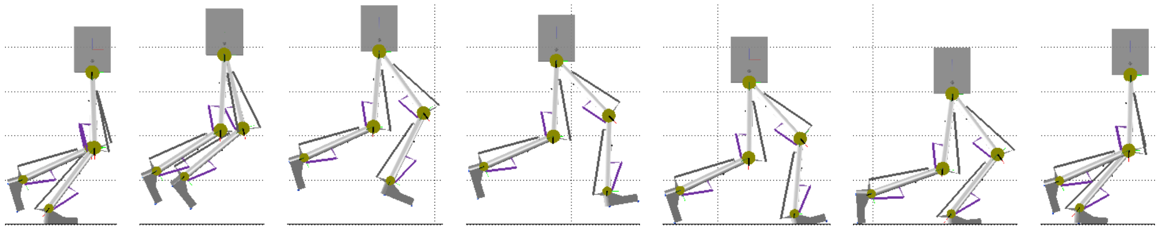


Figure 8.16.: The sequence shows the robot motion with the optimal configuration of active and passive control parameters for jogging (configuration number 1 in Tables 8.12 and 8.13).

Image source: own representation based on [72]

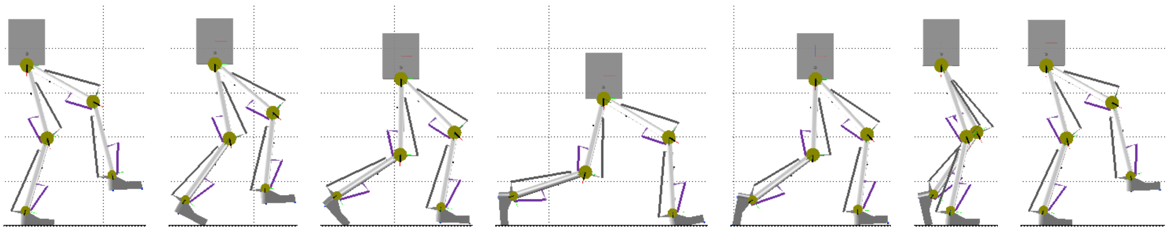


Figure 8.17.: The sequence shows the robot motion with the optimal configuration of active and passive control parameters for walking (configuration number 4 in Tables 8.12 and 8.14).

Image source: own representation based on [72]

8.4.6 Evaluation of requirements for embodiment

- **Three constituents:** *The requirements in form of ecological niche and desired tasks of an agent, need to be considered in agent development.*
  This example features a detailed mathematical model of the considered robot and the relevant dynamical interactions with the environment. Together with the description of the desired motion goals, all three constituents are considered.

- **Complete agent:** *Both the interactions between embodiment and environment (passive control), as well as the interactions between information processing and environment (active control) need to be considered in agent development.*
  During the simulation process all relevant interactions with the environment and all respective reactions of the robot embodiment are considered. Moreover a complex state-machine based control approach is included to enable active control triggered by ground contacts. A comprehensive consideration of the complete agent is therefore guaranteed.

- **Cheap design:** *Passive control elements should be preferred over active control.*
  This requirement is approached implicitly for the first problem formulation of fast jogging. Only with the efficient use of passive control elements a fast jogging motion is possible. For the second objective of energy efficient walking this requirement is considered explicitly: by minimizing the required energy effort of the actuators, the use of passive control elements is maximized.

- **Sensory-motor coordination:** *An appropriate setup and coupling of sensors and actuators can increase the performance of the agent, while reducing the active control effort. Furthermore reafference and sensor fusion can increase the amount of available information.*

This requirement is approached by the application of a sensor-based state-machine for the definition of target angles. The ground contact triggers a new state in the state-machine. The arrangement of a ground contact based trigger reduces the active control effort.

- **Ecological balance 1:** *Balance the complexity of sensor, motor, and information process.*
  Since the motor is modeled based on the actuator used in the real BioBiped2 robot, only the sensor and information process is balanced regarding their complexity. In fact both the sensor, and the information process have low complexity: the ground contact sensor provides information if a ground contact is established or not, while the active control structure selects a constant target angle for each relevant joint based on a simple state machine. As can be seen in Figure 8.14, this state-machine only involves four different states.

- **Ecological balance 2:** *Balance the task distribution between active and passive control (while preferring passive control as suggested in the principle of cheap design) by the application of complex kinematic structures, elasticity, damping, and compliance.*
  The BioBiped2 robot utilizes a complex structure to achieve motions. By using series elastic actuators for every joint, the exploitation of elasticity as passive control element is guaranteed.

- **Parallel processes:** *Tasks should be performed distributed, but loosely coupled via the embodiment and the interactions with the environment.*
  Both active and passive control tasks are performed distributed, but loosely coupled by the interaction with the ground. The application of a ground contact sensor and the inherent triggering of the applied state-machine represents a distributed but coupled processing of information. Although each joint has its respective target motor-angles, these are triggered by ground contacts. The applied passive control elements are distributed control elements by definition, as discussed in Section 3.1.7.

- **Value:** *Define values for different goals of the agent.*
  The desired motion goals are formed as objective functions. These functions represent the value of the respective motion of the robot. The concept of value therefore is a fundamental topic of the applied design of embodiment approach and therefore included in the solution of this example.

- **Versatility:** *Prefer passive control over active control while maintaining the required versatility of the agent defined by ecological niche and tasks.*
  Each considered motion goal requires a different passive control configuration for optimal performance. This information is required to apply strategies for ambiguous multi-objective solutions (see Section 7.2.3). By means of these approaches the required versatility can be achieved.

8.4.7 Discussion

This concluding example presents the application of the design of embodiment approach to a complex problem. The considered BioBiped2 robot is desired to achieve optimal performance, energy efficiency, and versatility by performing fast jogging and energy efficient walking. These motion goals are addressed by the dimensioning and setup of passive and active control elements. For that a complex simulation model of the BioBiped2 robot is extended with a state machine as discussed in Section 4.3.4. Suitable active and passive control parameters are selected and optimized in the subsequent optimization.

The assessment of 18 relevant passive control configurations for each considered motion goal reveals a set of Pareto-optimal configurations (see Table 8.12). The analysis of these configurations shows, that the optimal configurations for the considered motion goals (number 1 and 4 in Table 8.12) present an ambiguous solution. The introduction of a further objective is discussed in the following section, by including the 1D hopping as additional motion goal of the BioBiped2.

The subsequent evaluation shows, that the resulting configuration of the BioBiped2 satisfies the requirements for embodiment. The robot structure, the state-machine-based active control, the series elastic actuation concept, and the optimal active and passive control parameters provide for the adherence of all principles of embodiment. Only the determined optimal active and passive control parameters allow the exploitation of physical effects as desired. In the optimal configurations, the active and passive control elements perfectly work together to increase the performance, versatility, and energy efficiency. Moreover the initial configuration can be considered as disturbance in a transient oscillation. The successful achievement of a periodic motion therefore can be considered as robustness, although only one starting configuration is evaluated for each motion goal. Nevertheless, therefore also the desired property of robustness is evaluated and achieved in the resulting configuration of the robot.

