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A Bioinspired Concept for High Efficiency Locomotion in Micro Robots: the Jumping Robot Grillo

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***Abstract*— This paper presents a bioinspired concept of locomotion for small autonomous robots. Scale effects in locomotion highly influence gait efficiency and in lightweight micro-robots jumping can be more energetically efficient than just walking or climbing. In addition, a jump can make the robot overcome obstacles and uneven terrains. Inspired by nature, the actuation of the proposed robot is entrusted to loaded springs. During the flight phase, energy from an electric micro-motor is collected in springs, while it is released by a click mechanism during take-off. In this way instant power delivered by rear legs (about 5 W) is much higher than the one provided by the motor (0.3 W). Passive compliant legs and low-power actuation result in light, efficient micro-robot, designed to have long autonomy for environment exploration and monitoring. In order to verify these assumptions, a quadruped prototype was developed, with two active rear limbs and passive elastic forelegs. Robot Grillo is 50 mm long and weighs about 10 grams. In conservative simulations the micro-robot reaches a forward speed of 1.5 m/s, which corresponds to about 30 body length s^{-1}.**

***Index Terms*— Locomotion, jumping robot, compliance, passive dynamics, bioinspired robot.**

I. Introduction

Locomotion is a key issue for autonomous robots, especially if considering efficiency in micro-robots, which can be adopted for exploration and monitoring in unstructured environments. Despite the implicit mechanical and kinematic complication, legged locomotion presents several advantages in unstructured or uneven terrains. First, legs have a small foot-print characterized by static and non invasive contact with ground, particularly important in case of environmental monitoring. Legged walking on highly compliant terrains such as vegetation or soft wet earth can be also more efficient than rolling wheels. In addition, legged robots can climb higher obstacles than wheeled ones within the same size: as discussed in literature [10], a pair of legs can be considered as two radiuses of a wheel, with the hip representing the center and the feet two arcs. It becomes clear that a wheel having the same dynamics of a pair of legs would occupy much more volume.

The robot presented here has four legs, it is 50 mm long and weighs about than 10 grams. It has been prototyped in order to verify the locomotion of small robots in unstructured environments and to investigate new working principles for high performance locomotion in small scale. Many different prototypes of legged-robots have been built in order to find efficient and stable gaits, from bipeds [13],[14],[15], to hexapods [17],[18],[19], to one-legged hoppers [20],[21],[22]. Regarding scale effects in micro-robots, several researches have been carried out on system design [23] but few consider the issue of which strategy adopt according to robot size. In this case, lessons from nature often provide a good insight on design solutions . When dimensions get smaller, friction forces become more and more relevant, while mass-related forces decrease their influence. Famous is the example of the ant that can carry loads up to 20 times its own mass. This performance would be impossible for a bigger animal, due to structural bone limitation: decreasing the dimensions, volume forces such as weight decrease much faster than stress-related ones, the former proportional to l^3, the latter to l^2. Something similar happens in locomotion. Scale effects influence the choice of the optimal gait according to dimensions, speed or mass. This influence can be noticed also in nature. Different sized animals adopt different gaits [5],[6]. Elephants, despite their appearances, are able to run at about 6 m/s but in a way completely different from a chipmunk [7]. Comparison between different sized animals gives an insight of which can be the gait suited for a small robot. As smaller animals adopt longer step length in comparison to their leg length [8], jumping rather then walking can be considered as a possible gait in unstructured environments, and would also let the micro-robot overcome obstacles and uneven terrains.

Scale effects are not the only issue characterizing micro engineering. Efficiency in small autonomous robots is a central matter, as often the sole battery weights more than the entire rest of the robot. The prototype Grillo has passive forelegs, while the thrust for the jump is given by the rear longer limbs. The choice of passive legs allows to decrease the weight and the energy consumption. Elastic energy is stored through a motor loading two springs. This results in a much smaller actuator, consuming only 0.3 W, while the instant power of the legs is more than 5 W.

