DYLEMA: Using walking robots for landmine detection and location

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Abstract

Detection and removal of antipersonnel landmines is an important worldwide concern. A huge number of landmines has been deployed over the last twenty years, and demining will take several more decades, even if no more mines were deployed in future. An adequate mine-clearance rate can only be achieved by using new technologies such as improved sensors, efficient manipulators and mobile robots. This paper presents some basic ideas on the configuration of a mobile system for detecting and locating antipersonnel landmines efficiently and effectively. This paper describes the main features of the overall system, which consists of a sensor head that can detect certain landmine types, a manipulator to move the sensor head over large areas, a locating system based on a global-positioning system, a remote supervisor computer and a legged robot used as the subsystems' carrier. The whole system has been configured to work in a semi-autonomous mode with a view also to robot mobility and energy efficiency.

1 Introduction

Detection and removal of antipersonnel landmines is at present a serious political, economic, environmental and humanitarian problem. There exists a common interest in solving this problem, and solutions are being sought in several engineering fields.

The best solution, albeit perhaps not the quickest, would be to apply a fully automatic system to this important task. However, any such solution still appears to remain a long way from succeeding. First of all, efficient sensors, detectors and positioning systems would be needed to detect, locate and, if possible, identify different mines. Next—and this is of paramount importance—adequate vehicles would have to be provided to carry the sensors over the infested fields. The case posited above would require simple sensor arrays or terrain-scanning manipulators using just one simple sensor. During demining operations human operators would have to stay as far away as possible for safety. Full automation tends to produce complex systems. A reasonable intermediate solution might be found in teleoperation and human-machine collaboration in the control loop, a scheme that is becoming known as collaborative control (Fong 1999, Estremera *et al.* 2002).

Any potential vehicle can supposedly carry sensors over an infested field; wheeled, tracked and even legged vehicles can accomplish demining tasks effectively. Wheeled robots are the simplest and cheapest, and tracked robots are very good for moving over almost all kinds of terrain, but legged robots also exhibit interesting potential advantages in demining. For instance:

- Legged robots only require a finite number of ground-contact points, thus reducing their likelihood of stepping on an antipersonnel mine.
- After detecting an antipersonnel mine, a legged robot has a higher likelihood of going farther than do wheeled or tracked rovers. Wheels and tracks describe a continuous path, whilst legs only need to stand on discrete points along the path. This would enable all of a field's potential alarms to be located before starting the removal task, which is normally accomplished by experienced human teams or different kinds of robots.

- The inherent omnidirectionality of legged robots is also a great advantage for changing steering direction without performing turning-and-backing manoeuvres.

- Legged robots can negotiate irregular terrain whilst keeping their body always levelled. This is important when carrying onboard sensors and pieces of equipment that need to be levelled whilst measuring.

- Legged robots can easily walk on a slope with their body levelled without jeopardising their stability.

- Mobility on stairs, over obstacles and over ditches is one of the main advantages of legged robots. That means legged robots can be used to reach dangerous areas in both structured and unstructured environments.

- Legged robots can walk over loose and sandy terrain, and legs fitted with the proper force sensors can identify stepped terrain to prevent slippage.

- A legged robot provides additional motion along the x, y and z components and even body rotations without changing its footprints. Such motion can therefore be considered additional degrees of freedom for the robot's sensors and onboard equipment.

The idea of using legged mechanisms for humanitarian demining has been under development for at least the last five years, and some prototypes have been already tested. TITAN VIII, a four-legged robot developed for general purposes at the Tokyo Institute of Technology, Japan (Hirose and Kato 1998), was one of the first walking robots adapted for demining tasks. AMRU-2, an electropneumatic hexapod developed by the Free University of Brussels and the Royal Military Academy, Belgium (Baudoin *et al.* 1999), and RIMHO2, a four-legged robot developed at the Industrial Automation Institute (IAI-CSIC), Spain (see Figure 1), are two more examples of walking robots used as test beds for humanitarian demining tasks. COMET-1 was perhaps the first legged robot developed on purpose for demining tasks. It is a six-legged robot developed by a Japanese consortium, and it incorporates different sensors and location systems (Nonami *et al.* 2000). The COMET team is currently engaged in developing the third version of its robot. These four robots are based on insect configurations, but there are also different legged robot configurations, such as sliding-frame systems, being tested as humanitarian demining robots (Habumuremyi 1998, Marques 2002). To sum up, there is a great amount of activity in developing walking robots for this specific application field.

[Insert Figure 1 about here]

The IAI-CSIC legged-robot working team has long experience in the development of walking robots (Gonzalez de Santos *et al*. 1995, 2000, 2003, Grieco *et al.* 1998, Galvez *et al*. 2000). Since 1999 it has been working on the application of legged robots for detecting and locating unexploded ordnance (UXO) as a very important potential application for this kind of locomotion (see Figure 1). The IAI-CSIC holds experience in the design, development and control of walking robots, gait generation, terrain adaptation, robot teleoperation, collaborative control and other fields. All these technologies are mature enough to be merged in order to produce efficient robotic systems. The IAI-CSIC has, then, configured the DYLEMA system based on a legged robot for landmine detection and location. DYLEMA is a Spanish acronym meaning “Efficient Detection and Location of Antipersonnel Landmines”. The main aim of the DYLEMA project is to develop a whole system to integrate relevant technologies in the fields of legged locomotion and sensor systems in order to identify what needs exist when the result is applied to humanitarian demining activities. This paper presents the project's ongoing results in robot configuration, the sensor head, the scanning manipulator, locators, the control system and control strategies.

2 System description and main requirements

The DYLEMA project, as mentioned above, is conceived around a walking robot for detecting and locating antipersonnel landmines. The overall system is thus broken down into the following subsystems illustrated in Figure 2.

[Insert Figure 2 about here]

1. **Sensor head**. This subsystem contains the mine detector and additional elements for detecting the ground and objects in the way. The sensor head is configured to detect potential alarms but also to allow the controller to maintain the sensor head at a given height over the ground using simple range sensors. Touch sensors are also provided to detect objects in the sensor head's trajectory.

2. **Scanning manipulator**. The sensor head is basically a local sensor. That means it is able to sense just one point. The efficiency of such a device can be improved by moving the sensor head through a large area. The simple way of doing so is to use a manipulator, so the DYLEMA project uses a manipulator to move the sensor head and to adapt the sensor head to terrain irregularities. Section 4 explains why a 5-DOF manipulator was chosen for this purpose. The dimensions of the scanning manipulator depend on the dimension of the walking robot (leg spread and body height).

3. **Locator**. After detecting a suspect object, the system has to mark the object's exact location in a database for subsequent analysis and deactivation. We considered that an accuracy of about ±2 centimetres is adequate for locating

landmines. This accuracy can be obtained with commercial systems such as DGPS (Differential Global Positioning Systems).

4. **Mobile robot**. A mobile platform to carry the different subsystems across infected fields is of vital importance for thorough demining. In our case, the platform is based on a legged robot due to the advantages mentioned in Section 1. The following requirements are the starting point for configuring the walking robot:

   - The legged robot will be based on a hexapod configuration. Section 5 explains why this choice was made.
   - The legged robot should be lightweight enough to be handled by two adults. This requirement is important so the robot can be rescued from technical o logistic problems.
   - The robot should be autonomous from the energy point of view. Tethers should be avoided.
   - The robot should be semi-autonomous from the control point of view. Thus, a remote operator should be in the loop to control the system through teleoperation and collaborative control.

The robot is being configured to optimise power consumption, mobility and stability. These are antagonistic conditions which are being balanced through detailed design.

