# A control architecture for humanitarian-demining legged robots

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## ABSTRACT

The use of autonomous robots for humanitarian demining tasks is a promising solution. Among the different types of autonomous robots, walking robots exhibit significant advantages to negotiate uneven and unstructured terrain. However, the complete autonomous control of walking robots is still challenging. In this work, a hybrid reactive/deliberative control architecture is proposed for the autonomous control of a demining system composed of a hexapod walking robot and a scanning manipulator. This control architecture allows the control system to both plan global control and navigation strategies and react to unmodelled disturbances.

**Keywords:** Control architectures, deliberative control, reactive control,legged robots, humanitarian deminig.

## 1 INTRODUCTION

Detection and removal of antipersonnel landmines is, at the present time, a serious problem and solutions are being explored in different engineering fields. Hand-prodding, although slow, is today the most reliable method of mine removal. However, the process of mine detection can be easily performed by robots. Although different types of robots have been proposed for landmine detection, legged robots exhibit clear advantages for such an application due to the main features of legged locomotion [1, 2]. Some of them are omnidirectionality, terrain roughness adaptability, discrete footprints avoiding stepping on mines, mobility over obstacles and across ditches, a bility to operate in different types of soils. However, the complete autonomous control of legged robots in unstructured environments is challenging. The coordination of legs and body motions while maintaining robot stability is a relevant effort that wheeled or tracked robots do not need to perform.

Also, the avoidance of obstacles along the leg trajectories is exclusive to legged vehicles. An autonomous legged robot should select among different gaits as a function of terrain roughness, and must be able to change the height of the leg stroke autonomously. Apart from such exclusive difficulties, the application of robots to mine detection tasks requires an autonomous navigation that certifies the complete coverage of the infested area. Therefore, the election of the proper control architecture is of paramount importance for the successful application of legged robots to the humanitarian demining problem.

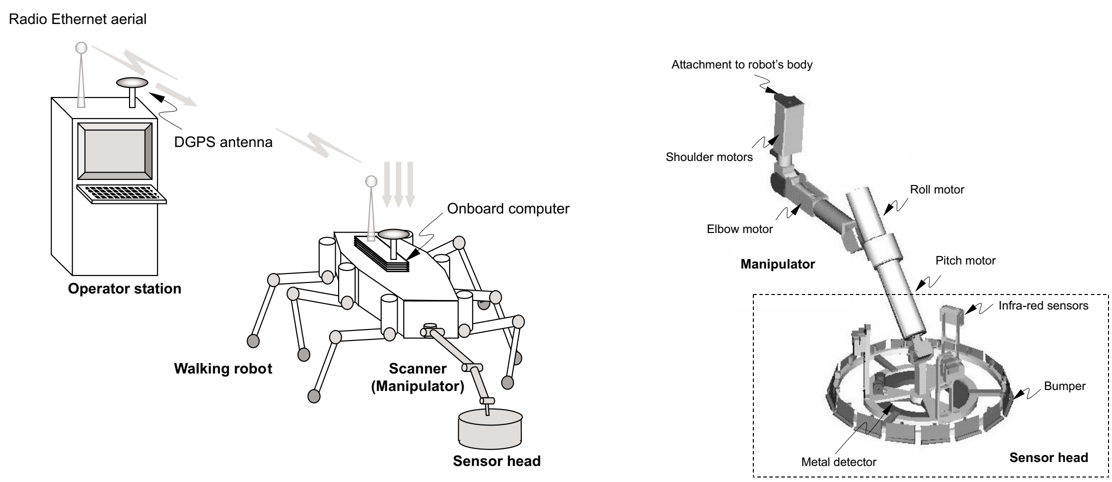
Control architectures of mobile robots mainly converge into three types: Deliberative [3], reactive [4] and hybrid [5]. Planning alone, without adaptation to possible disturbances during execution is insufficient for guiding a walking robot in natural terrain. Disturbances due to terrain roughness might cause the predefined task to fail. On the other hand, reacting alone is not valid to optimally perform global goals. Therefore a walking robot designed for mine detection tasks needs both to plan and react. Attempts to apply just one or the other fail or result inadequate [6].