Section 1 describes the choices done in designing the actuation of the quadruped and the passive fore legs, while section 2 presents simulations done first on a planar motion, then in 3D space. Section 3 illustrates the fabrication of the prototype, built as an open-platform for future developments, including an additional motor for steering and a compensator for the pitch motion.

II. The importance of elastic energy storing in legged locomotion

In dynamic legged locomotion, the main energetic losses related to the mere gait are due to the impacts that occur at every step [25]. In this sense, the use of elastic elements permits to partially recover this energy, that can be used to increase the robot performance, but also to buffer the impact, highly increasing the robot shock-tolerance [26]. Actuators with series elastic elements have been used in walking robots [27] [28] but also in robotics arms where stiffness control is needed [29]. In nature, tendon elasticity is at the base of every motion, from a fast catch to a running gait [1],[2]. Studies done on jumping performances in frogs point out that the peak power output at take off can be up to seven times the mean power given by hind limb muscles [3]. This apparent discrepancy is due to the beneficial effect of elasticity in tendons and muscles. As shown in fig.1, the presence of 1. an elastic tendon and 2. an inertial click mechanism let the system deliver more power than a simple muscle directly connected to the load. This happens because at the very first instants, when the lever arm l_2 is small, the muscle acts mainly on the spring, which store energy that is afterward relished when the rate l_2/l_1 - also called muscle mechanical advantage *EMA* - becomes more favorable.

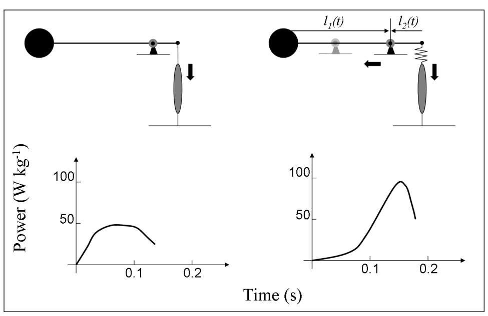


Fig. 1. Qualitative power output in two cases: muscle connected directly to the load, muscle with elastic tendon and variable lever arm [3]

Starting from these kind of observations, we designed a jumping prototype with an actuator connected to a spring and a catch-release mechanism. During the airborne phase, the motor compresses the spring with relatively low power. Soon after landing, the click mechanism releases the spring that is able to deliver an instant power of about ten times the one of the motor (fig.2). The small actuator needs 0.3 W to compress the spring and the hind legs thrust the body with more than 5 W, letting the 10 grams robot take jumps over 0.5 m long. Landing cushioning is entrusted to passive forelegs provided with spring-damper elements. The choice of using passive legs is still induced by the need of high efficiency of the robot. Many studies have been carried out on biped efficiency by T. McGeer, who proposed a passive walker able to perform a stable walk on a shallow slope without actuation [11]. As a

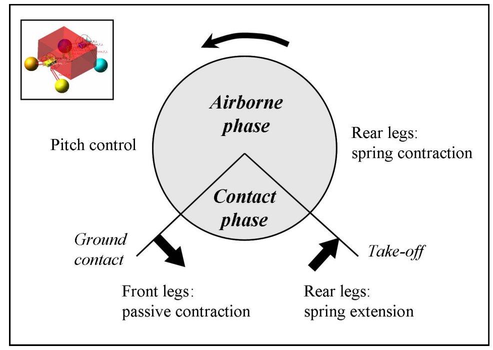


Fig. 2. A scheme for the Grillo jumping gait. The actuation is performed during the flight phase, while elastic elements characterize the ground contact

matter of facts, this kind of gait exploits the natural dynamics of the legs, exactly as it happens in nature [4]. Other examples of passive dynamics can be found in [16],[12]. In small robots, due to scale effects enhancing friction and increasing natural frequencies of the system, passive dynamics is not viable. In this sense, the use of compliant elastic joints can help in storing and releasing energy at the frequency characterizing the robot gait. Elastic elements can be used to passively orientate the legs [18], empower the robot gait [22] and make the robot hop [9] or jump.