5. **Controller**. The global control system will be distributed into two main computers, the onboard computer and the operator station. The onboard computer is in charge of controlling and co-ordinating the manipulator and leg joints, communicating with the DGPS, the detector and the operator station via

radio Ethernet. The operator station is a remote computer in charge of defining the mobile robot's main task and managing the potential-alarm database.

6. **Power Supply.** Two main solutions have been envisaged for autonomous configuration from the power standpoint, a DC power supply using batteries and an AC power supply using a fuel generator. The second solution ought to provide higher autonomy, but its heavy weight is a drawback. DC batteries feature lower weight but also less autonomy. Nevertheless, fuel-cell technology is growing quickly and promises to be the best option in the near future. The system will therefore be based on DC actuators and systems.

Hence, the walking robot is to be configured as a six-legged autonomous robot carrying a scanning manipulator, which handles the sensor head. The system will be controlled through teleoperation and collaborative techniques. The sections below give an overall view of the system's configuration. Section 3 presents the detecting and locating subsystems. Section 4 focuses on the scanning manipulator's configuration. Section 5 provides a sketch of the walking robot. Section 6 introduces the controller, and, lastly, Section 7 presents some preliminary conclusions.

3 Landmine detection and location

This section describes two DYLEMA subsystems, the sensor head and the locator, which are based on commercial devices. The sensor head is based on a commercial mine-detector set, but comprehensively speaking it is an innovative system that integrates several range and touch sensors. Section 3.1 describes the sensor head and discusses the grounds on which it was designed. The locator is a commercial DGPS system. Section 3.2 briefly comments on its features and explains the criteria for its selection.

3.1 Sensor head

There are different sensor technologies for detecting mines. The simplest consist in metal detectors. These sensors are simple, lightweight and easy to use. However, they only detect mines that have metal parts, and they are inefficient with non-metallic mines (plastic mines). Other sensor types are required in such cases, such as sensors based on ground-penetrating radar (GPR) (Gader *et al.* 2000), chemical sensors (Albert *et al.* 1999) or artificial noses (Rouhi 1997).

An efficient detection system, it is commonly thought, should blend different technologies. The DYLEMA project, however, is devoted to the development of mobile-robotics techniques for landmine identification and location. The project's scope does not include any sensor development. Therefore, the simplest course would be to select a metal detector as the demining sensor, just to help in the detection and location of potential alarms. After a suspect object is detected, its location must be marked in the system database for further analysis and possible deactivation.

The Schiebel AN-19/2 commercial mine-detecting set is used for the DYLEMA project's purposes. This detector is in service in the US Army as well as in several NATO countries. It has been designed to detect very small metallic objects, typically mines with a very small metal content. This detector may be seen in Figure 3, and the design of the full sensor head is shown in Figure 4. The sensor head consists of a support holding the metal detector plus additional range sensors (infrared sensors) for detecting the ground and controlling sensor-head height and attitude. These sensors are located in pairs defining the upper and lower limits of the band in which the sensor head works. This array allows the controller to adapt the sensor head to terrain irregularities.

A bumper based on switches with a flexible band is located around the sensor head as a shock absorber. This bumper alerts the controller to the position of objects in the sensor head's trajectory, enabling the controller to steer around them.

[Insert Figure 3 about here]

[Insert Figure 4 about here]

3.2 Locator

Marking the position of any suspect object is mandatory in demining. In an automated or semi-automated system, a computer database would seem to be the most efficient way to keep a record of alarms. First, however, the potential alarms must be located accurately. GPS technique is a good candidate for this task, as it is simple to use and accurate enough. However, GPS technology does exhibit some failings: It is extremely expensive, it is prone to malfunctions in areas covered with natural objects (trees, large rocks, etc.) and it requires additional equipment (another antenna) for getting accuracy. For that reason we have planned to study alternative solutions such as co-operating robots. Nevertheless, a DGPS system is going to be considered as the first solution. This system will be used afterward to calibrate incoming new systems.

The DYLEMA project's requirements state that alarms must be located with an accuracy of about ±2 centimetres. This accuracy can be reached with the real-time kinematics (RTK) technique, but the RTK technique requires an additional GPS antenna placed at the operator station (see Figure 2). With these preliminary specifications the DGPS 5700, manufactured by TRIMBLE, seems to be a good candidate for our application.

4 Scanning manipulator

The DYLEMA project will use a sensor head based on a metal detector, which is a device that senses a single point or very small areas. A scanning device is therefore needed that can sweep the sensor across large areas. The easiest system would be a manipulator tailor-made for this task. Such a manipulator would require three DOFs for positioning the sensor in a 3D area; assuming that the system is scanning a non-flat area, motions in the x, y and z components would be required. Also, the detector would have to be adapted to small terrain inclinations; hence, two additional DOFs would be needed at the wrist to control detector attitude. The detector has radial symmetry, so no additional DOFs would be needed for orientation control. To sum up, a manipulator with at least five DOFs is needed to accomplish the task.

The manipulator is designed to carry the sensor head, so the design is optimised to carry just this load. First, the load is balanced to move the detector ±45º in its pitch and roll wrist axes with the lower torque. This is accomplished by placing the detector in a configuration in which no torque is required in the normal position (detector levelled at rest). In the manipulator, a RRR arm configuration is good enough for this application. Mobility is adequate and, because the links lie along a single vertical plane, there will be less collisions with the environment (assuming the robot's body is levelled). Another key design point is to mount the joint motors at the required position to balance the loads and decrease required torques. Figure 4 shows a detailed design of the scanning manipulator taking into account the aforementioned design requirements. Table 1 lists the manipulator's features. Some of these features, such as manipulator-link lengths, depend on the robot's dimensions (body height and leg span).

[Insert Table 1 about here]

5 Walking robot configuration

Walking robots are intrinsically slow machines, and machine speed is well known to depend theoretically on the number of legs the machine has (Waldron *et al*. 1984). Therefore, a hexapod can achieve higher speed than a quadruped, and a hexapod achieves its highest speed when using a wave gait with a duty factor of $\beta = 1/2$, that is, using alternating tripods (Song and Waldron 1989). Although stability is not optimum when using alternating tripods, a hexapod configuration has been chosen just to try to increase the machine's speed. The walking-robot development is based on certain subsystems developed for the SILO4 walking robot. The SILO4 is a quadruped robot developed for basic research activities and educational purposes (Gonzalez de Santos *et al.* 2003). For this reason, this new walking robot is named SILO6, referring to its six legs.

5.1 Body structure

The main tasks of a walking robot's body are to support legs and to accommodate subsystems. Therefore, the body must be big enough to contain the required subsystems, such as an onboard computer, electronics, drivers, a DGPS and batteries. The preliminary volumes of these subsystems define the volume of the body (see Table 2).

"Alternating tripods" means that two non-adjacent legs on one side and the central leg on the opposite side alternate in supporting the robot. That means that, for a given foot position, the central leg in its support phase is carrying about half the robot's weight, whilst the two collateral legs in their support phase are carrying about one-fourth of the robot's weight. This is especially significant in traditional hexapod configurations, where legs are placed at the same distance from the longitudinal axis of the body. If the robot has similar legs, then the non-central legs will be over-sized, and to optimise the mechanism the central leg's design should differ from that of the rest of the legs. However, using just one leg design has many advantages in terms of design cost, replacements, modularity and so on.