In this work a Hybrid Deliberative/Reactive control architecture for a hexapod robot applied to mine detection tasks is proposed. Primarily, Section 2 briefly describes the demining system in which this work is focused on. Afterwards, Section 3 details the control architecture of the walking robot and finally some remarks and conclusions are given in Section 4.

## 2 DEMINING SYSTEM DESCRIPTION

The whole demining system is intended to detect and locate antipersonnel landmines and it is being configured around a walking robot [7]. For this purpose the overall system is broken down into the following subsystems illustrated in Figure 1(a):

1. **Sensor head.** This subsystem contains a commercial mine detector and additional elements to detect the ground (range sensors) and objects in the way (touch sensors). Figure 1(b) shows the sensor head.




a) b)

**Fig. 1 a) Demining system; b) Scanning manipulator and sensor head**

2. **Scanning manipulator.** A 5-DOF manipulator is used to move the sensor head and to adapt the sensor head to terrain irregularities (see Figure 1(b)).

3. **Locator.** After detecting a suspect object the system has to mark the exact location in a database for a posterior analysis and deactivation. The required 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 the infected field is of vital importance to de-mine entire fields. In our case, the platform is based on a hexapod legged robot (the SILO6 walking robot) for the advantages mentioned before. Six legs provide the best trade off between speed and stability. The legs are based on an insect configuration.

5. **Controller.** The global control system will be distributed in two main computers: on-board computer and operator station. The on-board computer is in charge of controlling and co-ordinating the manipulator and leg joints, communication with the DGPS and detector as well as communication with the operator station via radio Ethernet. The operator station is a remote computer in charge of defining the main task of the mobile robot and to manage the potential-alarm database. The on-board controller is a distributed hierarchical system composed of a PC-based computer, a data-acquisition board and eight three-axis control boards based on the LM629 microcontrollers, interconnected through an ISA bus.

Hence, the walking robot is to be configured as a six-legged-autonomous robot carrying a scanning manipulator, which handle the sensor head.

## 3 SILO6 CONTROL ARCHITECTURE

The SILO6 hexapod robot is aimed to walk on natural terrain to locate antipersonnel mines. Therefore a global planning to guide the walking robot along a predefined path and some mine-search algorithm are required. But also reactive locomotion is required so that the robot is able to respond robustly to uncertain disturbances during task execution. For this purpose a Hybrid deliberative/reactive control architecture based on four control levels is proposed for the SILO6 control architecture. These four levels of control are:

Level 1: Basic Control.

Level 2: Reactive Control.

Level 3: Deliberative Control.

Level 4: Supervisor.

and they are detailed in the following subsections (see Figure 2).

### 3.1 Basic Control Level

This layer of the control architecture implements the lower level controller of the walking robot. Based on joint positions, leg trajectories are defined and executed, while each joint PID controller assures trajectory following.

### 3.2 Reactive Control Level

The reactive control level is aimed to add robustness to the control system. Based on sensor data (joint positions and foot forces) the reactive control level helps to react to unpredictable changes in the environment. Two reactive behaviors improve the SILO6 controller performance (see Figure 2):

