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Chapter 28
Magnetic Wheeled Climbing Robot: Design and Implementation

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Abstract This paper presents a climbing robot, with wheeled locomotion and adhesion through permanent magnets. This machine was developed to be used in the inspection of several types of man-made ferromagnetic structures, such as towers for wind turbines, fuel storage tanks, ship hulls, etc., in order to, for instance, detect weaknesses due to corrosion. In this article are presented the main aspects taken into consideration for its design, as well as several constructive aspects, among which are detailed its mechanical and electrical construction, the implemented control architecture and the Human-Machine Interface (HMI) for its control. The distinguishing characteristic of this robot is its dynamic adjustment system of the permanent magnets to assure the machine adhesion to the surfaces when crossing slightly irregular and curved surfaces with a large radius.

28.1 Introduction

The interest in the development of climbing robots has grown rapidly in recent years, since these devices can be adopted in varied applications such as maintenance, building, inspection and safety, mainly in the process and construction industries. They are mainly adopted in places where direct access by humans is expensive, because of the need for scaffolding or special structures, or dangerous, due to the presence of a hostile environment. The main motivations for its use are to increase the operation efficiency, by eliminating the costly assembly of scaffolding, or to protect human health and safety in hazardous tasks. Several climbing robots

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have been developed, and others are under development, for applications ranging from cleaning to inspection of difficult to reach constructions [1].

Magnetic adhesion is a principle adopted for the creation of an adhesion force, in cases where the surface allows it, and it can be highly desirable due to its inherent reliability. This method is fast but, depending on the weight of the robot, may involve the use of heavy actuators to obtain the required adhesion force [1]. It is possible to use electromagnets [2] or permanent magnets for assuring the robot adhesion to surfaces, combined with the use of wheels (as in this case) or tracks to move [3]. The main advantages of using permanent magnets is that there is no need to spend energy in the adhesion process, the robot does not experience any loss of adhesion in the case of a power failure and the fact that they are suitable for application in hazardous environments, such as the ATEX zones associated with flammable products stored in warehouses or tanks [4]. Among the drawbacks of this adhesion strategy, one can mention the fact that if the surface is very thin, it can deform and bend. In the limit situation, the surface can enter in contact with the magnets, this way making difficult the locomotion of the robot. Another problem that can arise with this technology is associated with the fact that the surface can present irregularities. These irregularities can make the magnets very close to the surface, even causing their contact, leading to the manifestation of an increased friction; the opposite situation can also occur, i.e. an exaggerated clearance, which might jeopardize the ability of the robot to adhere to the surface where it is moving, that could even lead to his downfall [5].

To overcome these situations, in this machine is implemented a device to vary the distance between the magnets and the surface where the robot moves, depending on the dimensions of the detected irregularities, in order to maintain this distance constant and controlled. Thus, we propose a robot with permanent magnets, which are adjusted in real time to the surface of displacement, through the adoption of a system to detect the magnets distance from the surface, using two inductive sensors combined with a support structure coupled to an actuated worm shaft.

Bearing these ideas in mind, the sequel of this paper is organized as follows. Section 28.2 introduces the robot main design considerations and Sect. 28.3 its mechanical structure. Section 28.4 describes its control architecture and, based on this, on Sect. 28.5 is presented the programming architecture for the vehicle. Finally, on Sect. 28.6 are presented the main conclusions of the work.

28.2 Robot Main Design Considerations

The robot described in this article was developed as a prototype of a vehicle intended to inspect man-made ferromagnetic structures, such as fuel storage tanks, towers for wind turbines, and ship hulls. These structures generally present a smooth surface, without big curvatures and are characterized by the existence of welding cords (protrusions), in the majority of the cases of small height, along the surface. Given these specifications it was decided to adopt a wheeled robot, with