Finally the selected motion goals guarantee desired key properties of legged mobile robots with highly elastic actuation. The design of embodiment approach therefore can be considered as important tool for the design and setup of such robots.

In contrast to the preceding example, the resulting configuration could not be tested on the real hardware. Although the complex dynamic behavior is modeled very accurately, the mechanical strength is not considered in the mathematical representation. The insufficient mechanical strength of the robot prevents the implementation of the considered motions. A fast jogging or even an efficient walking motion exerts high forces to all involved links and joints. This could lead to a structural failure and destroy the robot.

Nevertheless, the acquired data can be used to setup active and passive control parameters of the BioBiped3 robot depicted in Figure 6.1c. This next generation of the BioBiped series is designed to withstand higher forces but is to date not yet operational.

8.5 Joint discussion of the two-legged robot examples

Since Sections 8.3 and 8.4 consider the same robot hardware, results are discussed jointly. Although both examples consider the same robot, different environment and different motion goals are desired. According to the principle of the three constituents (see Setion 3.1.1) each result is only optimal regarding the applied environment and motion goals however.

It must be considered, that the model used in the 1D hopping example does not include motor dynamics. The comparison of the results must therefore be reduced to passive control elements.

Table 8.15 lists the optimal objective values for each of the 18 passive control configurations considered in both experiments. The objective values of all presented problem formulations are included:

- Q_1: the hopping quality of the 1D hopping example presented in Section 8.3 (see Equation (8.32))
- Q_2: the minimal sagittal ground reaction energy of the 1D hopping example presented in Section 8.3 (see Equation (8.33))
- Q_3: the objective value for fast jogging presented in the 2D jogging and walking example in Section 8.4 (see Equation (8.34))
- Q_4: the objective value for energy efficient walking presented in the 2D jogging and walking example in Section 8.4 (see Equation (8.35))

Q_1 hopping quality	Q_2 hopping energy	Q_3 jogging	Q_4 walking	k_{VAS} [N/m]	k_{SOL} [N/m]	k_F [N/m]
-0.5774	1787149	-3.2374	485.0287	13000	7900	4100
-0.5607	1983481	0.09483	416.2751	13000	10000	4100
-0.5638	1660045	-6.8550	424.5881	13000	13000	4100
-0.6047	1771141	**-10.4729**	394.1314	15400	7900	4100
-0.5919	1634816	-5.01363	198.9065	15400	10000	4100
-0.5212	1574276	-9.30055	223.6709	15400	13000	4100
-0.6304	1862835	-10.0911	216.0677	17900	7900	4100
-0.4484	1268257	-8.22070	198.6963	17900	10000	4100
-0.4477	**1104572**	-8.06880	216.8314	17900	13000	4100
-0.5472	1692270	-6.72076	**186.8907**	13000	7900	5800
-0.5636	1179372	-7.46305	210.9733	13000	10000	5800
-0.5772	1496780	-7.54898	220.6063	13000	13000	5800
-0.5962	1286366	-8.32029	198.8135	15400	7900	5800
-0.5991	1559238	-9.77114	211.4248	15400	10000	5800
-0.6020	1138930	-7.37160	205.9551	15400	13000	5800
-0.6167	1347567	-8.43576	206.9457	17900	7900	5800
-0.5300	1213886	-9.13028	199.1190	17900	10000	5800
-0.6166	1275345	-9.70289	204.3811	17900	13000	5800

Table 8.15.: The table lists all passive control configurations which have been considered in both BioBiped examples. Furthermore all objective values of the considered examples are displayed. These include the hopping quality (Q_1) and minimal sagittal energy (Q_2) of the hopping example discussed in Section 8.3, and the objective values of fast jogging (Q_3) and energy efficient walking (Q_4) discussed in Section 8.4. The optimal results for each considered objective are highlighted.

The analysis of the gathered data reveals, that no unique solution for the considered motion goals exist. To approach this ambiguous solution, only Pareto-optimal solutions are considered. Table 8.16 lists all Pareto-optimal configurations regarding the four objectives according Definition 7.1. For convenience the table is sorted regrading the objective value of Q_1. A visual presentation of the Pareto-optimal solutions is displayed in Figure 8.18. To enable a convenient comparison the results are linearly scaled and mapped to the interval {0,...,1}. The different Pareto-optimal solutions are depicted on the x-axis, while the stacked objective values are shown on the y-axis.

It must be considered, that each presented Pareto-optimal solution is superior for one or more considered objectives. A selection of one optimal configuration without additional objectives is therefore not possible without further weighting or evaluation.

A possible approach to generate a unique solution is to weight the results of the considered objectives. When equally weighting all considered objectives for example, solution number three would be the desired configuration. If the capability to perform jogging is most important however, the objective Q_3 must be weighted most. In this case configuration number four would be the optimal solution.

For the remaining analysis, a weighting approach is performed. Hereby the importance of objective Q_2 is reduced to zero. Figure 8.19 shows the six remaining Pareto-optimal solutions when disregarding

	Q_1 hopping quality	Q_2 hopping energy	Q_3 jogging	Q_4 walking	k_{VAS} [N/m]	k_{SOL} [N/m]	k_F [N/m]
1	**-0.6304**	1862835	-10.0911	216.0677	17900	7900	4100
2	-0.6167	1347567	-8.43576	206.9457	17900	7900	5800
3	-0.6166	1275345	-9.70289	204.3811	17900	13000	5800
4	-0.6047	1771141	**-10.4729**	394.1314	15400	7900	4100
5	-0.6020	1138930	-7.37160	205.9551	15400	13000	5800
6	-0.5962	1286366	-8.32029	198.8135	15400	7900	5800
7	-0.5472	1692270	-6.72076	**186.8907**	13000	7900	5800
8	-0.4477	**1104572**	-8.06880	216.8314	17900	13000	4100

Table 8.16.: The table lists the Pareto-optimal configurations which have been considered in both BioBiped examples. For convenience all objective values of the considered examples are displayed. These include the hopping quality (Q_1) and minimal sagittal energy (Q_2) of the hopping example discussed in Section 8.3, and the objective values of fast jogging (Q_3) and energy efficient walking (Q_4) discussed in Section 8.4.

