4Steel-Robot: A Climbing Mobile Robot for Gas Containers Inspection

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Abstract: - The purpose of the project is to design and build a wireless wall climbing robot to accomplish remotely ultrasonic and visual inspections in large gas containers, avoiding in this way the necessity to use scalfolding and reduce the risks for the technicians in charge of these works.

The robot is proposed as a four-legged machine, whose legs are built by means of a servomotor and a linear actuator. Other objective of this work is prouve if two degrees of freedom are enough to achieve the movility required for the robot. For the control of the robot a single board computer is being used, employing for this purpose Max-FORTH as the programming language of the microcontroller.

At this moment several experiments have being carried out to demonstrate the performance of the gait proposed for this walking machine. The advances in the developing of this machine are here presented.

Key-Words: - Mobile Robot, Walking Machine, Magnetic Adhesion, Java Programming, Forth Programming Language, Gait

1. Introduction

Robotics has achieved to the date a great success in the world of manufacturing industry. Robotic arms, or manipulators, conform in the United States an industry of 2 trillions of dollars. Screwed by its shoulders to a fixed position in the line of joint, the robotic arm can move at great speed and exactitude to make repetitive tasks such as welding points and painting. In the electronic industry, the manipulators place superficial assembly components with super-human accuracy, making the cellular telephones and the portable computers possible.

In spite of all these successes, these commercial robots suffer of a fundamental disadvantage: lack of mobility. A manipulator of this type has a limited rank of movement that depends on where it has been screwed. On the other hand, a mobile robot is able to cross a manufacture plant, in a very flexible way, applying its talents where these are more effective.

Mobile robots are classified by the used types of control or by the kind of environment in which they must evolve. In accordance with this last characteristic, it is possible to have the following mobile robots: Terrestrial, Aerial, Aquatic, Space [1]. Even within these categories there is a great variety, depending on the specific characteristics of means. For example, if the land is flat, a wheel robot is preferable to develop high speeds; if the land is irregular, a caterpillar robot can be the best election; nevertheless, if the land is very irregular, a legged robot is superb.

Robots are used in tasks that represent a risk for the human integrity or in those that are repetitive or tedious [2]. The robotic system proposed in this project is to be used where works represent some risks for human operators.

In the National Institute of Nuclear Research (Mexico) there exists the Materials Department (MD), who is in charge to yield support to PEMEX (Mexican Oil Company) for inspection and monitoring of its fuel reservoirs. For example, MD's personnel must realize periodically ultrasonic and visual inspection to determine corrosion and failures in spherical gas storage containers. A lot of these spherical containers are 16 m diameter, with a storage capacity of 15,000 barrels (Fig. 1).

Ultrasonic inspection may be made above the inside or outside surface, but visual inspection must be made on both sides. So, to access the whole surface of the container, scaffolding must be erected both inside and outside of it before start inspection works. It represents an important amount of the operation costs.

A spherical container is composed of a set of welded segments, whose welding ribbons must be visually inspected and by means of magnetic particles. In the container internal illumination is null, so, artificial illumination must be provided to illuminate the current inspecting region. Ultrasonic inspection requires ultrasonic transceiver be placed normally to the testing surface to a distance from 0 to 3 cm. These two conditions are crucial for the inspection process.

Fig. 1.- Spherical gas storage container with scaffolding for visual and ultrasonic inspection.

PEMEX has near 90 spherical gas storage containers installed to store LP gas, butane, isobutane and propane in the country. In raison of that, the ININ has an important potential market, so, it is important to own an inspection system as that here proposed to eliminate the expenses produced by stands location.

2. Problem Formulation

There exist several mobile robots that have been developed to climb walls. Some of them use vacuum to produce adhesion forces, others use magnetic elements to stick to ferromagnetic walls (as in the case here described) [3]. Other robot (Clarifying Climber [4]) employs patented “tornado in a cup” technology from Avionic Instruments to scale and navigate on almost any surface, such as brick, wood, glass, stucco, plaster and many other more. The Climber can transition from horizontal to vertical and back again without assistance. It can travel with “head in low”, for example when navigating on ceilings.

For the inspection system described here a quadriped climbing robot is being designed . The four robot’s feet will be provided by magnetic elements in its extremityes to allow the robot adher to ferromagnetics walls and ceylings. In this way, 4Steel-Robot will be able to follow the internal and external surface of the container.

In order to be used to carry out ultrasonic and visual inspections taks, the robot must transport on board several equipement (CCD camera, ultrasonic transducers, delivering system to provide coupling gel, wireless communication devices, etc.).