In our micro robot, fore legs consist of a combination of linear and torsional springs with dampers, used to store and release impact energy in continuous gait, or to cushion the landing in case of a single jump.

III. The simulations

In order to verify the hypotheses exposed in the previous chapter, simulations were made using Adams View Software for dynamic modeling and the toolbox Simulink^{TM} for implementing a simple controller and user interface (fig.3). The mass distribution of the robot was given by the prototype design, while linear springs modeled the legs. Spherical joint were chosen to model the shoulders, constraining the rotations with torsional springs of different stiffness according to the legs and to the plane of rotation. Damping and friction were also included in order to model the losses in the actual prototype.

First, the robot motion has been modeled in 2D, keeping the body orientation always parallel to the ground. This very simplified model was done in order to test the advantages of using passive fore legs. The second step was to simulate the motion of the robot as a free body. In this case pitch rotation is studied as a critical parameter aimed at ensuring gait stability and landing capabilities.

A. The simplified model

Using a planar motion with a translating body allows to concentrate on the energetics of the robot, leaving all the stability issues to a next step, described in the following section. The control scheme is very simple: at landing, the contact sensor in the forelegs acts on the click mechanism

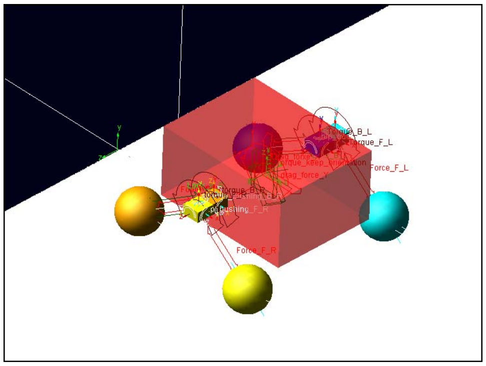


Fig. 3. The Adams model of the robot Grillo. Mass and dimensions where chosen using data from the prototype

to release the springs and a time delay can be set by the user (fig.2). In the flight phase the motor compress the spring till the click mechanism is engaged for the subsequent jump. Tuning the time delay is important in order to exploit the energy released by the forelegs. The best performance is given when the thrust finish just before take off [18]. Timing the passive front limbs with the actuation can be analyzed using a simplified model of the robot (fig.4.a)

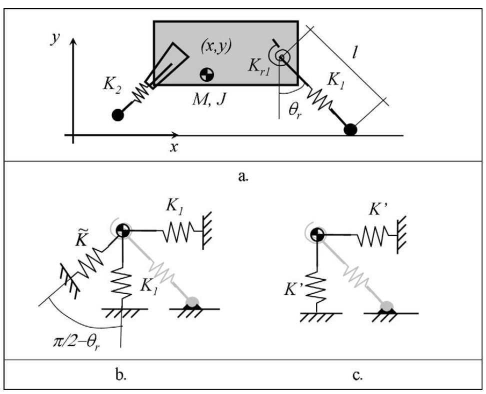


Fig. 4. Simplified model of the passive forelegs. Linear and torsional springs are used to sketch the compliant joint; damping was also included in the model

With the hypothesis that at landing the sole forelegs are touching the ground and that the body orientation is kept constant, the body mass can be concentrated in a point mass at the shoulder joint (fig.4.b). By considering the forces acting on the mass, we can easily substitute the spring K_1 with two springs of the same stiffness disposed horizontally and vertically. The presence of the torsional spring complicate the model a little, but an equivalent system can be built substituting the torsional spring with a virtual spring of stiffness $\tilde{K}$ so that the forces acting on the mass are the same:

$$M = K_{r1}(\theta_r - \theta) = F_{virtual} \cdot l \tag{1}$$

where l is the leg length, θ_r the rest angle and θ the variable for rotation at the shoulder. For small variations of θ:

$$F_{virtual} = \tilde{K}\Delta x \cong \tilde{K}l(\theta_r - \theta) \tag{2}$$

which lead to

$$\tilde{K} = \frac{K_{r1}}{l^2} \tag{3}$$

This spring perpendicular to the leg can be split in two horizontal and vertical springs and added in series to the previous ones. The resulting model is a mass suspended by a spring of stiffness K'

$$K' = \frac{K_1 \cdot \tilde{K}}{K_1 + \tilde{K}} = \frac{K_1 \cdot K_{r1}}{K_1 l^2 + K_{r1}} \tag{4}$$

The same considerations can be done on the damping ρ. Using the same conventions, it can be written:

$$M_d = \rho_{r1}\dot{\theta} = F_{virtual} \cdot l = \tilde{\rho} l \dot{\theta} \cdot l \tag{5}$$

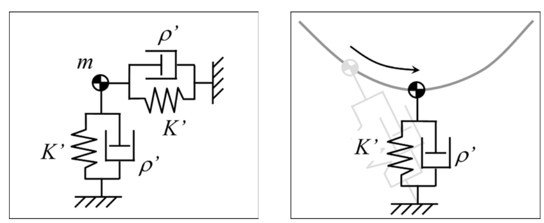
As done before the resulting damping ρ' is

$$\rho' = \frac{\rho_1 \cdot \tilde{\rho}}{\rho_1 + \tilde{\rho}} = \frac{\rho_1 \cdot \rho_{r1}}{\rho_1 l^2 + \rho_{r1}} \tag{6}$$

With these considerations, the front legs can be modeled as a non-linear spring-damper system. The parameters of the system such as stiffness and damping can be linearized around the midpoint of the contact trajectory (fig.5). This model resemble the well-known Raibert hopper in the instants close to the impact [20]. In order to figure out the right timing for rear legs actuation, we should focus on the vertical motion. As the model is a mass-spring-damper system, the dynamics is easily identified. The actuation of the rear legs has to be synchronized so that they completely extend before take-off. As the rear legs are a similar second order system, calculating the timing for actuation is quite straight forward.

$$\Delta T = \Delta\tau_{fore} - \Delta\tau_{aft} = \frac{\pi}{2\omega_f\sqrt{1-\xi_f^2}} - \frac{\pi}{2\omega_a\sqrt{1-\xi_a^2}} \tag{7}$$

where $w_n = \sqrt{\frac{K}{m}}$ and $\xi = \frac{\rho}{2\sqrt{Km}}$ are the natural frequency and relative damping for the forelegs -suffix *fore* - and rear legs - suffix *aft*.



a. b.

Fig. 5. When the body pitch rotation is controlled, the body can be sketched as a point mass and the model resembles in this case a one-legged hopper

The system parameters for the rear and front legs can be chosen in a way that ΔT is positive, otherwise the click mechanism should be released before the ground-impact. In any case, prolonging the contact sensor with a few-millimeter probe can be a solution.

Setting in this way the right timing, we run a simulation of the simple model, jumping in a plane with the body translating

TABLE I

ROBOT CHARACTERISTICS AS USED IN THE SIMULATION FOR THE CONTINUOUS GAIT

Parameter	Value
Mass	0.01 Kg
Rear leg stiffness K_2	0.4 N/mm
Rear leg relative damping	0.1
Rear leg elongation Δx	10 mm
Rear leg rotational stiffness (Yaw,Roll)	3 Nmm/rad
Rear leg rotational stiffness (Pitch)	60 Nmm/rad
Foreleg stiffness K_1	0.2 N/mm
Foreleg relative damping	0.1
Foreleg rotational stiffness (Pitch) K_{r1}	0.4 Nmm/rad
Foreleg rotational stiffness (Yaw,Roll)	1.5 Nmm/rad

parallel to the ground. The system parameters were set as shown in table I. In fig.6 the robot trajectory is plotted. Using the previous considerations, a continuous gait was achieved. What is interesting to observe is that despite the same actuation at every step, the performance increases after few jumps. The improvement is due to the energy released by the passive front legs, which increases the robot performance considerably.