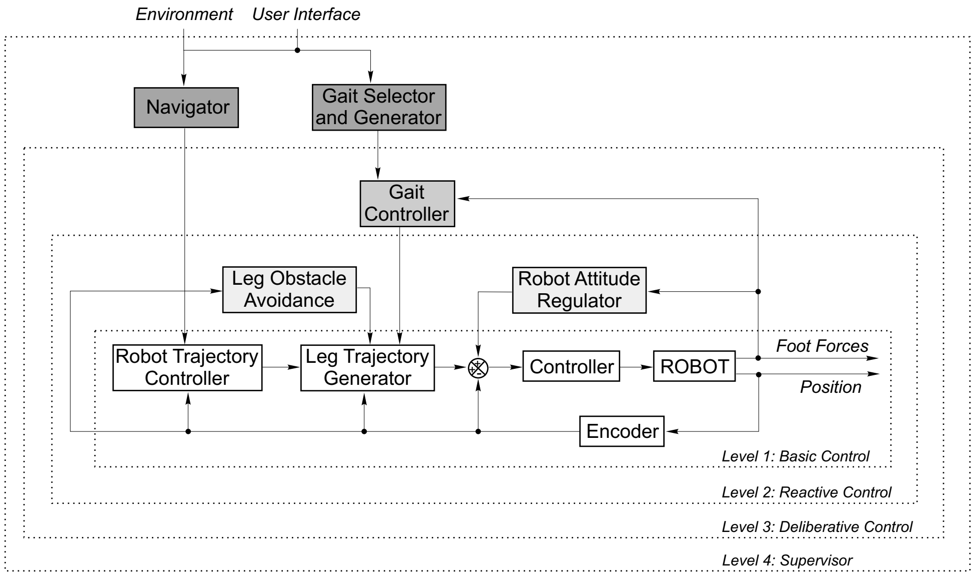



**Fig. 2 The SILO6 control architecture**

- Robot Attitude Regulator.
- Leg Obstacle Avoidance.

### *3.2.1 Robot Attitude Regulator*

During locomotion any non-constant dynamics (at leg swing, manipulation motion, when bumping against the environment) can disturb robot stability. Such disturbances could be balanced by means of posture regulation. The compensation is performed by active compliance [8, 9]. By commanding zero pitch and roll moments at the robot CG, and by force distribution to the supporting feet, the desired vertical foot forces are known at any time. Then an admittance controller corrects the basic joint controller reference trajectory to obtain the desired vertical foot forces.

The SILO6 walking robot performs an alternating-tripod gait, which consists of three states:

- First-tripod in transfer: The legs 1, 4 and 5 are in transfer phase while legs 2, 3 and 6 are supporting the body.
- All legs in support: All six legs supporting the body.
- Second-tripod in transfer: The legs 2, 3 and 6 are in transfer phase while legs 1, 4 and 5 are supporting the body.

During the body support phase the six feet are on the ground and the force distribution problem is ambiguous. Let $\mathbf{W_d}$ be the vector of vertical force and pitch and roll moments desired at the robot CG, that is:

$$\mathbf{W_d} = \begin{bmatrix} mg & 0 & 0 \end{bmatrix}^T \tag{1}$$

Let also $\mathbf{f_d}$ be the vector of vertical foot forces desired at each foot:

$$\mathbf{f_d} = \begin{bmatrix} f_{z_1} & f_{z_2} & f_{z_3} & f_{z_4} & f_{z_5} & f_{z_6} \end{bmatrix}^T \tag{2}$$

The static equilibrium equations are stated as:

$$\mathbf{W_d} = \mathbf{A}\mathbf{f_d} \tag{3}$$

where $\mathbf{A}$ is a $3 \times n$ matrix of the form:

$$\mathbf{A} = \{a_{ij}\} \tag{4}$$

with

$$a_{1j} = 1, \quad a_{2j} = y_j, \quad a_{3j} = -x_j, \quad j = 1..n \tag{5}$$

and $n = 6$ is the number of supporting feet.

To solve the force distribution problem the indeterminacy could be eliminated by adding an optimization condition. This condition is the one that satisfies:

$$\sum_{i \in I} (f_{z_i})^2 \rightarrow \min \tag{6}$$

which has the sense of energy optimization for supporting the weight. This is solved in the following manner:

$$\mathbf{f_d} = \mathbf{A}^{+}\mathbf{W_d} \tag{7}$$

where $\mathbf{A}^{+}$ is the pseudoinverse of matrix $\mathbf{A}$.

During the first and second tripod transfers only three feet are on the ground, matrix $\mathbf{A}$ is square, $\mathbf{A}^{+} = \mathbf{A}^{-1}$ and $n = 3$.

Once the desired foot forces that regulate the body are computed, the desired joint trajectories are modified through the following control law:

$$\dot{\mathbf{q}}_{\mathbf{d}} = \mathbf{K_p}(\mathbf{q_d} - \mathbf{q}) - \mathbf{K_f}\mathbf{J^T}(\mathbf{f_d} - \mathbf{f}) \tag{8}$$

where $\dot{\mathbf{q}}_{\mathbf{d}}$ is the vector of reference joint speeds commanded to the joint controllers and $\mathbf{q_d}$ are reference joint positions. $\mathbf{K_f}$ is the matrix of admittance gains and $\mathbf{K_p}$ is the matrix of position-control gains.