There exist commercially available several devices to accomplish these type of works, but the solution of mobility proposed here, is an option to reduce spended energy when robot moves.

The design of these devices currently in labors is based in the usage of magnetic wheels. In the case of the robot here presented, the idea is build a quadriped robot using legs provided of permanent magnets in their extremities. The goal of this approach is not spend energy when robot is in a steady configuration.

3. 4Steel-Robot, An Alternative Solution

Mobile robots need locomotion mechanisms that enable they to move unbounded throughout its environment. In general, most of these locomotion mechanisms have been inspired by their biological counterparts [5]. Nevertheless, there exist a paramout exception, the actively powered wheel is a human invention that achieves extremely high efficiency on flat ground. This is the main raison why there exist a lot of wheeled mobile robots in the research laboratories and in many real applications. Although wheeled mobile robots are more specialized and better adapted to flat surfaces, legged robots can be used in more general environments or even climb stairs [6]. The main disadvantage of legs to be used to locomotion is its mechanical complexity, which may include several degrees of freedom.

When working with legged robots, robots with six or more legs are prefered, because they have the advantage of static stability. It means that if three non-colinear legs stay on the ground at all times and if the robot's gravity center is within the triangle formed by the three legs on the ground, robot can stay without fall out the whole time. In a similar way, when robot moves, three non-colinear legs are on the ground at all times while three legs are moving to produce the step.

Four-legged robots are more difficult to balance, but are still fairly simple when compared to the dynamics of biped or single-legged hopping robots [5, 6]. A leg is composed at least of two degrees of freedom, but it may include several degrees of freedom in order to yields a higher maneuverability.

3.1 4Steel-Robot Cinematics

In the case of the robot here presented, a four-legs structure was chosen. In the general case, a leg is composed of three degrees of freedom, but here, each leg is composed of only a servomotor and a linear actuator, trying to maintain a reduced weight (fig. 2). Servomotors are easily interfaced and controlled, given that they need only two wires for alimentation and only other one to yield it a pwm signal. This signal indicates the required position, which is controlled internally by means of its built-in hardwired feedback loop. At other hand, if it is required to control position or torque, it is not possible, because the lack of external feeback [6].

Several gaits may be proposed using four legs (as for a horse, for example, walk, trot, canter and gallop). In general, the number of gaits that can be accomplished by a walking machine depends of the number of legs, and a gait have a specific pattern of leg movements. The total number of disctinct event sequences N for a legged robot is $N = (2k - 1)!$ [5]. For example, for the robot here proposed, $N = (2·4 - 1)! = 5040$. >From this very big number of events, it is necessary chose a useful sequence to produce a step.

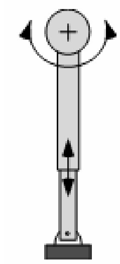

Fig. 2.- For 4Steel-Robot a leg is composed of only two degrees of freedom.

Any leg must be capable of sustaining part of the robot's total weight. The gait proposed for 4Steel-Robot implyes remain with at least three legs sticked to the ferromagnetic wall, as it is shown in figure 3. So, the body is displaced by a simultaneous mouvement of the four legs; this gait let us reduce the required power of the servomotors.

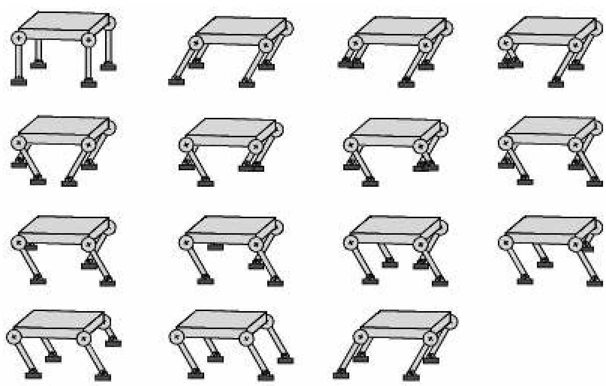

Fig. 3. The gait proposed for 4Steel-Robot unsticking only one leg at a time.

From the gait proposed for this robot it can be seen that when a leg is on the air, the gravity center is almost at the border of the supporting triangle. This is the case, for example in the third configuration of the robot in figure 4. For this situation, if robot is placed in an horizontal floor, and the gravity center is outside of the supporting triangle, it could fall to the side where the leg is on the air, but given that the legs stay sticked by the magnets, and overall the opposed leg, the robot will continue stable.