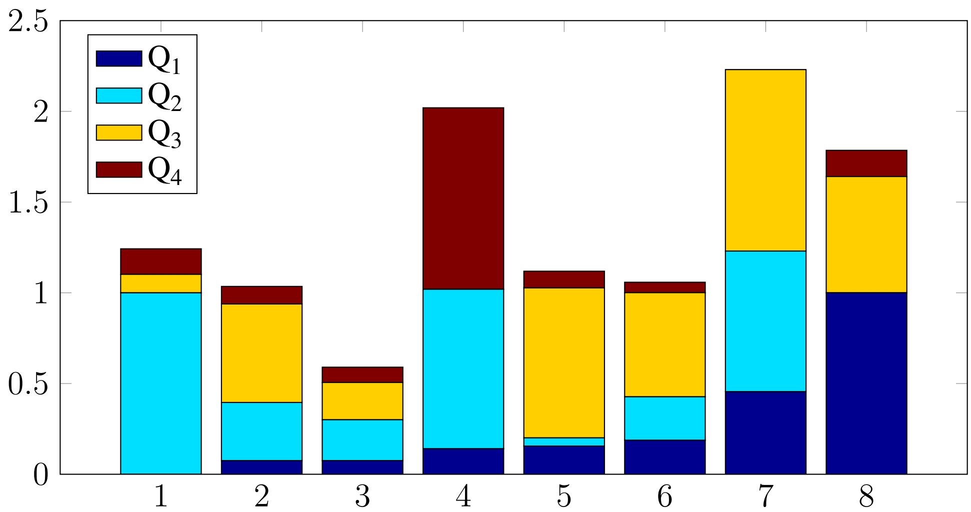


Figure 8.18.: The figure shows a visual presentation of the objective values of the four considered objectives for each Pareto-optimal configuration listed in Table 8.16. It must be considered, that the results are mapped to the interval {0,...,1} for each objective to enable a comparison.

Image source: own representation

objective Q_2. Based on the reduced Pareto-optimal set, two possible approaches to setup the passive control configuration will be discussed in the following.

Constant spring coefficients

By weighting the Pareto-optimal solutions a unique configuration can be selected. An equal weighting of the remaining three objectives Q_1, Q_3, and Q_4 would result in the configuration number 1 as optimal solution for the robot (see Table 8.16). Accordingly every other Pareto-optimal solution can be the result of a weighting. This solution has the benefit to achieve a fixed configuration of passive control elements. The structure of the robot must not be adapted. In a concrete example the capability to achieve

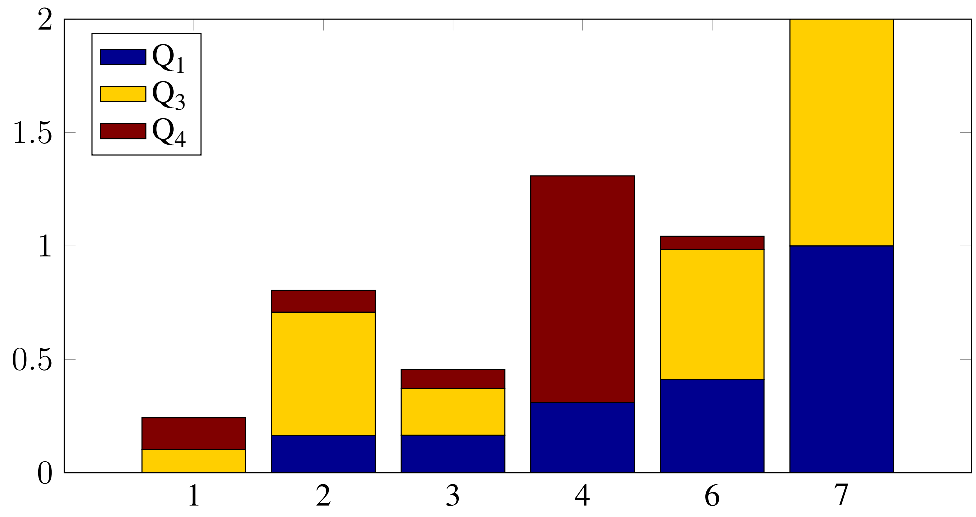


Figure 8.19.: The figure shows a visual presentation of the objective values of only three considered objectives. The problem formulation Q_2 is not considered in this visualization and the set of Pareto-optimal solutions is adapted accordingly. It must be considered, that the results are mapped to the interval {0,...,1} for each objective to enable a comparison.

Image source: own representation

a fast jogging motion Q_3 is ranked most important. The resulting optimal configuration is therefore configuration number 4 in table 8.16.

Springs with variable coefficients

To achieve optimal motion performance for every considered objective, it is required to adapt the spring coefficients for each motion. Several approaches to implement and control variable stiffness in SEAs have been introduced [7, 49, 86]. For convenience the optimal solutions for each objective are highlighted in Table 8.16. When disregarding objective Q_2, only 2 springs are subject to adaption: the SOL coefficient is equal for all optimal solutions.

The approach to adapt the spring coefficients of involved passive control parameters for each motion goal however requires to adapt the structure of the robot. Springs with switchable elasticity have to be implemented and controlled.

9 Conclusion

Legged robots require rich interactions with the environment to operate. When only considering the dynamics and kinematics of the robot, these interactions between robot and environment can be reduced to contacts (including friction and stiction) and gravity. In state-of-the-art development approaches these interactions however are typically considered as disturbances. Although interactions with the environment and the resulting dynamical behaviors are crucial for the considered motion goals of the robot, typical development approaches try to reduce these.

An alternative approach to design legged mobile robots introduces highly elastic joint actuation. This approach offers several benefits, which are relevant for robot locomotion in real world scenarios, including higher energy efficiency, increased robustness regarding time and position of interactions, and increased protection for motors and gears. Highly elastic joint actuation however presents challenges for the design, as well as for the operation of the robot. This thesis presents a new approach to design and setup such robots with highly elastic joint actuation based on the concept of embodiment.

The concept of embodiment considers the environment as indivisible part of the robot and claims, that the robot can only be designed to work efficiently by initially defining environment and desired tasks. A comprehensive analysis of the properties of embodied agents has been performed by Pfeifer and Bongard in [62] as list of principles to design an embodied agent. Despite being detailed and comprehensive these principles are missing a systematic approach to design and setup an embodied agent. In this thesis these design principles are analyzed and amplified regarding the application for the design and setup of legged mobile robots with series elastic actuation.

A mapping of these principles to a multi-objective, and multi-experiment optimization approach for a multi-body dynamics simulation guarantees the consideration of every requirement stated in the list of principles. The resulting new development approach is labeled **design of embodiment**. To enable the consideration of the principles to design an embodied agent in the design of embodiment approach, several new concepts and perspectives are introduced. These comprise the introduction of the term passive control for directed variation of the system behavior by mechanical elements. This way the consideration of effects, which influence the behavior of a robot, but are not actively controlled by information processing (see Definition 3.2) is enabled. To address the problem of multiple motion goals, which often require opposing control properties, the principle of efficient versatility is introduced.

This thesis furthermore presents challenges and details, that have to be considered in the generation of mathematical models for the simulation of the robot. Also general design considerations for a successful design of the hardware and active control structure of the robot are discussed. The exploitation of physical effects requires a suitable design of the robot to benefit from expected interactions with the environment.

The desired motion goals are unique for every considered robot. Typical design goals for legged mobile robots are presented within this thesis. The discussion of different exemplary motion goals presents not only objectives, which can be applied directly to other scenarios, but also presents typical metrics from the setting of locomotion.