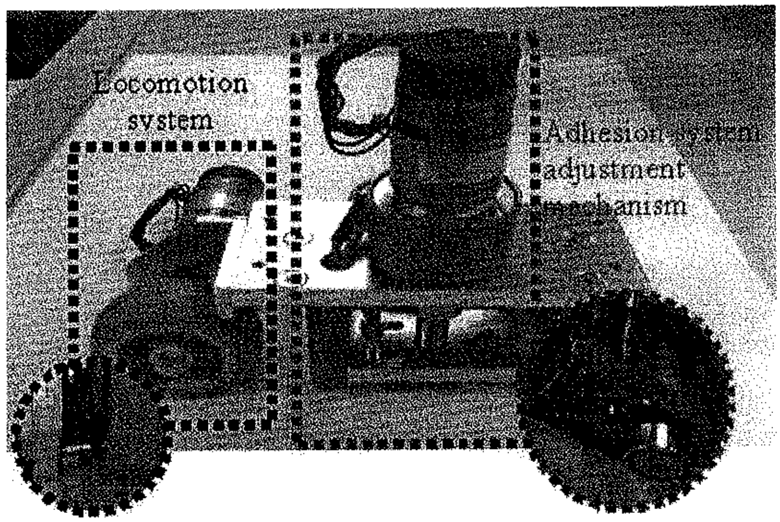

Fig. 28.1 Modular standard unit, where it is visible the locomotion system (*left*) and the adhesion system dynamic adjustment mechanism (*right*)

four wheels, and with some sort of "suspension system", to which we refer as the dynamic adjustment of the adhesion system, able to cope with the welding cords.

To choose the adequate permanent magnets for the robot under development some considerations regarding the weight of the final vehicle were first made.

The idea was to build a robot adopting a modular structure, being constituted by a rigid PVC base and four equal standard units, assembled on it [6]. Each of these units (Fig. 28.1) is composed of an actuated locomotion system (a set motor/wheels for locomotion) composed by a pair of wheels, one in rubber and the other magnetic (that was not considered in the initial phase of the project) (Fig. 28.1, lower left corner), and an actuated structure to adjust the permanent magnet distance to the displacement surface (a set motor/magnet for adhesion) (Fig. 28.1, lower right corner). The assembly of the four modules, to give rise to the robot, can be seen in Fig. 28.2, where it is possible to clearly identify the four equal standard units.

The weight of each motor, given by the manufacturer is 1.78 N. Since each module possesses two motors, their weight is 3.56 N. Each rubber wheel weights 1.36 N. For the modular metallic structure (in steel) we estimated a weight of approximately 5 N, for each unit. Summing up these values, it was considered a weight of 9.92 N for each module. On top of this structure was assumed that would be assembled an Allen Bradley MicroLogix 1100/1763 Programmable Logic Controller (PLC) weighting 8.3 N, without considering the I/O modules. These modules add about 4.9 N to the vehicle weight. Furthermore, the adoption of a few printed circuit boards (PCB) was predicted, for the implementation of the discrete control of the motors of the vehicle. For all the needed PCB we estimated a weight of 5 N. Summing all these values, we concluded that the total estimated weight of the vehicle would be around 57.88 N.

Based on these estimates for the total robot weight, the worst condition was assumed: the robot would need to be supported on the displacement surface upside down. This meant that the four permanent magnets had to develop a force, at least, equal to 57.88 N (or approximately 15 N for each magnet).

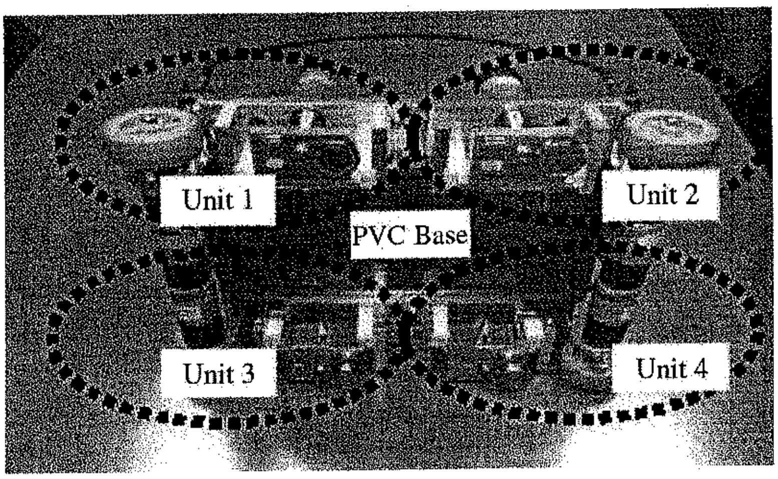

Fig. 28.2 Robot built using four equal sets, for locomotion and vertical position magnet adjustment

The magnetic force developed by permanent magnets depends heavily on the following factors: distance between magnet and object (the force decays rapidly with the distance), material of object of magnetic attraction (there is a loss of 30% of the magnetic force if the surface where the robot moves is built of construction steel, which is the usual for the applications under consideration), direction of the force, and surface area and thickness of the object of magnetic attraction.