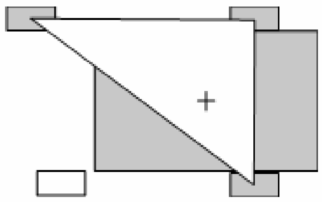

Fig. 4.- Robot with three legs sticked and the fourth on the air (top view).

The longer step of the robot is constrained by the maximum run of the linear actuator, which is of only 2.6 cm. So, in ordet ro avoid the friction of the limb against the wall, swing of the legs can't be of more than two times 32°. Then, the maximum advance of a step with this gait is less than 18 cms (fig. 5).

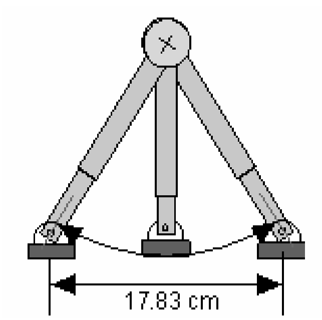

Fig 5.- Maximum swing of the leg is constrained by the maximum run of the linear actuator.

3.2 4Steel-Robot Hardware

As already mentioned, each leg is composed by a servomotor and a linear actuator. In the first version of this robot the employed servomotor is a HS-311 from Hitec, which may develop 3.3 kg/cm of output torque when feeded from 6.0 V. The linear actuator, at other hand, is alimented from a source of 12 V. with a consumption of up 3 A (linear actuators are as those used for lock and unlock the automobile's doors).

As mentioned before, to control the position of a servomotor it is enough to provide it a 50 Hz PWM signal (T = 20 ms). The whole swing of the motor is obtained with a width pulse going from 1.0 to 2.1 ms. Central position of the servomotor is obtained when width pulse is 1.5 ms. At the other hand, linear actuator is double acting and performs in two well defined states, extend and retract strokes For this linear actuator there is no way to control intermediate positions, however, for the purpose in this structure, it is enough to lift the leg.

To control the double acting of the linear motors, four DMOS full bridge driver L6203 are used. These power integrated circuits have a current capacity of 5A maximum peak current. All its logic inputs are TTL, CMOS and μC compatible, so, it may be driven directly from our Newmicros single board computer (SBC) NMIN-12A256B. This SBC is built around the 16-bit powerful microcontroller MC9S12A256 from Motorola. Some of the more important features of this μC are the following [7]:

16-bit HCS12 CPU,
256 KByte Flash EEPROM,
4 KByte EEPROM,
12 KByte RAM,
8-channel, 10-Bit Analog-to-Digital Converter,
8 PWM channels,
Up to 50 GPIO lines,
Two Asynchronous Serial Communication Interfaces
etc.

3.3 Software to control the Robot

4Steel-Robot was designed to work as a teleoperated robot. Its operation is based fundamentally in two programs, the one programmed in Java and running in a PC, and the second one in Max-FORTH and running in the NMIN-12A256B board.

Max-FORTH is a derivative of FORTH programming language, and it is exclusively used with NMI's product SBC only. A unique feature of FORTH, and Max-FORTH, is it simplicity to learn, to use, and to understand [8]. FORTH is built around the concept of a stack, a storage mechanism which allows any number of items of information to be stored and retrieved [9]. Forth is an interactive computer language that let the user input data and process them knowing inmediately the results. This feature permits to the user program a piece of code and test it interactively with the computer. Newmicros SBC works in this same way by means of Max-FORTH interpreter placed in its Flash EEPROM.

Some functions coded in Max-FORTH (called "words") let establish the parameters for the operation of the PWM's and other resources contributed by the MC9S12A256 microcontroller.

To control the servomotors of the four legs, four PWMs of the NMIN-12A256B board are employed, and they are used to generate the signal mentioned in section 3.2. To control the four linear actuators an other PWM is employed in conjunction with four output pins to select the state of each actuator (extended or retracted). This PWM is used to generate a 50% duty cycle signal in order to avoid saturation currents in the motors of the linear actuators.