To guarantee a successful design and setup of the considered robot, the set of adaptable parameters must be addressed regarding a new perspective. Parameters must be allocated according to their ability to be varied during robot operation. Hereby the property of passive control elements are considered, by including these in a comprehensive optimization approach.

By the evaluation of the selected parameters of the robot model regarding the desired motion goals in an optimization approach, an optimal configuration of passive and active control parameters for each motion goal can be found. In this thesis typical approaches to address the resulting multi-experiment, and multi-objective optimization are presented. Furthermore approaches to address the results of multi-objective optimizations are discussed.

To emphasize the applicability of the design of embodiment approach and the advantages of the embodiment concept, this thesis includes a series of examples. The examples are ordered in raising complexity. In the second example the design of embodiment approach is applied to a throwing arm, to analyze the performance of the new approach in systems with hybrid dynamic properties. Examples three and four assess the complex setup of the BioBiped2 robot. These examples prove, that the design of embodiment approach can be used to setup complex hardware as intended. Each of the four examples presents the implementation of the design of embodiment approach in detail. Moreover the abstract swinging mass example, and the throwing arm example are systematically compared to established design approaches for robot systems. The comparison reveals, that the design of embodiment approach generates equal or better results regarding the desired motion goals. The results of the 1D hopping example are furthermore verified by comparing these to a real hardware experiment. The concluding walking and jogging example proves the applicability of the design of embodiment approach even to complex robots with opposing motion goals.

The analysis of the conducted examples reveals, that the examples do not only fulfill the stated requirements to be considered as embodied agents. They are also optimally designed to achieve the desired motion goals by following the principles to design an embodied agent. Although the presented design of embodiment approach is discussed and assessed for the design and setup of legged mobile robots with highly elastic actuation, the design approach can be transferred to other problem areas. The application of the principles of embodiment allow for the design of efficient machines, which have rich interactions with their environment. By adapting the components of the design of embodiment approach, a whole new class of design and setup problems can be addressed. In established approaches the interplay between hardware, active control, and environment is typically difficult to consider. Nevertheless this fruitful exploitation of the respective advantages regarding the control properties is a key feature of embodied agents. The new design of embodiment approach allows for a systematic consideration of these effects however. By evaluating every considered configuration in simulated operation, the fruitful interactions between the several constituents of the embodied agent are implicitly included in the approach.

The presented design of embodiment approach furthermore has the property, to allow for a systematic and straightforward implementation of the desired motion goals. Instead of solving equations of motion or performing a detailed analysis of motion properties, the new approach shifts this effort to an optimization approach. The equations of motion however are solved implicitly within the optimization.

The new design of embodiment approach presents a bio-inspired approach to design and setup embodied agents. Alike in the evolution of species, configurations are chosen based on their performance in operation. The configuration, which optimally meets the requirements defined by the task and ecological niche, while considering the restrictions of possible parameters to adapt, is preferred. Robot development is an interdisciplinary process. It typically requires knowledge from engineering to approach dynamics and kinematics, from electrical engineering to address active control loops, and computer science to optimize and control the robot. In the design of embodiment approach this interdisciplinarity is considered by focusing on the operation of the robot from the beginning of the development process. Instead of first creating a hardware structure, which is then equipped with sensors and actuators for active control, and afterwards programmed for its task, these constituents are considered in each development step. Only by this highly interdisciplinary approach, the advantages of all involved components can be utilized.

In the application of manipulators, as well as in many more machines, which have a rich interaction with the environment, the use of series elastic actuators can improve the performance. The newly presented design of embodiment approach can be transferred to these areas by adapting the models, goals, and parameters respectively. As presented in the throwing arm example in Section 8.2, the design and setup of an elastically actuated robot arm can be performed straightforward.

The next step is to apply the achieved results of the BioBiped2 examples to the BioBiped3 robot. Although the optimization must be repeated with updated information of the dynamics data of the new robot, a fast and efficient approach to identify suitable passive and active control elements is at hand with this thesis. Currently this robot is not yet operational, but offers a promising platform to perform dynamic locomotion.

In future experiments the application of the design of embodiment approach to other machines with series elastic actuation, or other suitable passive control properties can be evaluated. In the presented state, the approach is used for the design and setup of dynamical properties of the considered robot only. Future considerations could include even more relevant properties of robots in simulation, as for example the mechanical strength, to guarantee a suitable design and setup, and the transferability to real hardware.

Appendix

A Differential equation of motion of the 1D BioBiped hopping example

In the following the set of differential equations to describe the 1D hopping motion of the BioBiped2 is presented. This set of equations is applied in the 1D hopping example, which is discussed in Section 8.3. A detailed derivation of this equation is presented within [27].

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma\gamma & \gamma\alpha & \gamma\beta & \gamma ya \\ 0 & 0 & 0 & 0 & \gamma\alpha & \alpha\alpha & \alpha\beta & \alpha ya \\ 0 & 0 & 0 & 0 & \gamma\beta & \alpha\beta & \beta\beta & \beta ya \\ 0 & 0 & 0 & 0 & \gamma ya & \alpha ya & \beta ya & yaya \end{bmatrix} \begin{bmatrix} \gamma_p \\ \alpha_p \\ \beta_p \\ ya_p \\ \gamma_{pp} \\ \alpha_{pp} \\ \beta_{pp} \\ ya_{pp} \end{bmatrix} = \begin{bmatrix} w_\gamma \\ w_\alpha \\ w_\beta \\ v_{ya} \\ rs_\gamma \\ rs_\alpha \\ rs_\beta \\ rs_{ya} \end{bmatrix}$$

$$\begin{aligned}
\gamma\gamma &= l_a^2 \mathrm{m_a} - 2 l_a \mathrm{m_a} s_a + \mathrm{m_a} s_a^2 + \theta_a \\
\gamma\alpha &= l_b \mathrm{m_a} s_a \sin(\alpha(t) - \gamma(t)) - l_a l_b \mathrm{m_a} \sin(\alpha(t) - \gamma(t)) \\
\gamma\beta &= -l_a l_c \mathrm{m_a} \sin(\beta(t) + \gamma(t)) + l_c \mathrm{m_a} s_a \sin(\beta(t) + \gamma(t)) \\
\gamma ya &= \mathrm{m_a} s_a \cos(\gamma(t)) - l_a \mathrm{m_a} \cos(\gamma(t)) \\
\alpha\alpha &= l_b^2 \mathrm{m_a} + l_b^2 \mathrm{m_b} - 2 l_b \mathrm{m_b} s_b + \mathrm{m_b} s_b^2 + \theta_b \\
\alpha\beta &= -l_b l_c \mathrm{m_a} \cos(\alpha(t) + \beta(t)) - l_b l_c \mathrm{m_b} \cos(\alpha(t) + \beta(t)) + l_c \mathrm{m_b} s_b \cos(\alpha(t) + \beta(t)) \\
\alpha ya &= l_b \mathrm{m_a} \sin(\alpha(t)) + l_b \mathrm{m_b} \sin(\alpha(t)) - \mathrm{m_b} s_b \sin(\alpha(t)) \\
\beta\beta &= l_c^2 \mathrm{m_a} + l_c^2 \mathrm{m_b} + l_c^2 \mathrm{m_c} - 2 l_c \mathrm{m_c} s_c + \mathrm{m_c} s_c^2 + \theta_c \\
\beta ya &= l_c \mathrm{m_a} \sin(\beta(t)) + l_c \mathrm{m_b} \sin(\beta(t)) + l_c \mathrm{m_c} \sin(\beta(t)) - \mathrm{m_c} s_c \sin(\beta(t)) \\
yaya &= \mathrm{m_a} + \mathrm{m_b} + \mathrm{m_c} + \mathrm{m_d}
\end{aligned}$$