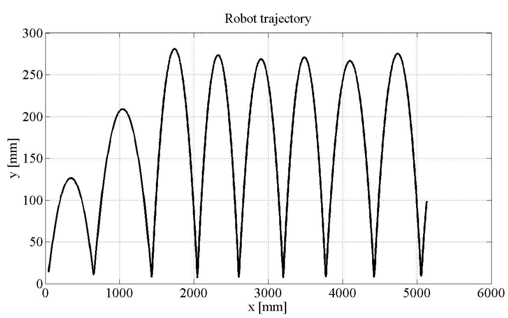


Fig. 6. The trajectory followed by the planar model. It can be noticed that, within few steps, the jumping height is increased

Fig.7 shows the moment of the simulation when the robot impact the ground. It can be noticed the rotation and elongation of the forelegs, which passively store and release part of the impact energy. In the model, the air friction was included, considering a possible profile for the robot.

B. Modeling the robot as a free body

In jumping as a free body, the pitch rotation of the robot (rotation in the fore-aft plane) is a critical issue for the gait stability. As a matter of facts, jumping rather than hopping involves much greater contact forces, even ten times higher than the robot weight. Considering also the very low duty factor - in the continuous gait the feet are on the ground for about 1.7% of step period - it becomes clear that the best way to control the pitch is in the airborne phase. Due to the relatively small moment of inertia of the robot, a small actuator can accomplish the task. This kind of control exploits

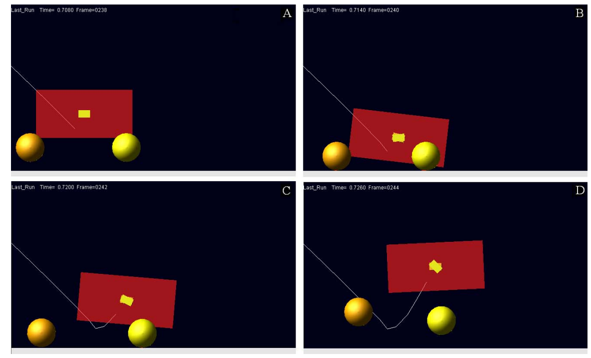


Fig. 7. The robot at ground contact during a simulation of the continuous gait. The tracing marker shows the robot *cm* trajectory

the holonomy generated by inertial forces to compensate disturbances deriving from ground impacts, and has been already implemented on one-legged hoppers [30], [31]. Before introducing an additional actuator, the possibility of a triggered gait was studied. In this kind of gait, the robot takes only one jump at time, in order to take-off always from the horizontal position. Adopting this pace implies that impact energy cannot be used, unless introducing an actuated brake in the forelegs to control the elastic recoil.

To avoid pitch rotation, a fine balancing of the center of mass (*cm*) is needed. As shown in fig.8, the *cm* was placed behind the rearlegs reaction point, identified by the spring thrust. In this way a stabilizing torque is generated by the inertial force which is opposed to the thrust. This expedient is similar to the one that let a boat float having the *cm* beneath the center of hydrostatic thrust.

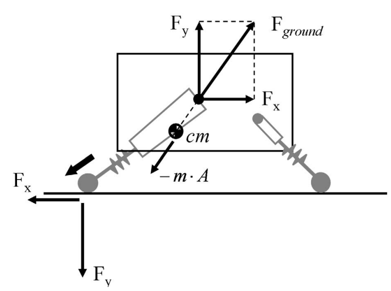


Fig. 8. The position of the *cm* is critical for pitch stability. Placing it beneath the actuation's reaction point creates a stabilizing torque

In this way it is possible to obtain a triggered gait. The robot jumps, with a small pitch rotation during the whole airborne phase. When landing, the forelegs impact the ground and, at this stage, dissipate the energy in the damper. When all the legs are in contact with the ground, the robot is ready to restart again a new jump. The robot trajectory obtained in this way is similar to the one in fig.6, without the beneficial effect of the fore legs on performances. Fig.9 shows the robot height as function of time. It can be noticed that the maximum height remains much lower than in the previous case, and close to the first-jump height of the planar model.