Satisfactory force distribution and system homogenisation can be achieved by shifting the central leg slightly from the body's longitudinal axis so that the central legs support less weight and the corner legs increase their contribution to supporting the body. This effect is illustrated in Figure 5, which shows a legged robot supported on three legs. The equilibrium equations that balance forces and moments are given by (Klein 1990):

$$\begin{bmatrix} x_1 & x_5 & x_4 \\ y_1 & y_5 & y_4 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} F_1 \\ F_5 \\ F_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ W \end{bmatrix} \tag{1}$$

The condition for sharing the weight of the robot evenly among the supporting legs is:

$$\begin{bmatrix} X & -X & 0 \\ Y & Y & -Y_4 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} W/3 \\ W/3 \\ W/3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ W \end{bmatrix} \tag{2}$$

Rows 1 and 3 are always satisfied and row 2 is satisfied if:

$$2Y = Y_4 \tag{3}$$

This last condition produces an unusual configuration that does not look very suitable for our application. In any case, the farther the central foot is from the body's longitudinal axis, the more homogeneously the forces are distributed.

[Insert Figure 5 about here]

The solution chosen was to select equal legs and situate the central legs in a forward position with reference to the body's longitudinal axis. The final leg location was a compromise between body shape and leg positions. Figure 6 illustrates how the central leg's supporting torques decrease as the distance to the body's longitudinal axis increases. A distance of about 125 mm was finally selected, because it produces an adequate body shape and reduces the required torques by about 14%.

[Insert Figure 6 about here]

The Yobotics Simulation Construction Set was used to compute leg torques and for graphic simulations as well (Yobotics 2002). This commercial package enables users to define robot kinematics, robot dynamic parameters (masses, moments of inertia, etc.), control laws, etc., and computes a graphic simulation that provides the required torques. These torques are the first basis for actuator selection. Figure 7 shows a graphic simulation of the walking robot endowed with a manipulator in both insect-like and mammal-like configurations. Figure 8 shows the torques obtained for a wave gait with a duty factor of $\beta=1/2$ (alternating tripod gait in insect-like configuration). The simulation was computed using the leg structure and dimensions presented in the section below. The preliminary dimensions of the walking robot are provided in Table 2. The subsection below explains how the leg configuration was selected for the DYLEMA project.

[Insert Figure 7 about here]

[Insert Table 2 about here]

5.2 Leg structure

Walking robots need leg configurations that provide just contact points with the ground, so a 3-DOF device is sufficient to accomplish motion. Legs have to be designed to be lightweight mechanisms and have to support the robot's weight. Therefore, the load carried by each leg is very heavy and must be supported with the leg in different configurations. A mammal configuration is the most efficient leg configuration from the energy point of view (lower torques are required). However, it is not very efficient in terms of stability. Insect-like legs seem to be more efficient stability-wise, but power consumption increases extraordinarily in an insect-like configuration. The idea is to provide a leg configuration that can accomplish its job with both stability and energy efficiency (a very important factor for outdoor mobile robots). Development is therefore underway on a leg that can be used in both the mammal and the insect configuration. The starting point is to consider the torques the robot has to endure in the worst-case scenario, an insect configuration. These torques, for the selected body configuration, have been computed through simulation. Figure 8 shows the torques at every one of the robot’s joints when the machine performs a tripod gait. As expected, joint 2 must withstand the highest torque. One good way to reduce motor size is to use actuators working in parallel, that is, actuators placed so that two actuators work at the same time to accomplish motion in a single joint. Simultaneous motions in two joints are also allowed. This configuration gives the benefit of using small motors. Therefore, a differential driving mechanism will be used for joints 2 and 3. Figure 9 shows a preliminary design for the leg, and Table 2 presents the leg’s main features.

[Insert Figure 8 about here]

[Insert Figure 9 about here]

Feet can be designed in two basic configurations, a ball fixed to the ankle or a flat sole with articulated passive joints. The first design is the simplest and can work for applications in loose terrain if the radius of the ball is big enough.

6 Control system

The control system is distributed between the operator station and the onboard controller. Both of them are based on PC-based computers (see Figure 2). The operator station will run under the Windows XP operating system, and the onboard controller (the robot's controller) will run under QNX, a UNIX-like real-time multitasking operating system. Communication between operator station and onboard computer will be performed by radio Ethernet. The main hardware and software aspects are discussed below.

6.1 Operator station

The operator station is based on a PC-bus computer set up remotely from the walking robot and is in charge of robot/user communication. It consists of the following modules:

1. Man-machine interface.
2. Alarm database manager.
3. Mobile robot communication.

6.1.1 Man-machine interface

This module is a Java-based program intended to fulfil three main requirements: (a) robot-state monitoring, (b) robot teleoperation and (c) task definition. The user will have the ability to govern robot motion remotely, with real-time visual information on what the robot is doing. The man-machine interface also allows the user to define the task, a process that involves the definition of mine-field features (field dimensions, roughness, etc.), robot path and autonomous navigation strategies. Figure 10 shows what the man-machine interface looks like.

[Insert Figure 10 about here]

6.1.2 Alarm-database manager

Each time the robot detects an alarm, the spatial position of the suspect object is stored in a relational database. The user can access every alarm location found in a given field of a given country. Field and mine features are also stored. This database enables mines to be removed with precision.

6.1.3 Mobile-robot communication

Communication between the operator computer and the onboard computer is conducted by means of a radio Ethernet card. The operator computer runs under the Windows XP operating system, whilst the onboard controller runs under the QNX operating system. Because different operating systems are used, the communications protocol has to be compatible with any operating system. One such protocol is the TCP/IP (Transmission Control Protocol/Internet Protocol) used world-wide for Internet connection. A client-server architecture was chosen for inter-process communications, where the operator computer is the server and the onboard computer is the client.

6.2 Onboard computer

6.2.1 Hardware architecture

The onboard controller is a distributed hierarchical system comprising a PC-based computer, a data-acquisition board and eight three-axis control boards based on the LM629 microcontrollers, interconnected through an ISA bus. The LM629 microcontrollers include digital PID filters provided with a trajectory generator used to execute closed-loop control for position and velocity in each joint. Every microcontroller commands a DC motor-joint driver based on the PWM technique. An analogue data-acquisition board is used to acquire sensorial data from the range of external equipment (sensors, locators, etc.). A radio Ethernet card is provided for network communication with the operator station. Additional electronic cards for interfacing with the detector are also provided, as well as communication with the DGPS systems via RS232. A general diagram of the SILO6 hardware architecture is shown in Figure 11.

[Insert Figure 11 about here]

6.2.2 Software architecture

The onboard computer is in charge of the walking robot's gait and trajectory generation, manipulator control, signal processing and communications, as well as coordination of the microcontrollers. These tasks are distributed in a software architecture that consists of layers developed on a bottom-up basis. These layers can be mainly divided into:

- Hardware interfaces: These layers contain the software drivers for both the walking robot and its manipulator.
- Axis-control layers: These layers control the individual joints for both the walking robot and its manipulator. Individual joints are controlled through a dedicated microcontroller, which runs a PID control algorithm.
- Leg control: This layer is in charge of coordinating all three joints in a leg to perform coordinated motions.
- Leg kinematics: This layer contains the direct and inverse kinematic functions of a leg.

- Trajectory control: This module is in charge of coordinating the simultaneous motion of all four legs to perform straight-line or circular motions.
- Stability module: This layer determines whether a given foot-position configuration is stable or not.
- Gait generator: This layer generates the sequence of leg lifting and foot placement to move the robot in a stable manner. Dynamic stability is guaranteed by the stability module. The SILO6 gait generator will be based on three gaits: a tripod gait, a spinning gait and a turning gait.
- Communications: This layer handles communications with the operator interface through radio Ethernet via the TCP/IP protocol.
- Manipulator kinematics: This layer is in charge of solving the manipulator kinematics.
- Equipment and sensor-data acquisition layer: This layer provides interfaces with external equipment.