$$\begin{aligned}
rs_\gamma = {} & -b_{d\gamma} \cdot \gamma(t) - g l_a \mathrm{m_a} \cos(\gamma(t)) + g \mathrm{m_a} s_a \cos(\gamma(t)) - l_a l_b \mathrm{m_a} \dot{\alpha}^2(t) \cos(\alpha(t) - \gamma(t)) \\
& + l_b \mathrm{m_a} s_a \dot{\alpha}^2(t) \cos(\alpha(t) - \gamma(t)) - l_a l_c \mathrm{m_a} \dot{\beta}^2(t) \cos(\beta(t) + \gamma(t)) + l_c \mathrm{m_a} s_a \dot{\beta}^2(t) \cos(\beta(t) + \gamma(t)) \\
& - \gamma_{\mathrm{nw}} \mathrm{k_{SOL}} \mathrm{rf}_{\mathrm{SOL}}^2 \mathrm{rv}_{\mathrm{SOL}}^2 - \gamma_{\mathrm{nw}} \mathrm{k_{TA}} \mathrm{rf}_{\mathrm{TA}}^2 \mathrm{rv}_{\mathrm{TA}}^2 + \mathrm{rf_{SOL}} \mathrm{rv_{SOL}} \mathrm{F_{mK}}(t) + \gamma(t) \left(\mathrm{k_{SOL}} \mathrm{rf}_{\mathrm{SOL}}^2 \mathrm{rv}_{\mathrm{SOL}}^2 + \mathrm{k_{TA}} \mathrm{rf}_{\mathrm{TA}}^2 \mathrm{rv}_{\mathrm{TA}}^2 \right) \\
rs_\alpha = {} & -b_{d\alpha} \cdot \alpha(t) + g l_b \mathrm{m_a} \sin(\alpha(t)) + g l_b \mathrm{m_b} \sin(\alpha(t)) - g \mathrm{m_b} s_b \sin(\alpha(t)) \\
& + l_b l_c \mathrm{m_a} \dot{\beta}^2(t) \sin(\alpha(t) + \beta(t)) + l_b l_c \mathrm{m_b} \dot{\beta}^2(t) \sin(\alpha(t) + \beta(t)) - l_c \mathrm{m_b} s_b \dot{\beta}^2(t) \sin(\alpha(t) + \beta(t)) \\
& + l_a l_b \mathrm{m_a} \dot{\gamma}^2(t) \cos(\alpha(t) - \gamma(t)) - l_b \mathrm{m_a} s_a \dot{\gamma}^2(t) \cos(\alpha(t) - \gamma(t)) \\
& - \alpha_{\mathrm{nw}} \mathrm{k_{BF}} \mathrm{rk}_{\mathrm{BF}}^2 \mathrm{rv}_{\mathrm{BFK}}^2 - \alpha_{\mathrm{nw}} \mathrm{k_{VAS}} \mathrm{rk}_{\mathrm{VAS}}^2 \mathrm{rv}_{\mathrm{VAS}}^2 \\
& + \alpha(t) \left(\mathrm{k_{BF}} \mathrm{rk}_{\mathrm{BF}}^2 \mathrm{rv}_{\mathrm{BFK}}^2 + \mathrm{k_{VAS}} \mathrm{rk}_{\mathrm{VAS}}^2 \mathrm{rv}_{\mathrm{VAS}}^2 \right) + \mathrm{rk_{VAS}} \mathrm{rv_{VAS}} \mathrm{F_{mK}}(t) \\
rs_\beta = {} & -b_{d\beta} \cdot \beta(t) + g l_c \mathrm{m_a} \sin(\beta(t)) + g l_c \mathrm{m_b} \sin(\beta(t)) + g l_c \mathrm{m_c} \sin(\beta(t)) \\
& - g \mathrm{m_c} s_c \sin(\beta(t)) + l_c \dot{\alpha}^2(t) \sin(\alpha(t) + \beta(t)) (l_b (\mathrm{m_a} + \mathrm{m_b}) - \mathrm{m_b} s_b) \\
& - l_a l_c \mathrm{m_a} \dot{\gamma}^2(t) \cos(\beta(t) + \gamma(t)) + l_c \mathrm{m_a} s_a \dot{\gamma}^2(t) \cos(\beta(t) + \gamma(t)) \\
& - \beta_{\mathrm{nw}} \mathrm{k_h} + M_{\mathrm{mH}} + \mathrm{k_h} \beta(t) \\
rs_{ya} = {} & g(\mathrm{m_a} + \mathrm{m_b} + \mathrm{m_c} + \mathrm{m_d}) + \mathrm{m_b} \left((l_b - s_b) \dot{\alpha}^2(t) \cos(\alpha(t)) + l_c \dot{\beta}^2(t) \cos(\beta(t)) \right) \\
& + \mathrm{m_c} \left((l_c - s_c) \dot{\beta}^2(t) \cos(\beta(t)) \right) + \mathrm{m_a} \left(l_b \dot{\alpha}^2(t) \cos(\alpha(t)) + l_c \dot{\beta}^2(t) \cos(\beta(t)) + (l_a - s_a) \dot{\gamma}^2(t) \sin(\gamma(t)) \right)
\end{aligned}$$