While *cm* position influences the flight phase, the stiffness

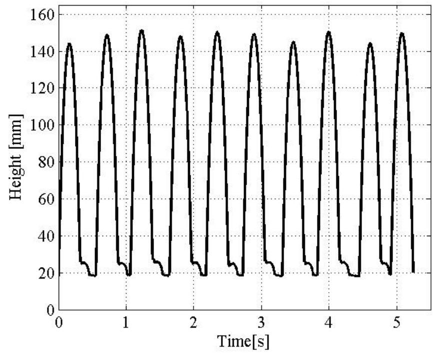


Fig. 9. The robot jumping height. Here, in the landing phase, the impact energy is lost

TABLE II
ROBOT CHARACTERISTICS AS USED IN THE SIMULATION FOR THE TRIGGERED GAIT

Parameter	Value
Mass	0.01 Kg
Rear leg stiffness K_2	0.4 N/mm
Rear leg relative damping	0.1
Rear leg elongation Δx	10 mm
Rear leg rotational stiffness (Yaw,Roll)	3 Nmm/rad
Rear leg rotational stiffness (Pitch)	60 Nmm/rad
Foreleg stiffness K_1	1 N/mm
Foreleg relative damping	1
Foreleg rotational stiffness (Pitch) K_{r1}	10 Nmm/rad
Foreleg rotational stiffness (Yaw,Roll)	1.5 Nmm/rad

and damping of the leg determines the landing capability of the robot. The forelegs need high damping to buffer the impact, but often a too stiff contact can cause the robot to jump a little backward or to bounce before stopping (fig.10). Anyway, it is not difficult to obtain a soft landing even on all the four feet calibrating manually the legs parameters (table II). A theoretical optimization was not performed at this stage, also considering the difficulties in fabricating and measuring compliant legs.

In the simulation, the robot has been able to achieve a speed of 1.5 m/s that is about 30 body length sec^{-1}. The influence of leg parameters in 3D gait stability and landing should be studied more in deep in order to optimize robot performances and to have a more robust locomotion.

IV. FABRICATION OF THE PROTOTYPE

The first prototype has been realized with a 3D printer in order to test the feasibility of the design. It has only one motor, as at this stage the focus is on locomotion in just one direction. The motor used is a tiny pager motor, providing 1200 rpm at 3V requiring 100mA (fig.11). This motor acts on both springs of the two rear legs that are always actuated together for locomotion in one direction. The battery, the heaviest part of the robot, is placed behind the spring base, in order to keep the center of mass in the desired position. In any case, the *cm* position can be adjusted calibrating a screw-driven mass.

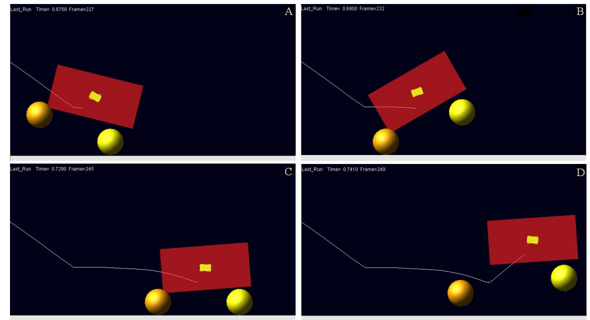


Fig. 10. A typical bouncy landing and subsequent take-off in discontinuous gait. In this case, impact energy is dissipated