Given these considerations, was assumed the rather unfavourable situation that on normal robot operating conditions the magnet would only develop approximately 15% of the maximum possible force. This implied that the maximum achievable force by the permanent magnet would be around 100 N. Looking at the SUPERMAGNETE manufacturer catalogue permanent magnets characteristics, were chosen SUPERMAGNETE FTN-20 permanent magnets. Each of these permanent magnets presents a maximum magnetic force of approximately 108 N, under "optimum conditions".

28.3 Mechanical Structure

28.3.1 Adhesion System

The adhesion module is responsible for supporting the robot when it is placed in a vertical ferromagnetic surface. This unit is composed by the permanent magnets and by two inductive sensors, responsible for detecting the distance to the locomotion surface, as can be seen in Fig. 28.3.

The actuated mechanism for the real time adjustment system is composed by the motor (Gearmotor 12 V DC, 33 rpm) coupled to the support structure, the permanent magnet (SUPERMAGNETE FTN-20) and the inductive sensors (IFM IY5049). Using the distance information obtained by the two inductive

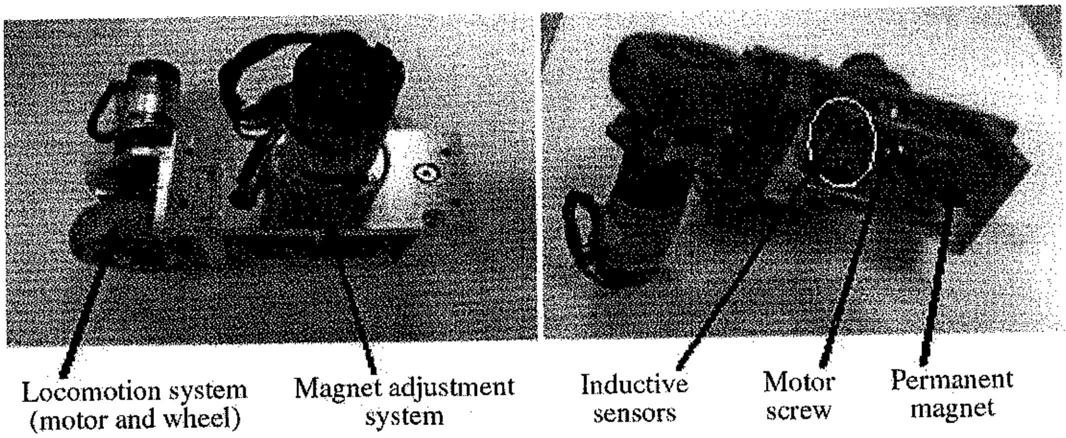

Fig. 28.3 The two inductive sensors, motor screw and magnet

sensors, it dynamically adjusts the magnet distance to the contact and locomotion surface using an actuated worm shaft [7], to keep a constant distance between the permanent magnets and the surface where the robot is moving, in the presence of irregularities.

28.3.2 Locomotion System

Regarding the locomotion system, each standard unit consists of a motor (Gearmotor 12 V DC, 62 rpm, with encoder) and a 50 mm diameter wheel, with rubber exterior to improve the adhesion to the surface of displacement. Each of these structures, which are mounted on a set that also contains the system of vertical adjustment of the magnet, presents in an almost parallel assembly to the outermost part of the wheel, a 10 mm diameter circular magnet with the possibility of rotation in synchronism with its wheel. Its purpose is to maximize the adherence to the contact surface, and allowing the robot to move from a horizontal to a vertical surface.

In order to improve the adherence of the four locomotion units to the contact and locomotion surface, even when it does not present perfectly flat and regular characteristics, an auto-levelling structure was implemented in the two rear systems (Fig. 28.4), which is composed of a mechanism with a sliding guide and compensated through a spring.