Figure 12 diagrams the different software modules and their interconnections.

[Insert Figure 12 about here]

7 Conclusions

Detection and location of antipersonnel landmines is being done at present mainly by human operators handling manual equipment. The robotisation of this activity can give so many benefits to the human community in many countries. There is worldwide interest in eradicating deployed landmines, and solutions are coming from new, emerging engineering fields.

New kinds of sensors are required to detect landmines efficiently, but current sensors can be carried by mobile robots. Legged locomotion offers some important advantages for moving on natural terrain and appears to be a good solution for carrying mine sensors efficiently over infested fields.

Some preliminary work has been done to study the potential of using walking robots for demining. This paper addresses the development of a walking robot endowed with a manipulator able to scan areas with a sensor head based on a metal detector. It also presents the potential advantages of walking robots and a new system for landmine detection. This paper introduces the main system and provides some details of the configuration of the walking robot and the manipulator, and it outlines the hardware and software architecture as well.

The system has to be completed with the tools it needs for forming databases of potential alarms and providing the operator with adequate images and graphs. The incorporation of new sensors, detectors, and software for signature analysis will be addressed in the second step of this project.

Acknowledgement

This work has been funded by the Spanish Ministry of Science and Technology under Grant CICYT DPI2001-1595.

References

Albert, K.J., Myrick, M.L., Brown, S.B., Milanovich, F.P. and Walt D.R., 1999, High-speed fluorescence detection of explosives vapor, *SPIE*, *3710*, pp. 308-314.

Baudoin, Y. Acheroy, M., Piette, M., and Salmon, J.P., 1999, Humanitarian demining and robotics, *Mine Action Information Center Journal*. Vol. 3, No. 2.

Fong, T, Thorpe, C. and Baur, C., 1999, Collaborative control: A robot-centric model for vehicle teleoperation, AAAI 1999 Spring Symposium: Agents with Adjustable Autonomy, Stanford, CA, pp. 210-219.

Gader, P.D., Nelson, B., Frigui, H., Vaillette, G. and Keller, J., 2000, Landmine detection in ground penetrating radar using fuzzy logic, *Signal Processing, Special Issue on Fuzzy Logic in Signal Processing (Invited Paper)*, Vol. 80, No. 6, pp. 1069-1084.

Galvez, J.A., Estremera, J. and Gonzalez de Santos, P., 2000, SILO4: A versatile quadruped robot for research in force distribution, *Proceedings of the 3rd International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, Professional Engineering Publisher, U.K., pp. 371-383.

Gonzalez de Santos, P. and Jimenez, M.A., 1995, Generation of discontinuous gaits for quadruped walking machines, *Journal of Robotics Systems*, Vol. 12, No. 9, pp. 599-611.

Gonzalez de Santos, P., Armada, M.A. and Jimenez, M.A, 2000, Ship building with ROWER, *IEEE Robotics and Automation Magazine*, Vol. 7, No. 4, pp. 35-43.

Gonzalez de Santos, P., Galvez, J.A., Estremera, J. and Garcia, E., 2003, Towards the use of common systems in walking machine research, *IEEE Robotics and Automation Magazine*, In Press.

Grieco, J.C., Prieto, M., Armada, M.A. and Gonzalez de Santos, P., 1998, A six-legged climbing robot for high payloads, *Proceedings of the IEEE International Conference on Control Applications*, Trieste, Italy, pp. 446-450.

Habumuremyi, J.C., 1998, Rational designing of an electropneumatic robot for mine detection, *Proceedings of the 1st International Conference on Climbing and Walking Robots*, pp. 267-273, Brussels, Belgium.

Hirose, S. and Kato, K., 1998, Quadruped walking robot to perform mine detection and removal task, *Proceedings of the 1st International Conference on Climbing and Walking Robots*, pp. 261-266, Brussels, Belgium.

Klein, C.A. and Kittivatcharapong, S., 1990, Optimal force distribution for the legs of a walking machine with friction cone constraints, *IEEE Transactions on Robotics and Automation*, Vol. 6, No. 1, pp. 73-85.

Marques, L., Rachkov, M. and Almeida, A.T., 2002, Control system of a demining robot, *Proceedings of the 10th Mediterranean Conference on Control and Automation*, Lisbon, Portugal, July 9-12.

Nonami, K., Huang, Q.J., Komizo, D., Shimoi, N. and Uchida, H., 2000, Humanitarian mine detection six-legged walking robot, *Proceedings of the 3rd International Conference on Climbing and Walking Robots*, pp. 861-868, Madrid, Spain.

Rouhi A.M., 1997, Land Mines: Horrors begging for solutions, chemical & engineering news, Vol. 75, No. 10, pp. 14-22.

Song, S.M. and Waldron, K.J., 1989, MACHINES THAT WALK: The Adaptive Suspension Vehicle. The MIT Press Series in AI.

Waldron, K.J., Vohnout, V.J., Perry, A. and McGhee, R.B., 1984, Configuration design of the adaptive suspension vehicle, *The International Journal of Robotic Research*, Vol. 3, No. 2, pp.37-48.

Yobotics, 2000, Simulation construction set: User guide. Yobotics Inc. Boston, MA, 2002, Available at http://www.yobotics.com.

Figures

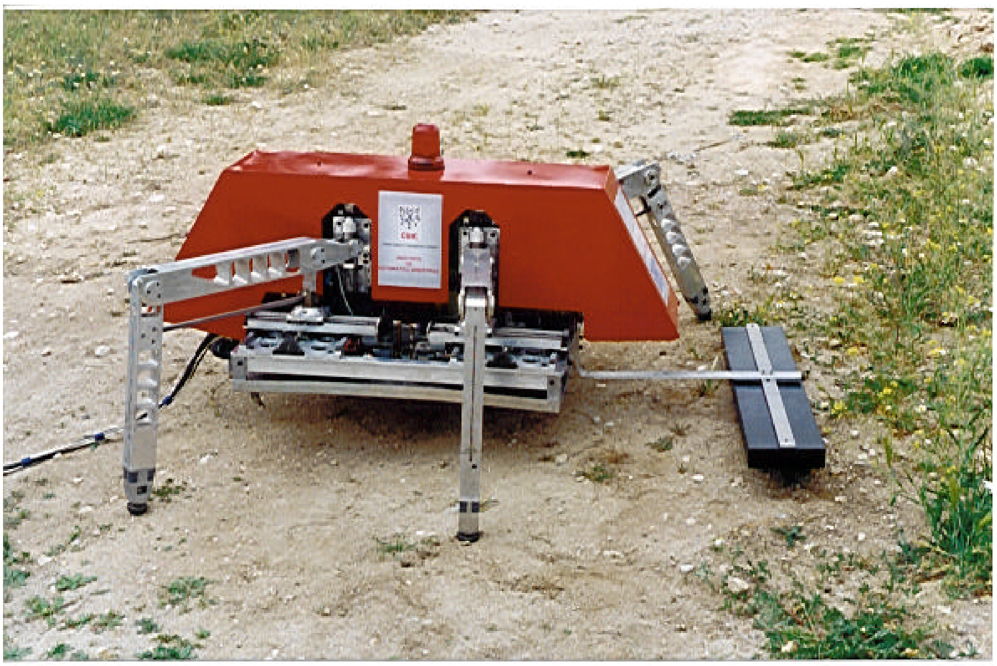


Figure 1. The RIMHO2 walking robot (IAI-CSIC)