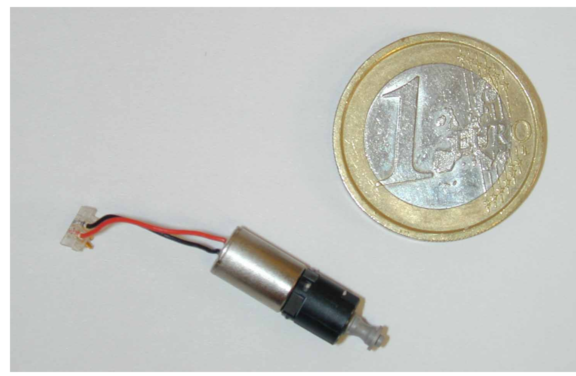


Fig. 11. The tiny pager motor that actuate the rear legs in the prototype

An important parameter during take-off is friction between rear feet and ground: it ensures the right thrust for the jump. Also in this case, nature inspiration suggests design solutions. In facts, jumping animals, such as cricket or locusts, have tibia and tarsus covered with spines, enabling the correct grip for taking long jumps. Experiments done on crickets proved the importance of such spines in determining the jumping performances [19]. According to these observations, we provided hind legs with micro spines, build with metallic materials.

The resulting robot is 5 cm long and weights about 10 grams. The design takes into account future developments of the robot, including an additional motor for steering and aerial appendages, increasing the robot performances and ensuring at the same time a better pitch stability.

V. CONCLUSIONS AND FUTURE WORKS

The micro robot Grillo represents a novel concept for robot locomotion. Designed for exploration and for monitoring in unstructured environments, the robot moves by taking long jumps. Inspired by frog locomotion, the actuation of the rear legs is mainly done through a pair of springs and a click mechanism. During the airborne phase, a tiny pager motor loads the springs that, during take-off, release that energy. In

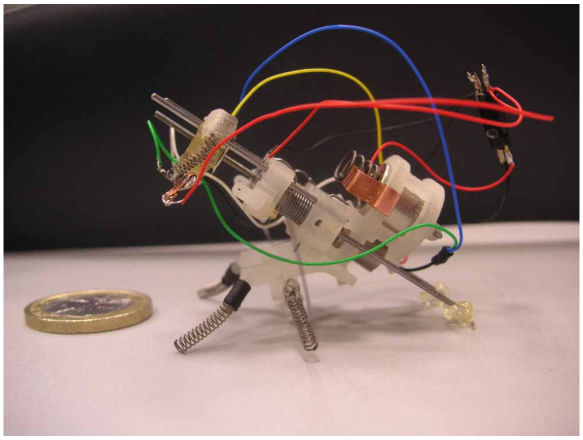


Fig. 12. The very first prototype. It can be noticed the presence of elastic elements in the forelegs and in the actuation of the inclined rear legs

this way, the power delivered by the legs is several times higher than motor power. The robot is also provided with compliant and passive forelegs, that can cushion the ground impact and empower the jump with their elastic recoil. A simplified model has been elaborated to study the robot resonant gait in the fore-aft plane and in the 3D space. Assuming robot's free rotation, pitch motion becomes critical for gait stability. Before adopting a stabilizing control in the airborne phase, the robot can still perform a simple triggered gait: after each jump, the robot lands completely before the next jump. With this pace, and in the case no active energy storage is present, impact energy is dissipated.

Future work will analyze flight stability. An active control on pitch motion could be adopted, with a small motor moving a mass to compensate body rotations. Also wings can be adopted for increasing jump length and stabilizing the jump. Another relevant issue is to study landing capability: impact analytical models can be studied to find the right parameters. Also bioinspiration can lead to unexpected results. The choice of stiffness and damping as function of step length and body mass should be figured out in order to optimize the performances and landing abilities in uneven terrains. Finally, the steering capabilities of the robot still have to be addressed. Airborne turning versus force distribution in the legs should be considered as a possible solution, keeping in mind the desired gait efficiency.

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