28.4 Control Architecture

28.4.1 PLC Inputs/Outputs

The control of this robot is based on an Allen Bradley MicroLogix 1100/1763 PLC. One characteristic of this PLC is that it presents a rather limited number of I/O, being necessary to attach one expansion board with 8 digital inputs (1762-IQ8) and

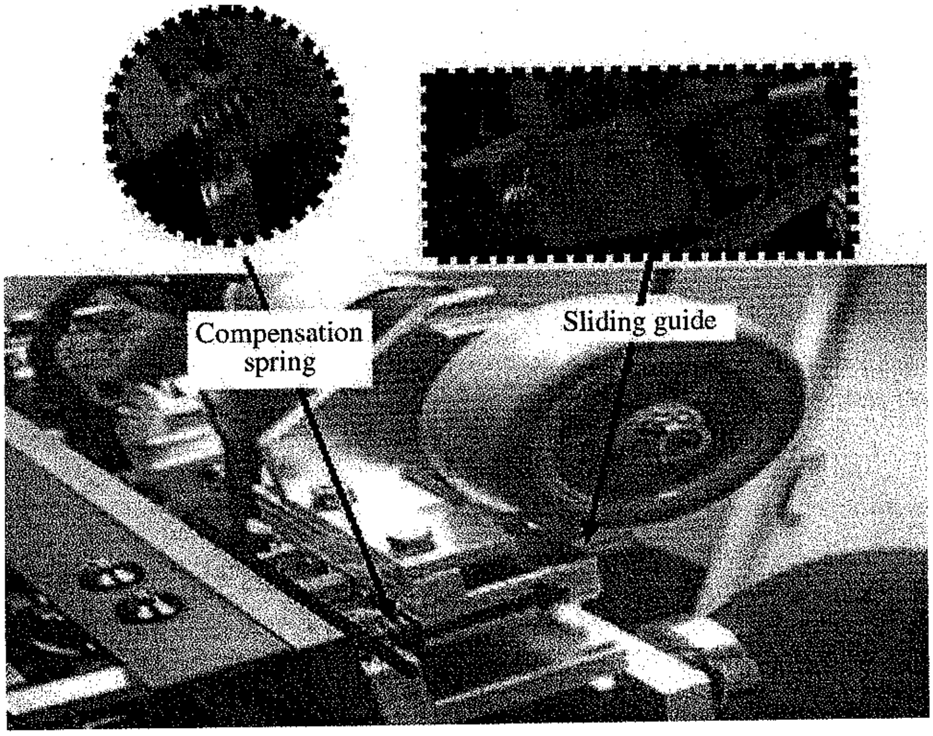

Fig. 28.4 Photo of the auto-levelling system, with the sliding guide and spring compensated structure

another with 8 digital relay outputs (1762-OW8). Since the PLC allows the use of 10 inputs, there are a total of 18 inputs available for use, of which only two are direct analog inputs. These can be configured to be connected to devices that have voltage output (in this case, the sonars in the front and rear of the robot, used to detect obstacles).

The used outputs are obtained directly from the PLC (two using Fast FET, two using FET and two using relays) and from the expansion module (8 outputs, all of them using relays), which is coupled by a dedicated bus to the PLC.

28.4.2 Logical and DC Power Circuits

There was also the need to develop several dedicated PCBs to support the adequate control of the system [7]. This electronics is devoted to power the entire system and to its configuration and logical control (the Adhesion and the Locomotion Units are associated with a logic circuit that allows its optimized control by the PLC and have each a DC Power Supply circuit associated [7]).

In the case of the Adhesion Unit control logic electronic circuit, its working principle is based on a binary up/down counter (74HCT4516 IC), aided by logical inverters and Quad Push-Pull Drivers. Since the control over this unit has to be fast, are used PLC outputs of the type FET and Fast FET [7].

The Quad Push-Pull Drivers are of the L293D type and serve to drive the four motors, with a voltage of 12 V DC. In each L293D are combined the four Half-H Drivers to form two H bridges, which drive two motors (on the same side of the climbing robot). This system allows setting the rotation direction and the start of each motor in an individual and independent way.