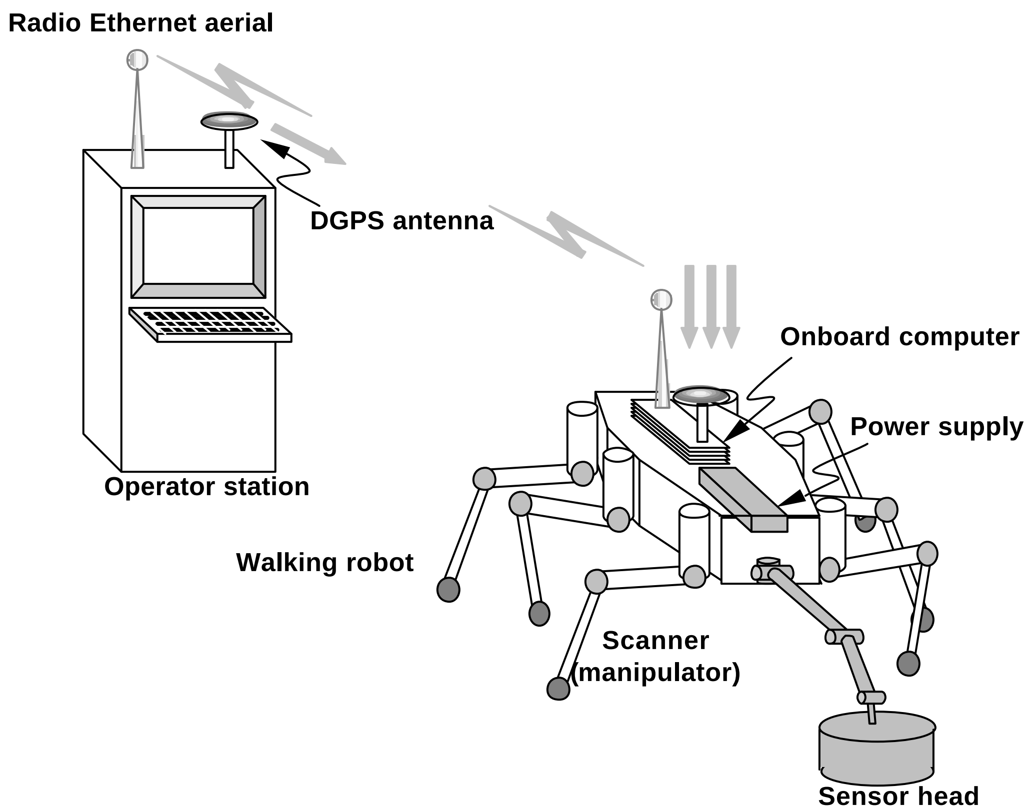


Figure 2. DYLEMA system

Figure 3. Metal detector

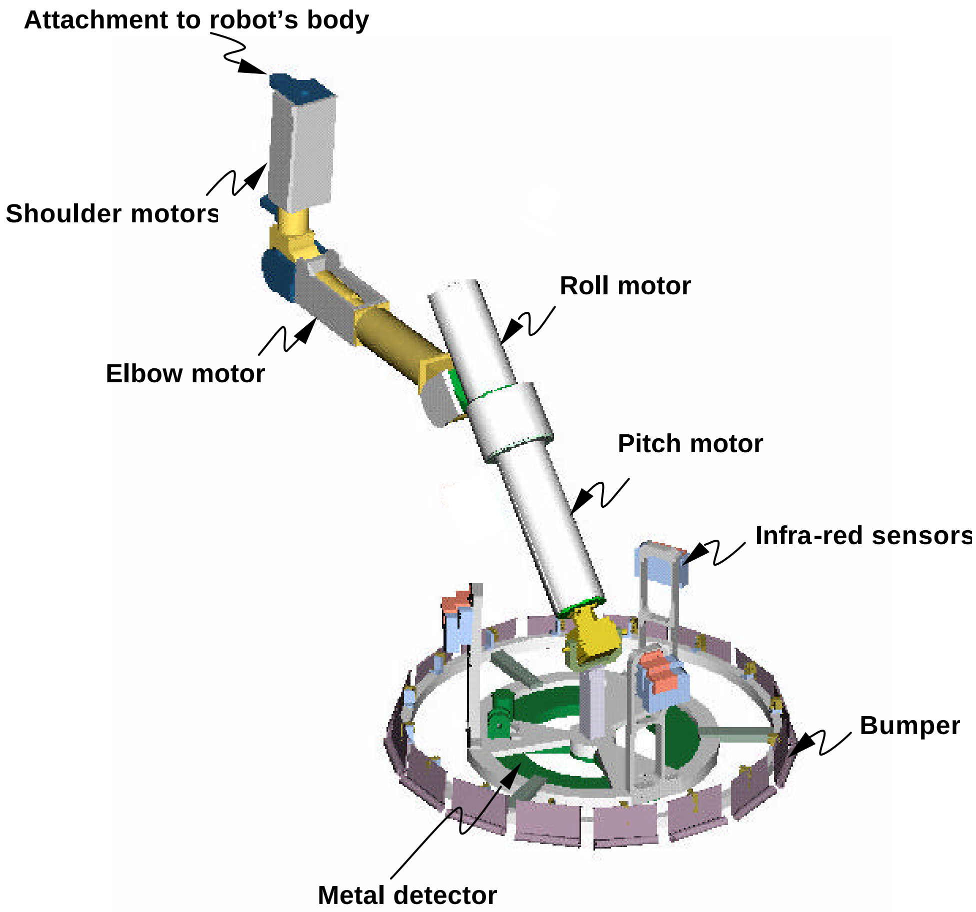


Figure 4. Scanning manipulator and sensor head

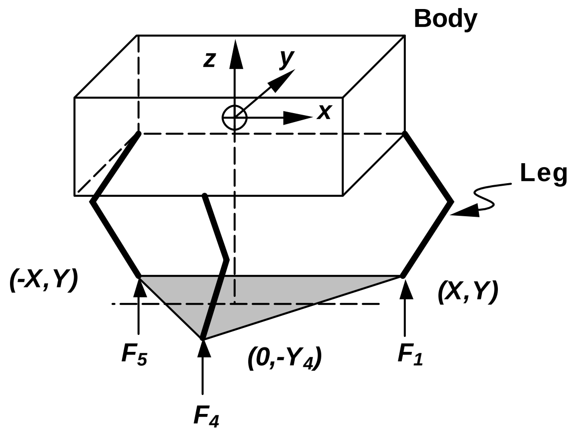


Figure 5. Force distribution for a tripod configuration

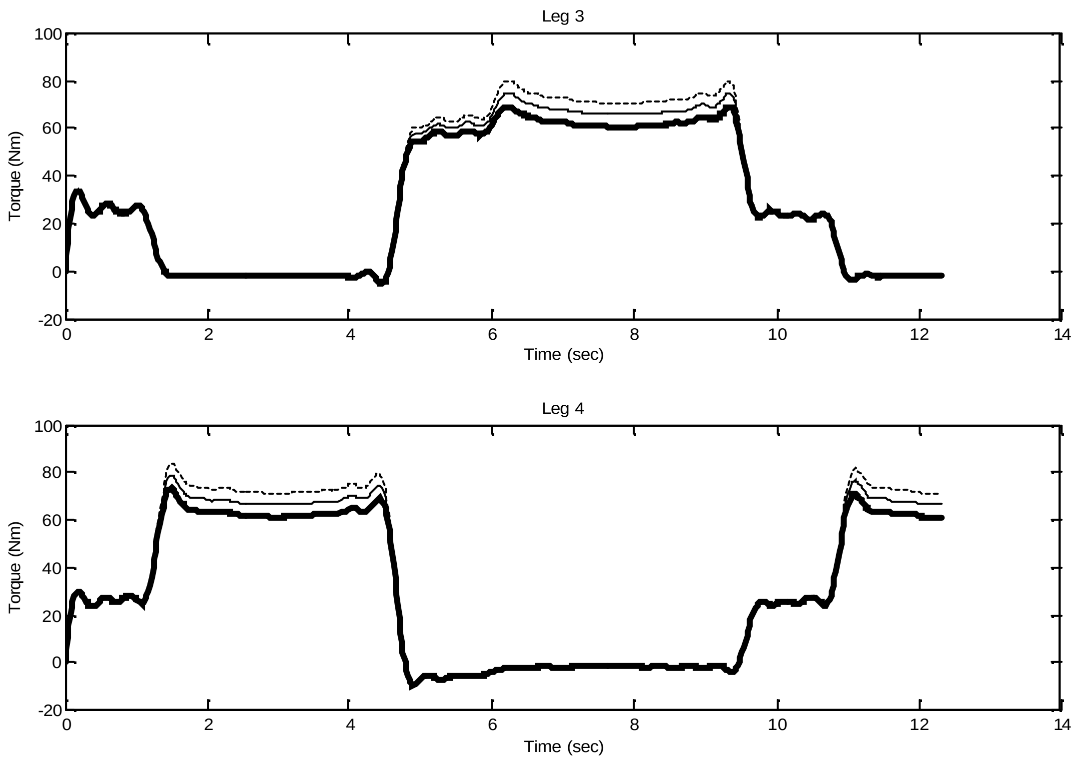
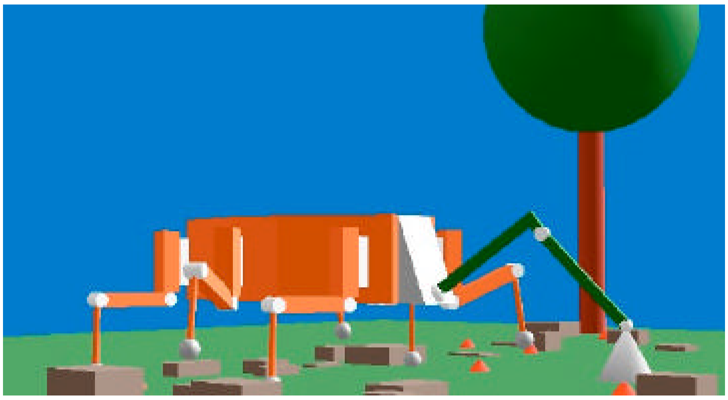
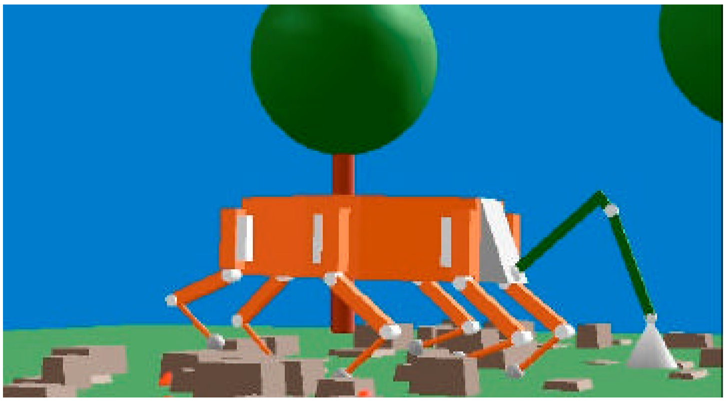