#### *3.2.2 Leg Obstacle Avoidance*

The leg obstacle avoidance behavior reacts when terrain obstacles interrupt leg transfer trajectories. When a position error threshold is detected in a leg motion the transfer trajectory is modified to enable the obstacle avoidance. This is performed by moving the leg a bit backwards and lifting the foot some predefined distance to continue the initial trajectory. If an error is again detected the same sequence of movements is performed once again, until the obstacle is avoided (see Figure 3). The Navigator module decides if the obstacle is too big to be avoided by the Leg Obstacle Avoidance module (see Figure 2).

### 3.3 Deliberative Control Level

The deliberative control level is aimed to plan the robot motion. The Gait Controller performs deliberative actions in the SILO6 control system:

#### *3.3.1 Gait Controller*

This module must govern the actions required to maintain a given gait. That is, it selects the next leg or body motion and gait parameters.

Based on the sensed foot forces the Normalized Energy Stability Margin (NDESM) is

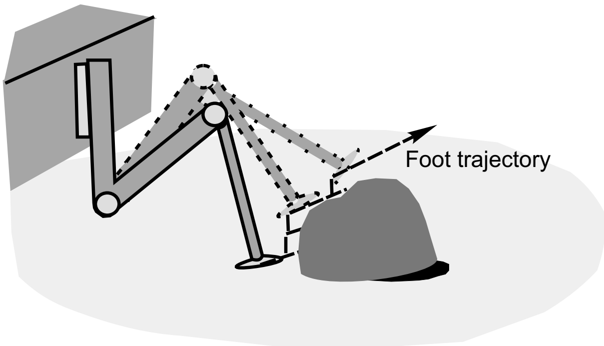



**Fig. 3 Foot trajectory during obstacle avoidance**

computed [10]. It provides the optimum stability margin when uneven terrain and dynamic effects are significant. Then, the Gait Controller guarantees that a given NDESM is mantained during robot motion.

### 3.4 Supervisor Level

Two supervisor modules lead the robot motion:

- Gait Selector
- Navigator

Both supervisor modules are also of the deliberative type.

#### *3.4.1 Gait Selector*

Based on user decision, if teleoperation is used, or based on sensor data (from range sensors located in the sensor head) that determines the grade of terrain roughness, the Gait Selector switches between three gaits, which are:

**Alternating-tripod gait:** Preferable for even terrain. High speed is achieved.

**Two-phase discontinuos gait:** Preferable for quite uneven terrain. Robot speed is lower than in an alternating-tripod gait, but stability is increased.

**Free gait:** Preferable for very uneven terrain with forbidden areas. Robot speed is low.

#### *3.4.2 Navigator*

The Navigator generates the robot trajectory, based on the user input (when teleoperation is used) or environmental sensor data (when autonomous operation is used). The planned trajectory must be controlled by the Robot Trajectory Controller (see Figure 2). At autonomous operation, the navigator generates on-line a complete-coverage trajectory based on the *Boustrophedon Cellular Decomposition* [11]. This method divides the mine field into cells free of obstacles, so that each cell is completely covered by the robot with back-and-forth boustrophedon motions. Two main problems have to be solved to achieve complete coverage of the entire mine field:

1. On-line cellular decomposition based on sensed obstacles.
2. Ensure that the walking robot visits every cell in the mine field.

The method to achieve complete coverage in unknown spaces solves for the two problems above simultaneously during the robot motion. The robot starts covering the space with back-and-forth motions until it detects an obstacle (see Figure 4(a)). The sensor head of the scanning manipulator is surrounded by an array of 16 bumpers to detect obstacles