Regarding the Locomotion Unit control logic electronic circuit, the operating principle is similar to what was described for the control of the Adhesion Unit, with minor differences associated with the particularities of this Unit. Since this type of control does not need to be as fast as the one in the Adhesion Unit, the Reset and Parallel Load signals are commanded by PLC relay outputs, while the Clock signal is commanded by a PLC FET output.

Regarding the Adhesion and the Locomotion Units DC Power Supply circuits these are implemented based on monolithic type regulators. The climbing vehicle possesses two of these circuits. One of them is used to provide the 5 V DC that powers all the digital circuits and 2 × 12 V DC for each pair of motors of the Locomotion Unit. The other circuit is used to provide the 5 V DC that powers the Access Point (AP) Wi-Fi 802.11 g (the system for the remote communication with the robot), and 2 × 12 V DC for each pair of motors of the Adhesion Unit.

The remaining electronic circuitry, such as the PLC and the whole set of sensors, are powered directly from the 24 V DC supply (except for the sonars, that are 5 V DC powered by the digital part). Therefore, there is a system of power distribution at the 24 V DC voltage level.

The Main Power Control Panel allows powering the entire mobile robot, and presents the future possibility of integration with batteries and their electrical charging circuit.

There is also integrated into the power supply system a DC-to-DC converter to dissipate as heat, through a controlled fan, the excess of power delivered from the 24 V DC supply, given the lower voltages also needed, such as 5 V DC and 12 V DC. This converter is powered from the 24 V DC (Main Power) and provides two distinct voltage levels at its output: 9 V DC, used to supply the monolithic type circuit that provides 5 V DC / 700 mA to the AP Wi-Fi communication system, and 12 V DC, supplying the monolithic circuit that provides 5 V DC / 200 mA to all logic / digital circuits complementary to the PLC logical operation.

28.5 Programming of the Control System

28.5.1 PLC Program

The control program adopted for the vehicle operation is implemented on the PLC with the aid of the RSLOGIX 500 programming software (Rockwell Automation).

In this program was established a main routine and four subroutines. The main program (main routine) is associated with LAD 2, and the remaining LAD (LAD 3, LAD 4, LAD 5, and LAD 6) are called by the main routine.

Besides calling the other routines, the main routine (LAD 2) is responsible for some initialization logic of the robot and for the main control over the locomotion and adhesion systems. It is also responsible for handling the logic required to connect the external logic circuits to the PLC, allowing an interface with the motors through the binary counters and the H bridges. The LAD 3 routine implements the logic required to configure and manually control (by a robot operator) the locomotion and adhesion systems. Routine LAD 4 has all the logic needed to automatically control the adhesion and locomotion systems of the robot, without requiring any operator intervention. It is this routine that controls the magnets position regarding to the robot locomotion surface. This is also the routine that handles the possibility of autonomous surface exploitation by the robot. The LAD 5 routine processes the signals sent by the sensors that control the movement of the robot, in particular as regards the sonars for obstacle detection, and the motors rotational asymmetry detected by the encoders. Finally, LAD 6 is associated with the logic control of a local manual control physical interface, which is coupled to two digital inputs in the PLC. This interface allows acting on the adhesion and locomotion systems, enabling some local features, such as:

1. Activation of the adhesion system.
2. Displacement of the four adhesion units towards the locomotion surface.
3. Stop the adhesion and locomotion systems.
4. Move the four adhesion units to the security zone, i.e. in a direction opposite to the locomotion surface.

The local manual command interface is also used for the connection of the robot sonars to the +5 V DC power supply and to the IV1 and IV2 PLC analog inputs.

28.5.2 Human-Machine Interface

Although it can be manually controlled, the vehicle is designed to have a semi-autonomous behaviour, allowing a remote inspection process controlled by a technician, this way reducing the risks associated with the human inspection of tall structures and ATEX places.

In order to have a friendlier graphical environment for those who remotely operate the climbing robot, a software application was developed and is used as a HMI. This HMI application is of the Supervision Control and Data Acquisition (SCADA) type. The used software is the RSView32 (Rockwell Automation), which provides greater ease of manipulation of the variables defined in the program that runs on the MicroLogix 1100 PLC.