Figure 6. Joint torques in leg joint 2 for different leg locations: legs at the same distance from the body's longitudinal axis (dotted line); legs at 55 mm (thin line) and legs at 125 mm (thick line)



a)



b)

Figure 7. SILO6 sketch in simulation: a) insect-like configuration and b) mammal-like configuration

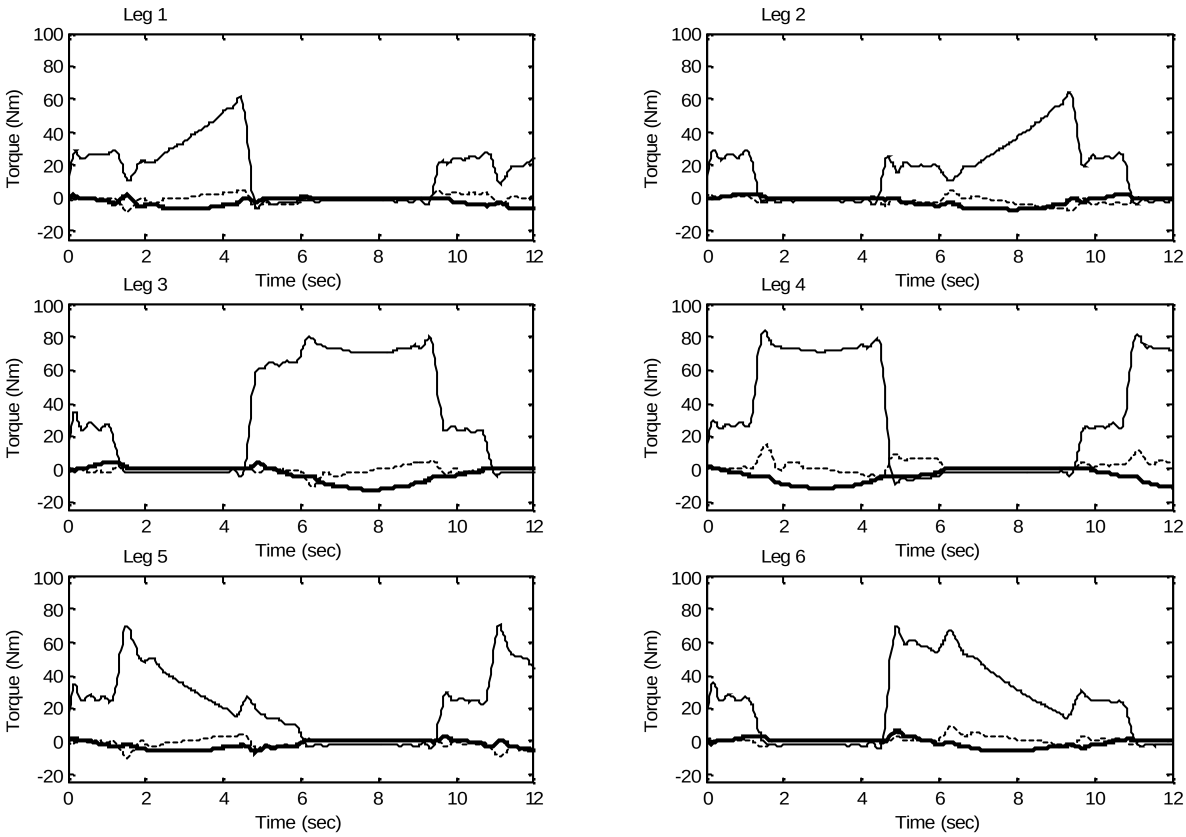


Figure 8. Joint torques required for a tripod gait: joint 1 in dotted line, joint 2 in thin line and joint 3 in thick line