$$
\begin{aligned}
U &= g(-\mathrm{m_a} l_b \cos(\alpha(t)) - l_c \cos(\beta(t)) - (l_a - s_a)\sin(\gamma(t)) - s_{dy} + y_a(t) \\
&\quad - \mathrm{m_b}(l_b - s_b)\cos(\alpha(t)) - l_c\cos(\beta(t)) - s_{dy} + y_a(t) - \mathrm{m_c}(l_c - s_c)\cos(\beta(t)) - s_{dy} + y_a(t) + \mathrm{m_d} y_a(t)) \\
&\quad + \frac{1}{2}\mathrm{k_{VAS}}\mathrm{dk}^2_{\mathrm{VAS}}(t) + \frac{1}{2}\mathrm{k_{SOL}}\mathrm{df}^2_{\mathrm{SOL}}(t) + \frac{1}{2}\mathrm{k_{TA}}\mathrm{df}^2_{\mathrm{TA}}(t) + \frac{1}{2}\mathrm{k_{BF}}\mathrm{dk}^2_{\mathrm{BF}}(t) + \frac{1}{2}\mathrm{k_h}\mathrm{dk}^2_{\mathrm{H}}(t) \\
&\quad + \frac{1}{2}\mathrm{k_{bx}}\mathrm{d}^2_{\mathrm{kx}}(t) + \frac{1}{2}\mathrm{k_{by}}\mathrm{d}^2_{\mathrm{ky}}(t) + \frac{1}{2}\mathrm{k_{bxff}}\mathrm{d}^2_{\mathrm{kxff}}(t) + \frac{1}{2}\mathrm{k_{byff}}\mathrm{d}^2_{\mathrm{kyff}}(t) \\
Q_\gamma &= -b_{d\gamma}\cdot\gamma(t) + min\left(0, -\mathrm{b_{dx}} l_a \sin(\gamma(t))\left(-l_b\dot\alpha(t)\cos(\alpha(t)) + l_c\dot\beta(t)\cos(\beta(t)) - l_a\dot\gamma(t)\sin(\gamma(t))\right)\right) \\
&\quad + min\left(0, -\mathrm{b_{dy}} l_a \cos(\gamma(t))\left(l_b\dot\alpha(t)\sin(\alpha(t)) + l_c\dot\beta(t)\sin(\beta(t)) - l_a\dot\gamma(t)\cos(\gamma(t)) + \dot y_a(t)\right)\right) \\
Q_\alpha &= -b_{d\alpha}\cdot\alpha(t) + min\left(0, -\mathrm{b_{dx}} l_b \cos(\alpha(t))\left(-l_b\dot\alpha(t)\cos(\alpha(t)) + l_c\dot\beta(t)\cos(\beta(t)) - l_a\dot\gamma(t)\sin(\gamma(t))\right)\right) \\
&\quad + min\left(0, \mathrm{b_{dy}} l_b \sin(\alpha(t))\left(l_b\dot\alpha(t)\sin(\alpha(t)) + l_c\dot\beta(t)\sin(\beta(t)) - l_a\dot\gamma(t)\cos(\gamma(t)) + \dot y_a(t)\right)\right) \\
Q_\beta &= -b_{d\beta}\cdot\beta(t) + min\left(0, \mathrm{b_{dx}} l_c \cos(\beta(t))\left(-l_b\dot\alpha(t)\cos(\alpha(t)) + l_c\dot\beta(t)\cos(\beta(t)) - l_a\dot\gamma(t)\sin(\gamma(t))\right)\right) \\
&\quad + min\left(0, \mathrm{b_{dy}} l_c \sin(\beta(t))\left(l_b\dot\alpha(t)\sin(\alpha(t)) + l_c\dot\beta(t)\sin(\beta(t)) - l_a\dot\gamma(t)\cos(\gamma(t)) + \dot y_a(t)\right)\right) \\
Q_{ya} &= min\left(0, \mathrm{b_{dy}}\left(l_b\dot\alpha(t)\sin(\alpha(t)) + l_c\dot\beta(t)\sin(\beta(t)) - l_a\dot\gamma(t)\cos(\gamma(t)) + \dot y_a(t)\right)\right)
\end{aligned}
$$