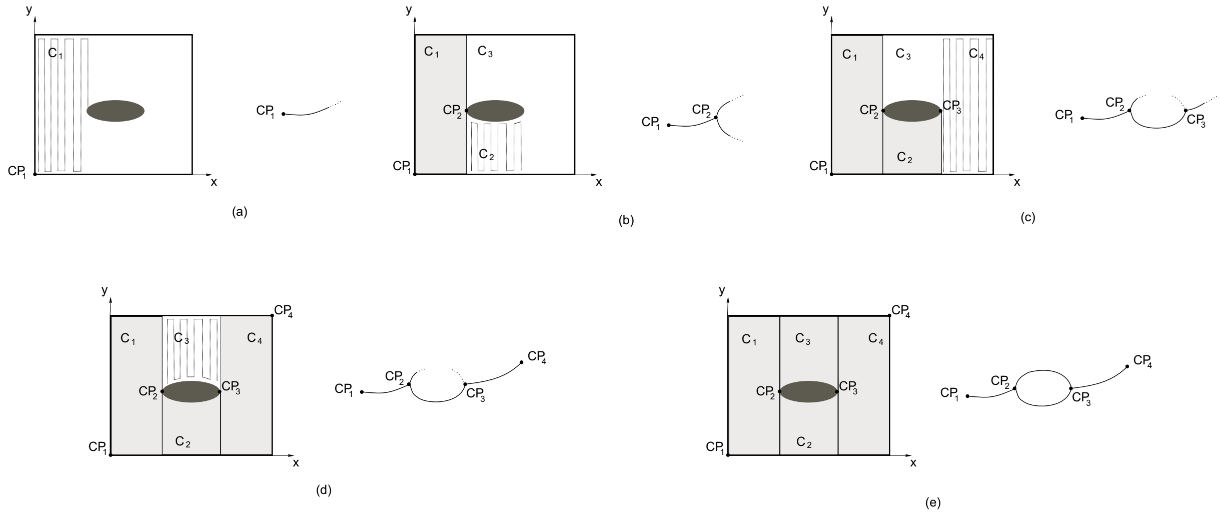



**Fig. 4 Incremental cellular decomposition and Reeb graph construction**

in the mine field (see Figure 1(b)). When an obstacle is found, then a *critical point* is searched for. Each critical point opens new cells or closes existing ones. Then the cellular decomposition consists on detecting all critical points in the field. At the same time, a Reeb graph [11] is incrementally constructed which has the global information of already visited cells.

*3.4.2.1 Critical Point Detection Method*

The walking robot starts covering the mine field in a point at the origin of the field's reference frame, which will be considered as $CP_1$. While the robot is moving forward and backward along the current cell the scanning manipulator moves searching for buried mines. However, in a given instant the bumper of the sensor head detects an object. Then the robot stops and the manipulator changes its trajectory to follow the object contour, $\mathcal{C}$, until it finds a local minimum or maximum of the function:

$$h(x, y) = x, \quad \forall x, y \in \mathcal{C} \tag{9}$$

The local minimum found is a critical point, named $CP_2$. At this time the current cell is closed and two new cells are opened. A local minimum opens two new cells while a local maximum closes two existing cells. Figure 4(b) shows the detection of a local minimum ($CP_2$), which closes one existing cell, $C_1$, and opens two new cells, $C_2$ and $C_3$, while Figure 4(c) shows the detection of a local maximum ($CP_3$), which closes two existing cells, $C_2$ and $C_3$, and opens one new cell, $C_4$.

*3.4.2.2 Reeb Graph Construction*

The Reeb graph represents the critical points as nodes and the cells as edges. Each time a critical point is sensed a new node is plotted. If the critical point is a minimum, two edges diverge, and if it is a maximum two edges converge at the new node. When the last corner in the field is found (named $CP_4$), then the robot is guided to any critical point with diverging edges disconnected. Such edges represent cells not visited. The Reeb graph ensures that every cell in the mine field is visited by the walking robot. The right side of Figure 4 shows the incremental construction of the Reeb graph.

## 4 CONCLUSIONS

This paper has been aimed to improve the adaptability of walking robots to those applications (as humanitarian demining) where autonomous control is required in hostile and unstructured terrains.
The use of autonomous robots for humanitarian demining tasks is a promising solution. Among the different types of autonomous robots, walking robots exhibit significant advantages to negotiate uneven and unstructured terrain. However, the complete autonomous control of walking robots is still challenging. In this work, a hybrid reactive/deliberative control architecture has been proposed for the autonomous control of a demining system composed of a hexapod walking robot and a scanning manipulator. This control architecture permits the control system to both plan global control and navigation strategies and react to unmodelled disturbances. This architecture allows the robot to complete cover a minefield while adapting to terrain irregularities and avoiding obstacles in a reactive manner. This control architecture will allow the complete autonomous control of walking robots in unstructured environments.

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