It is possible to access all the configuration parameters of the adopted adhesion and locomotion process, and have feedback from the physical variables measured by the climbing robot sensors, from any computer running this SCADA, and the dedicated programming associated, with its graphical interface directed towards the remote operation of the robot (HMI).

In developing the SCADA/HMI program, which runs on the RSView32 software, it was essential to create Tags in an organized way, of the digital, analog or character (Strings) types, which are stored in the Tag Database, with the aim of obtaining a structured and synchronized programming with the PLC program and its labels.

In this project were created, and programmed with the labels previously created, seven graphs, whose general function is associated with the remote control of the climbing robot. The characteristic of each chart and its particular function is described below.

1. The graphic/display "General", which is the HMI display screen.
2. The graphic/display "Choice", which is the "gateway" to the other graphics/displays.
3. The graphic/display "Alarms Register" allows the operator to view the list of active alarms and the occurrences log file, besides allowing to act on its recognition, activation or deactivation.
4. The graphic/display "Auto" is responsible for monitoring the remote operation capability, over the surrounding environment, on automatic mode.
5. The graphic/display "CFG General" is used to set some parameters related to the functioning of the robot.
6. The graphic/display "Manual Adhesion" allows to manually operate the various features of the climbing robot that constitute the adhesion system.
7. The graphic/display "Manual Locomotion" allows to manually operate the various features of the climbing robot integrating the locomotion system.

To assist the manual remote control of the robot locomotion, it is shown in the graphic/display "Manual Locomotion" the distance travelled for each motor, allowing to identify asymmetries in the movement. There is also an indication of the distance to any obstacles that are on the front or rear of the robot. When an obstacle is within the preset distance to the robot, it stops, unless this option is disabled.

With all these graphics/displays, provided by the remote monitoring system of the robot (its HMI), it is possible for an operator to have "access" to all equipment placed on board the autonomous climbing robot. This allows the internal and external monitoring of the mobile system and the operation, in a controlled manner, of the various features available.

28.6 Conclusions

This paper presented a climbing robot with wheeled locomotion and adhesion through permanent magnets (Fig. 28.5), to be used in the inspection of various types of ferromagnetic structures. The distinguishing characteristic of this machine is its real time system for the adjustment of the magnets in order to assure the machine adhesion to the surfaces, even when crossing irregular and curved surfaces.

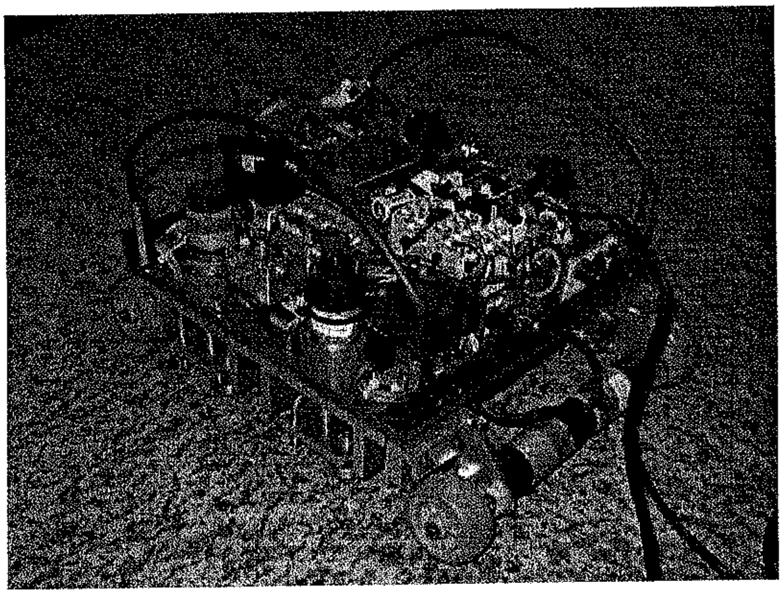

Fig. 28.5 Photo of the final prototype of the developed climbing robot with locomotion through wheels and adhesion with permanent magnets

The robot development is now complete and several tests have confirmed the adequacy of the vehicle to the intended application, while manually and remotely controlled, verifying its locomotion in ferromagnetic vertical surfaces with irregularities and curvatures, while in autonomous mode.

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