$$
\begin{aligned}
rs_\gamma &= -b_{d\gamma}\cdot\gamma(t) + min\left(0, -\mathrm{b_{dx}} l_a \sin(\gamma(t))\left(-l_b\dot\alpha(t)\cos(\alpha(t)) + l_c\dot\beta(t)\cos(\beta(t)) - l_a\dot\gamma(t)\sin(\gamma(t))\right)\right) \\
&\quad + min\left(0, -\mathrm{b_{dy}} l_a \cos(\gamma(t))\left(l_b\dot\alpha(t)\sin(\alpha(t)) + l_c\dot\beta(t)\sin(\beta(t)) - l_a\dot\gamma(t)\cos(\gamma(t)) + \dot y_a(t)\right)\right) \\
&\quad - l_a l_b \mathrm{m_a}\dot\alpha^2(t)\sin(\alpha(t))\sin(\gamma(t)) - l_a l_b\mathrm{m_a}\dot\alpha^2(t)\cos(\alpha(t))\cos(\gamma(t)) + l_b\mathrm{m_a}s_a\dot\alpha^2(t)\sin(\alpha(t))\sin(\gamma(t)) \\
&\quad + l_b\mathrm{m_a}s_a\dot\alpha^2(t)\cos(\alpha(t))\cos(\gamma(t)) + l_a l_c\mathrm{m_a}\dot\beta^2(t)\sin(\beta(t))\sin(\gamma(t)) - l_a l_c\mathrm{m_a}\dot\beta^2(t)\cos(\beta(t))\cos(\gamma(t)) \\
&\quad - l_c\mathrm{m_a}s_a\dot\beta^2(t)\sin(\beta(t))\sin(\gamma(t)) - g l_a\mathrm{m_a}\cos(\gamma(t)) \\
&\quad + g\mathrm{m_a}s_a\cos(\gamma(t)) + l_c\mathrm{m_a}s_a\dot\beta^2(t)\cos(\beta(t))\cos(\gamma(t)) \\
&\quad + \mathrm{k_{bx}} l_a l_b\sin(\alpha(t))\sin(\gamma(t)) + \mathrm{k_{by}} l_a l_b\cos(\alpha(t))\cos(\gamma(t)) - \mathrm{k_{by}} l_a l_b\cos(\alpha_0)\cos(\gamma(t)) \\
&\quad - \mathrm{k_{bx}} l_a l_c\sin(\beta(t))\sin(\gamma(t)) + \mathrm{k_{by}} l_a l_c\cos(\beta(t))\cos(\gamma(t)) - \mathrm{k_{by}} l_a l_c\cos(\beta_0)\cos(\gamma(t)) \\
&\quad + \mathrm{rf_{SOL}}\mathrm{rv_{SOL}}\mathrm{F_{mF}}(t) + \mathrm{k_{bx}} l_a^2\cos(\gamma_0)\sin(\gamma(t)) - \mathrm{k_{by}} l_a^2\sin(\gamma_0)\cos(\gamma(t)) - \mathrm{k_{bx}} l_a^2\sin(\gamma(t))\cos(\gamma(t)) \\
&\quad - \mathrm{k_{bx}} l_a x_{\mathrm{a0}}\sin(\gamma(t)) + \mathrm{k_{by}} l_a^2\sin(\gamma(t))\cos(\gamma(t)) - \mathrm{k_{by}} l_a y_a(t)\cos(\gamma(t)) + \mathrm{k_{by}} l_a y_{\alpha_0}\cos(\gamma(t)) \\
&\quad + \gamma(t)\left(\mathrm{k_{SOL}}\mathrm{rf}^2_{\mathrm{SOL}}\mathrm{rv}^2_{\mathrm{SOL}} + \mathrm{k_{TA}}\mathrm{rf}^2_{\mathrm{TA}}\mathrm{rv}^2_{\mathrm{TA}}\right) - \gamma_{\mathrm{nw}}\mathrm{k_{SOL}}\mathrm{rf}^2_{\mathrm{SOL}}\mathrm{rv}^2_{\mathrm{SOL}} - \gamma_{\mathrm{nw}}\mathrm{k_{TA}}\mathrm{rf}^2_{\mathrm{TA}}\mathrm{rv}^2_{\mathrm{TA}} \\
rs_\alpha &= -b_{d\alpha}\cdot\alpha(t) + min\left(0, -\mathrm{b_{dx}} l_b \cos(\alpha(t))\left(-l_b\dot\alpha(t)\cos(\alpha(t)) + l_c\dot\beta(t)\cos(\beta(t)) - l_a\dot\gamma(t)\sin(\gamma(t))\right)\right) \\
&\quad + min\left(0, \mathrm{b_{dy}} l_b \sin(\alpha(t))\left(l_b\dot\alpha(t)\sin(\alpha(t)) + l_c\dot\beta(t)\sin(\beta(t)) - l_a\dot\gamma(t)\cos(\gamma(t)) + \dot y_a(t)\right)\right) \\
&\quad + l_b l_c\mathrm{m_a}\sin(\alpha(t))\dot\beta^2(t)\cos(\beta(t)) + l_b l_c\mathrm{m_a}\cos(\alpha(t))\dot\beta^2(t)\sin(\beta(t)) + l_b l_c\mathrm{m_b}\sin(\alpha(t))\dot\beta^2(t)\cos(\beta(t)) \\
&\quad + l_b l_c\mathrm{m_b}\cos(\alpha(t))\dot\beta^2(t)\sin(\beta(t)) - l_c\mathrm{m_b}s_b\sin(\alpha(t))\dot\beta^2(t)\cos(\beta(t)) - l_c\mathrm{m_b}s_b\cos(\alpha(t))\dot\beta^2(t)\sin(\beta(t)) \\
&\quad + g l_b\mathrm{m_a}\sin(\alpha(t)) + g l_b\mathrm{m_b}\sin(\alpha(t)) - g\mathrm{m_b}s_b\sin(\alpha(t)) + l_a l_b\mathrm{m_a}\sin(\alpha(t))\dot\gamma^2(t)\sin(\gamma(t)) \\
&\quad + l_a l_b\mathrm{m_a}\cos(\alpha(t))\dot\gamma^2(t)\cos(\gamma(t)) - l_b\mathrm{m_a}s_a\sin(\alpha(t))\dot\gamma^2(t)\sin(\gamma(t)) - l_b\mathrm{m_a}s_a\cos(\alpha(t))\dot\gamma^2(t)\cos(\gamma(t)) \\
&\quad + \mathrm{k_{by}} l_b^2\cos(\alpha_0)\sin(\alpha(t)) + \mathrm{k_{byff}} l_b^2\cos(\alpha_{\mathrm{0ff}})\sin(\alpha(t)) - \mathrm{k_{bx}} l_b l_c\cos(\alpha(t))\sin(\beta(t)) \\
&\quad - \mathrm{k_{bxff}} l_b l_c\cos(\alpha(t))\sin(\beta(t)) - \mathrm{k_{by}} l_b l_c\sin(\alpha(t))\cos(\beta(t)) - \mathrm{k_{byff}} l_b l_c\sin(\alpha(t))\cos(\beta(t)) \\
&\quad + \mathrm{k_{by}} l_b l_c\cos(\beta_0)\sin(\alpha(t)) + \mathrm{k_{byff}} l_b l_c\cos(\beta_{\mathrm{0ff}})\sin(\alpha(t)) - \mathrm{k_{bx}} l_a l_b\cos(\alpha(t))\cos(\gamma(t)) \\
&\quad - \mathrm{k_{by}} l_a l_b\sin(\alpha(t))\sin(\gamma(t)) + \mathrm{k_{bx}} l_a l_b\cos(\gamma_0)\cos(\alpha(t)) + \mathrm{k_{by}} l_a l_b\sin(\gamma_0)\sin(\alpha(t)) \\
&\quad + \alpha(t)\left(\mathrm{k_{BF}}\mathrm{rk}^2_{\mathrm{BF}}\mathrm{rv}^2_{\mathrm{BFK}} + \mathrm{k_{VAS}}\mathrm{rk}^2_{\mathrm{VAS}}\mathrm{rv}^2_{\mathrm{VAS}}\right) + \mathrm{k_{bx}} l_b^2\sin(\alpha(t))\cos(\alpha(t)) - \mathrm{k_{bx}} l_b x_{\mathrm{a0}}\cos(\alpha(t))
\end{aligned}
$$

$$+ \mathrm{k_{bxff}} l_b^2 \sin(\alpha(t)) \cos(\alpha(t)) - \mathrm{k_{bxff}} l_b \mathrm{ya_{0ff}} \cos(\alpha(t)) - \mathrm{k_{by}} l_b^2 \sin(\alpha(t)) \cos(\alpha(t))$$
$$\mathrm{k_{by}} l_b y_a(t) \sin(\alpha(t)) - \mathrm{k_{by}} l_b y_{\alpha_0} \sin(\alpha(t)) - \mathrm{k_{byff}} l_b^2 \sin(\alpha(t)) \cos(\alpha(t)) + \mathrm{k_{byff}} l_b y_a(t) \sin(\alpha(t))$$
$$- \mathrm{k_{byff}} l_b \mathrm{ya_{0ff}} \sin(\alpha(t)) - \alpha_{\mathrm{nw}} \mathrm{k_{BF}} \mathrm{rk_{BF}^2} \mathrm{rv_{BFK}^2} - \alpha_{\mathrm{nw}} \mathrm{k_{VAS}} \mathrm{rk_{VAS}^2} \mathrm{rv_{VAS}^2} + \mathrm{rk_{VAS}} \mathrm{rv_{VAS}} \mathrm{rk_{VAS}} \mathrm{F_{mK}}(t)$$