Figures 6 and 7 show two pieces of code writen in Forth to control the 4Steeel-Robot.

```
// High level output for the duty cycle
: SET_POL      // Name of this word (subroutine or function)
    FF         // Value to establish high level polarity (1111 1111)
    PWMPOL     // Address of the MC9S12A256 polarity register ($A1)
    C!         // Forth word to write eight bits
;
```

Fig. 6.- A Forth word to set output level polarity for the PWMs.

```
// Start of the PWMs of the MC9S12A256, with a frequency E/128,
// maximum period $FF (default) and 7% duty cycle (13H)
// to set the servomotors in central position

: INIT_PWMS
    PRESET_CLKA&B     // Pre-scaling the whole clocks of the PWMs
    SET_CLK_A&B       // Scaling clocks ClkA y ClkB
    SELECT_CLK_SRC    // Clock select for the PWMs (SA y SB)
    SET_POL           // Polarity of the PWM pulse
    PWENABLE          // PWMs enable
    8 0               // initial and final indexes for the loop
    DO                // DO loop
      13 I PWDUTY     // Neutral position of the servomotors (~ 2 ms)
    LOOP              // DO loop end
;
```

Fig. 7.- Forth word to init the working of the PWMs.

3.4 Software for the Teleoperation Base

4Steel-Robot is intended to be teleoperated by the technicians in charge to realize visual and ultrasonic inspections of gas containers. So, in order to provide them the way to control the performance of the robot, a graphical user interfase (GUI) in Java is at this moment developped [10]. This GUI will contain a window to display the image taken by the robot camera, a graphical representation of the ultrasonic readings and controls to let the operator place the robot at the desired position. Other window will let the operator watch where the robot is currently placed.

At the present time, the program developped for this project let control the displacements of the robot with the purpose to test the performance of the gait proposed. The program contains some arrays where the positions of the servomotors are defined in order to produce the walking (in a similar way as that defined in [6], pp. 189). Other similar structure is used for the control of the linear actuators. Figure 8 shows a portion of Java code to define the call of Forth word PWDUTY that serve to control the position of the servomotor to produce forward or backward movement. As one can see in figure 8, the execution (better said interpretation) of PWDUTY needs two parameters, a hexadecimal value to specify position and the number of the PWM whose the servomotor is attached. The string composed in this way is sent to the NMIN-12A256B board via a serial wireless link.

```
final String FW = "19 ";
final String BK = "0E ";

String gait[] = {FW + "1 PWDUTY",   // Positions of the servos
                 BK + "5 PWDUTY",
                 FW + "7 PWDUTY",   // to advance or go back
                 BK + "3 PWDUTY",
                 BK + "1 PWDUTY",
                 FW + "5 PWDUTY",
                 BK + "7 PWDUTY",
                 FW + "3 PWDUTY"};
```

Fig. 8.- A piece of Java code of the program developped to control the robot from the teleoperation base.

These strings are sequentially sent to the robot while it must keep moving; a delay is inserted between two PWDUTY commands to give the servos time to assume the specified positions; it is the same case for the linear actuators.

When robot is turned on, it comes to its initial configuration (first pose in fig. 3). After, if forward motion is commanded, to advance all the servomotors are activated in such a way to push the body ahead. Subsequently, the next actions are executed over each leg:

Leg up → Leg swing → Leg down

After that four legs have been advanced, the four servomotors are simultaneously activated in such a way to advance newly the body (two last poses in fig. 3).

Before lift a leg, it must be detached from the ferromagnetic wall, for this an opposed magnetic force is generated. For this purpose, a current is feeded through an electromagnet around the limb of each leg. This part of the robot is in developping and will be tested later.

In relation to the communications, two serial links are supported by the Java program in order to send commands to the robot and receive data and visual information from this one. The whole system may be depicted as in fig. 9.

Fig. 9.- The graphical user interfase to control the robot performance and display data and visual information.

At this date the performance of the gait proposed for this robot is being tested, and several other features are being developed.

4. Conclusion

In this paper we have presented a four legged robot that is intended to be used as a tool to carry out inspection tasks in gas containers. This machine will be very useful in these works when it will be used to access remotely very high sites, reducing in this way the risks for the technicians in charge of the inspections.

At this date, the robot may move and several experiments are being accomplished to determine the performance of both the gait proposed and the implementation of the legs beginning from the utilization of a servomotor and a linear actuator.

The programming languages chosen have proven be easy to use, Max-FORTH to program the words (subroutines) to make work the MC9S12A256 Motorola microcontroller, and Java to implement the GUI from where the robot is going to be commanded.

This system is being designed and built to be used by technicians of the Materials Department of the National Institute of Nuclear Research (Mexico) for the purpose of examining large steel gas containers.

In parallel to the designing and construction of this robot, an other quadriped robot is being built using only servomotors. Next a comparison between both robots will be made.

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