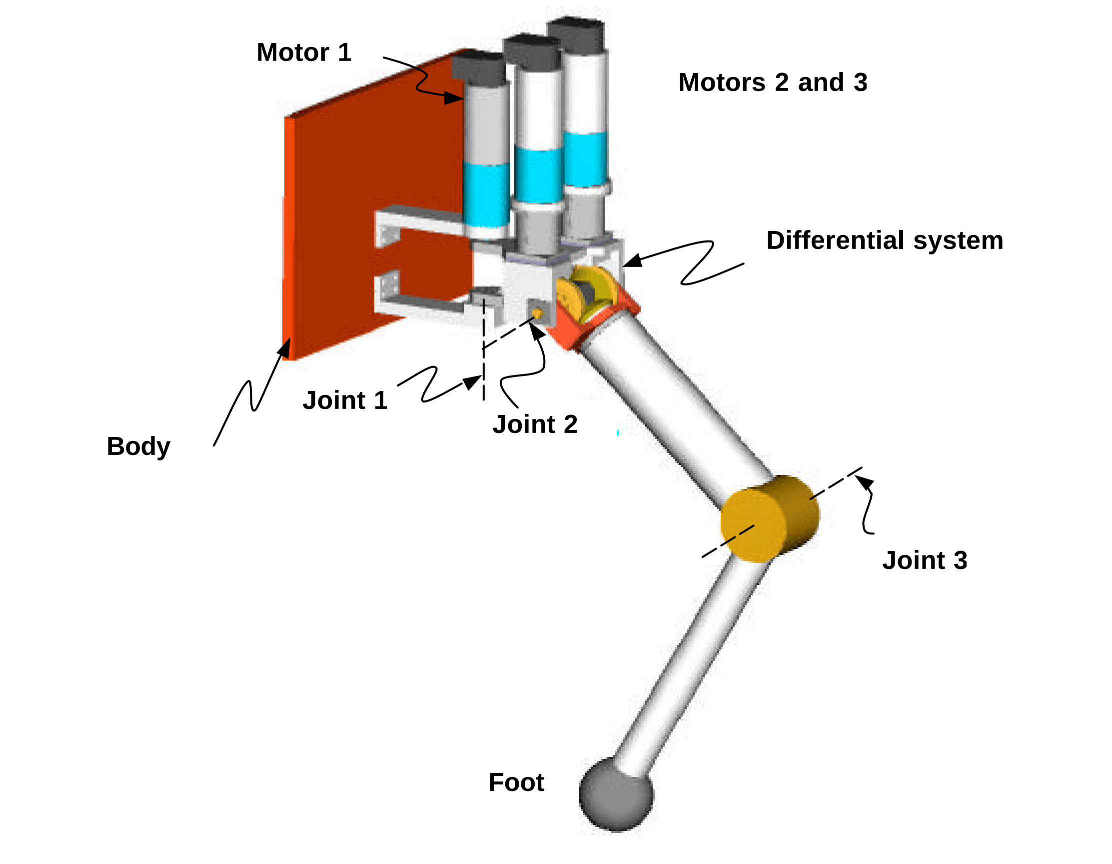


Figure 9. SILO6 leg configuration

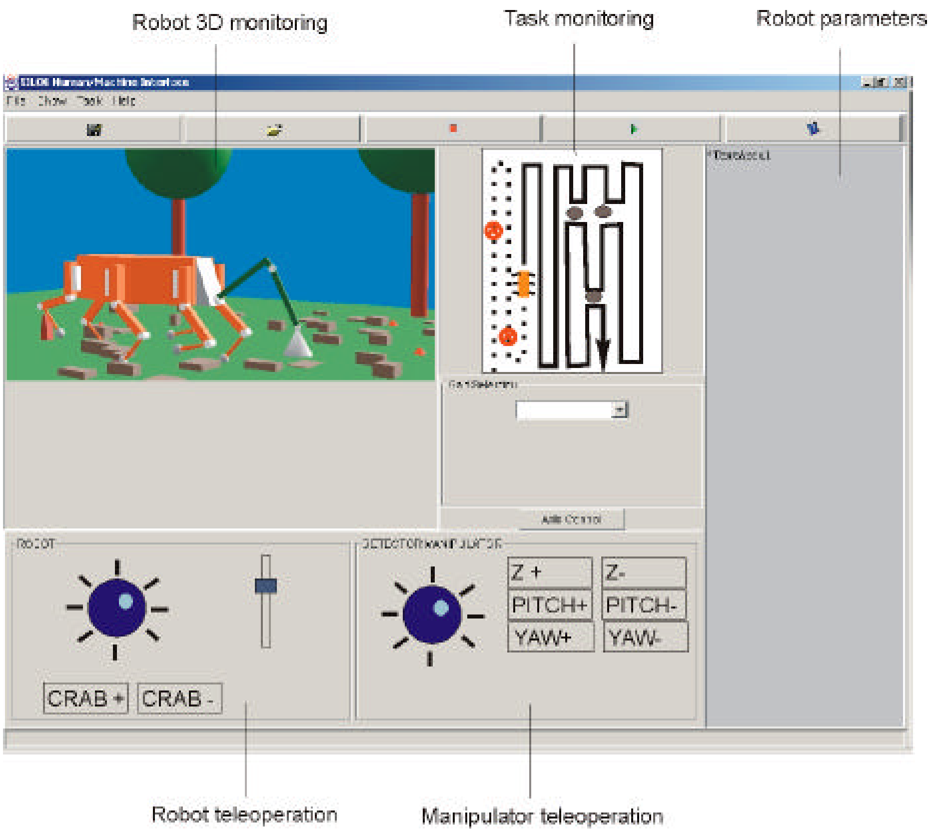


Figure 10. Man-machine interface

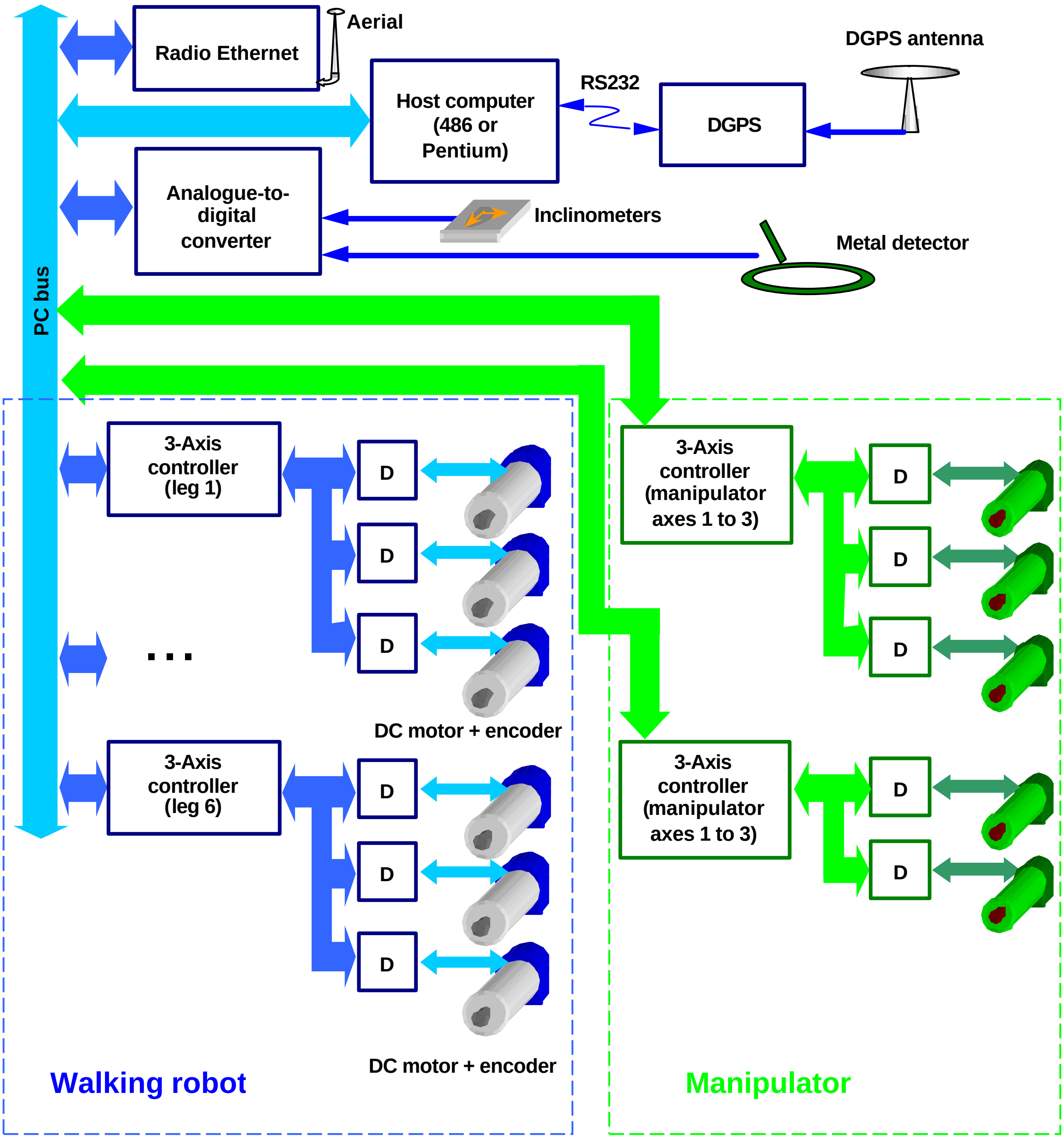


Figure 11. SILO6 hardware architecture

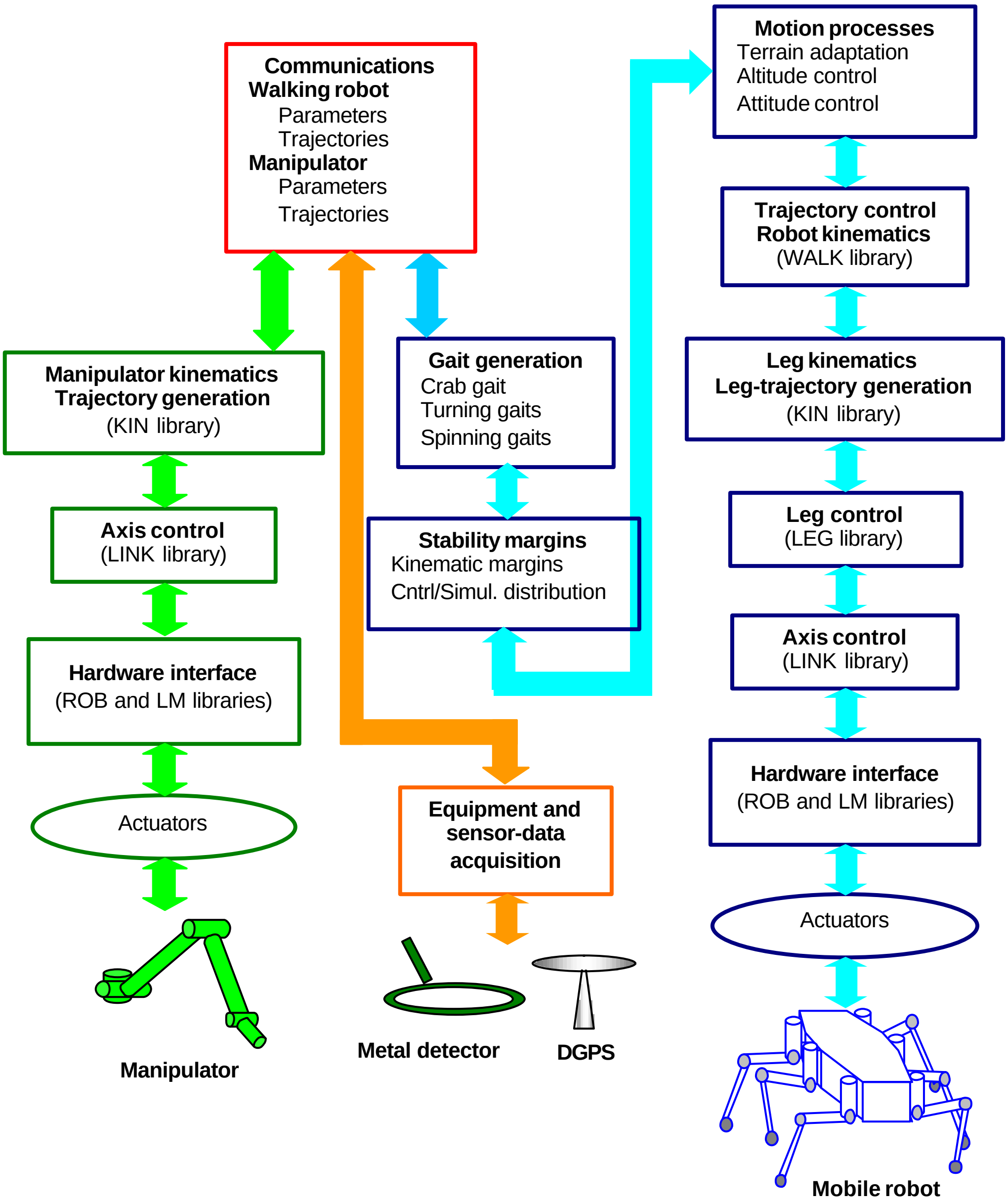


Figure 12. Software architecture

Table 1. Main scanning manipulator features

Joint/Link	**Link length (mm)**	**Motor power (watt)**	**Gearing**	**Mass (kg)**
1	60	14	246:1	1.5
2	341	72	357:1	2.1
3	341	26	357:1	1.9
4	200	12	246:1	0.2
5	--	12	246:1	--
Total				5.7

Table 2. Main walking robot features.

<table>
<tr><td rowspan="9">Body</td><td rowspan="4">Dimensions (m)</td><td colspan="2">Length</td><td>0.88</td></tr>
<tr><td rowspan="2">Width</td><td>Front/rear</td><td>0.2</td></tr>
<tr><td>Middle</td><td>0.45</td></tr>
<tr><td colspan="2">Height</td><td>0.26</td></tr>
<tr><td rowspan="3">Moments of inertia (kgm^2)</td><td colspan="2">I_{xx}</td><td>0.99</td></tr>
<tr><td colspan="2">I_{yy}</td><td>3.11</td></tr>
<tr><td colspan="2">I_{zz}</td><td>0.99</td></tr>
<tr><td colspan="3">Mass (kg)</td><td>44.34</td></tr>
<tr><td colspan="3">Speed (mm/s)</td><td>50</td></tr>
</table>

<table>
<tr><td rowspan="8">Leg</td><td colspan="2">Link</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td colspan="2">Length (mm)</td><td>94</td><td>250</td><td>250</td></tr>
<tr><td rowspan="3">Moments of inertia (kgm^2)</td><td>I_{xx}</td><td>0.016</td><td>0.0027</td><td>0.0031</td></tr>
<tr><td>I_{yy}</td><td>0.016</td><td>0.0027</td><td>0.0031</td></tr>
<tr><td>I_{zz}</td><td>0.018</td><td>0.0001</td><td>$3\ 10^{-5}$</td></tr>
<tr><td colspan="2">Mass (kg)</td><td>1</td><td>0.5</td><td>0.6</td></tr>
<tr><td rowspan="2">Foot speed (mm/s)</td><td>Transfer phase</td><td colspan="3">140</td></tr>
<tr><td>Support phase</td><td colspan="3">50</td></tr>
</table>