$$rs_\beta = -b_{d\beta} \cdot \beta(t) + min\left(0, \mathrm{b_{dx}} l_c \cos(\beta(t)) \left(-l_b \dot\alpha(t) \cos(\alpha(t)) + l_c \dot\beta(t) \cos(\beta(t)) - l_a \dot\gamma(t) \sin(\gamma(t))\right)\right)$$
$$+ min\left(0, \mathrm{b_{dy}} l_c \sin(\beta(t)) \left(l_b \dot\alpha(t) \sin(\alpha(t)) + l_c \dot\beta(t) \sin(\beta(t)) - l_a \dot\gamma(t) \cos(\gamma(t)) + \dot y_a(t)\right)\right)$$
$$+ l_b l_c \mathrm{m_a} \dot\alpha^2(t) \sin(\alpha(t)) \cos(\beta(t)) + l_b l_c \mathrm{m_a} \dot\alpha^2(t) \cos(\alpha(t)) \sin(\beta(t)) + l_b l_c \mathrm{m_b} \dot\alpha^2(t) \sin(\alpha(t)) \cos(\beta(t))$$
$$+ l_b l_c \mathrm{m_b} \dot\alpha^2(t) \cos(\alpha(t)) \sin(\beta(t)) - l_c \mathrm{m_b} s_b \dot\alpha^2(t) \sin(\alpha(t)) \cos(\beta(t)) - l_c \mathrm{m_b} s_b \dot\alpha^2(t) \cos(\alpha(t)) \sin(\beta(t))$$
$$+ g l_c \mathrm{m_a} \sin(\beta(t)) + g l_c \mathrm{m_b} \sin(\beta(t)) + g l_c \mathrm{m_c} \sin(\beta(t)) - g \mathrm{m_c} s_c \sin(\beta(t))$$
$$+ l_a l_c \mathrm{m_a} \sin(\beta(t)) \dot\gamma^2(t) \sin(\gamma(t)) - l_a l_c \mathrm{m_a} \cos(\beta(t)) \dot\gamma^2(t) \cos(\gamma(t)) - l_c \mathrm{m_a} s_a \sin(\beta(t)) \dot\gamma^2(t) \sin(\gamma(t))$$
$$+ l_c \mathrm{m_a} s_a \cos(\beta(t)) \dot\gamma^2(t) \cos(\gamma(t))$$
$$- \mathrm{k_{bx}} l_b l_c \sin(\alpha(t)) \cos(\beta(t)) - \mathrm{k_{bxff}} l_b l_c \sin(\alpha(t)) \cos(\beta(t)) - \mathrm{k_{by}} l_b l_c \cos(\alpha(t)) \sin(\beta(t))$$
$$- \mathrm{k_{byff}} l_b l_c \cos(\alpha(t)) \sin(\beta(t)) + \mathrm{k_{by}} l_b l_c \cos(\alpha_0) \sin(\beta(t)) + \mathrm{k_{byff}} l_b l_c \cos(\alpha_{\mathrm{0ff}}) \sin(\beta(t))$$
$$+ \mathrm{k_{by}} l_c^2 \cos(\beta_0) \sin(\beta(t)) + \mathrm{k_{byff}} l_c^2 \cos(\beta_{\mathrm{0ff}}) \sin(\beta(t)) + \mathrm{k_{bx}} l_a l_c \cos(\beta(t)) \cos(\gamma(t))$$
$$- \mathrm{k_{by}} l_a l_c \sin(\beta(t)) \sin(\gamma(t)) - \mathrm{k_{bx}} l_a l_c \cos(\gamma_0) \cos(\beta(t)) + \mathrm{k_{by}} l_a l_c \sin(\gamma_0) \sin(\beta(t))$$
$$+ \mathrm{k_{bx}} l_c^2 \sin(\beta(t)) \cos(\beta(t)) + \mathrm{k_{bx}} l_c x_{\mathrm{a0}} \cos(\beta(t)) + \mathrm{k_{bxff}} l_c^2 \sin(\beta(t)) \cos(\beta(t))$$
$$+ \mathrm{k_{bxff}} l_c \mathrm{ya_{0ff}} \cos(\beta(t)) + l_c(\mathrm{k_{by}} + \mathrm{k_{byff}}) y_a(t) \sin(\beta(t)) - \mathrm{k_{by}} l_c^2 \sin(\beta(t)) \cos(\beta(t))$$
$$- \mathrm{k_{by}} l_c y_{\alpha_0} \sin(\beta(t)) - \mathrm{k_{byff}} l_c^2 \sin(\beta(t)) \cos(\beta(t)) - \mathrm{k_{byff}} l_c \mathrm{ya_{0ff}} \sin(\beta(t)) + \mathrm{k_h} \beta(t) - \beta_{\mathrm{nw}} \mathrm{k_h} + M_{\mathrm{mH}}$$
$$rs_{ya} = min\left(0, \mathrm{b_{dy}} \left(l_b \dot\alpha(t) \sin(\alpha(t)) + l_c \dot\beta(t) \sin(\beta(t)) - l_a \dot\gamma(t) \cos(\gamma(t)) + \dot y_a(t)\right)\right)$$
$$+ g(\mathrm{m_a} + \mathrm{m_b} + \mathrm{m_c} + \mathrm{m_d}) + \mathrm{m_b} \left((l_b - s_b) \dot\alpha^2(t) \cos(\alpha(t)) + l_c \dot\beta^2(t) \cos(\beta(t))\right)$$
$$- \mathrm{k_{by}}(l_b \cos(\alpha(t)) - l_b \cos(\alpha_0) + l_c \cos(\beta(t)) - l_c \cos(\beta_0) + l_a \sin(\gamma(t)) - l_a \sin(\gamma_0) - y_a(t) + y_{\alpha_0})$$
$$- \mathrm{k_{byff}}(l_b \cos(\alpha(t)) - l_b \cos(\alpha_{\mathrm{0ff}}) + l_c \cos(\beta(t)) - l_c \cos(\beta_{\mathrm{0ff}}) - y_a(t) + \mathrm{ya_{0ff}})$$
$$+ \mathrm{m_c} \left((l_c - s_c) \dot\beta^2(t) \cos(\beta(t))\right) + \mathrm{m_a} \left(l_b \dot\alpha^2(t) \cos(\alpha(t)) + l_c \dot\beta^2(t) \cos(\beta(t)) + (l_a - s_a) \dot\gamma(t) \sin(\gamma(t))\right)$$

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K. Radkhah, S. Kurowski, T. Lens and O. von Stryk, *Compliant Robot Actuation by Feedforward Controlled Emulated Spring Stiffness*, Simulation, Modeling, and Programming for Autonomous Robots (SIMPAR), 2010.

K. Radkhah, S. Kurowski, T. Lens and O. v. Stryk, *An Extended Antagonistic Series Elastic Actuator for a Biologically Inspired Four-Legged Robot*, Workshop on New Variable Impedance Actuators for the Next Generation of Robots, IEEE International Conference on Robotics and Automation (ICRA), 2010.

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D. Scholz, C. Maufroy, S. Kurowski, K. Radkhah, O. von Stryk and A. Seyfarth, *Simulation and Experimental Evaluation of the Contribution of Biarticular Gastrocnemius Structure to Joint Synchronization in Human-Inspired Three-Segmented Elastic Legs*, 3rd Int. Conf. on Simulation, Modeling and Programming for Autonomous Robots (SIMPAR), 2012.

S. Kurowski and O. von Stryk , *A Systematic Approach to the Design of Embodiment with Application to Bio-Inspired Compliant Legged Robots*, Int. Conf. on Intelligent Robots and Systems (IROS), 2015. *accepted to appear*

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Erklärung[2]

Hiermit erkläre ich, dass ich die vorliegende Arbeit, mit Ausnahme der ausdrücklich genannten Hilfsmittel, selbständig verfasst habe.

[1] gemäß §20 Abs. 3 der Promotionsordnung der TU Darmstadt
[2] gemäß §9 Abs. 1 der Promotionsordnung der TU Darmstadt