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SURFY: A LOW WEIGHT SURFACES CLIMBING ROBOT
(Design, Control, Assembly and Preliminary Tests)

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Abstract: Climbing and Walking Robots can be used to resolve some problems of maintenance, inspection and safety in industry. The first prototypes already developed have proved able to perform tasks in hostile environments and serve as a work platform for manipulators in inaccessible areas. The inspection of storage tanks is a task that has been standardised by the American Petroleum Institute, with the API Standard 653. This paper describes the design and the construction of a prototype climbing robot and reports the results of various motion trials performed on walls of different inclinations and of different materials to verify the correct functioning of the movement and of the adhesion system used.

Keywords: Climbing Robot, NDT Controls, Fuzzy Logic, Pneumatic systems, Industrial Inspections.

1 INTRODUCTION.

The commercial applications of robots which can walk and climb were first evaluated by the nuclear and space industries which identified the tasks of maintenance and inspection in environments intrinsically hostile to man. Until now, research into the development of these particular robots has concentrated on these applications and, particularly in Europe, the nuclear industry has had a primary interest in their future development.

These robots should be able to move with some reliability inside indeterminate environments, employing a certain degree of autonomy to assist the operator. Further, the machines are required to be light, to have a high force-weight ratio, to be able to adapt to changing situations in an intelligent way, to be able to climb up vertical surfaces, to cope with floor-wall and wall-ceiling type transfers, and to be able to avoid obstacles. Clearly it is not necessary that each single machine is able to perform all these tasks, especially since many applications require only one or two of these abilities. It is evident that climbing and walking robots can be used for some problems of maintenance, inspection and safety in industry. The first prototypes have proved capable of carrying out tasks in hostile environments and of serving as work platforms for manipulators in inaccessible areas.

The success of the first prototypes, however, has indicated to industry which technology to use. All this, coupled with the increased attention given to problems of safety and health in the work-place, has persuaded industry of the potential benefits afforded by the future development of these technologies. Other environments dangerous for human operators have also been identified, for example the increasing number of off-shore platforms in the petroleum industry and the inspection of high structures (such as storage tanks for petroleum products), which have delineated the characteristics of the robots which can operate intelligently in hostile environments.

The problem of safety in industrial plants of any type is now the principle concern of those operating in the sector. An industrial storage tank, for example, can contain extremely corrosive petroleum products and is highly exposed to the action of atmospheric agents. The inspection of storage tanks has been standardised by the American Petroleum Institute, with the API Standard 653. This standard specifies the type and the frequency of inspections in great detail. Among the most important factors to be inspected are the rate of corrosion, the potential risk of air or water pollution and the detection of leaks, etc. The interval between inspections depends on the particular site, but the standard recommends a maximum interval of one month.

To evaluate the degree of corrosion of the metal plates, periodic inspections are made using equipment to control their thickness and integrity. It is precisely in the prevention of accident risk in the storage of petroleum products in reservoir tanks that non-destructive tests (NDT) have assumed a strategic role, allowing the measurement of thickness and the evaluation of integrity without causing any damage to the area under examination. The primary necessity is, therefore, that of positioning the sensors and the measurement and transmission systems; a pay-load of a few kilos which is a little more than 300 mm x 300 mm in size.

The need to perform periodic inspections of the metal shells of industrial storage tanks, together with the need to reduce the cost of performing them, has directed research towards new equipment, remote controlled and able to perform the measurements autonomously, which offers advantages in terms of cost and safety. The aim, therefore, was to design a robot able to:

- hold itself up on a vertical wall, even on a cylindrical surface with a large radius of curvature (such as that of the shell of a storage tank);
- advance step-by-step in a given direction;
- change direction.

In the trials, the robot will be equipped with a system suitable for carrying an ultrasonic probe or other NDT equipment, which can evaluate the thickness and the integrity of the metal wall.

2. STRUCTURAL DESCRIPTION.

The robot (Figure 1) basically consists of two bodies: one external which supports a plate for the transport of the pay-load, and one internal which is connected to the former by guide rails and is able to traverse longitudinally with respect to it (both the bodies have four suction cups to anchor them to surface they move over). The longitudinal traverse of one body with respect to the other allows the robot to take a step in the direction of movement: when the external body is attached to the surface by means of its four suction cups, the internal body is raised from the surface by a pneumatic actuator, and is moved along the guide rails by a second pneumatic actuator. Vice versa, when the internal body has completed its longitudinal movement and has been lowered onto the surface and anchored by its own four suction cups, the external body is raised by the same pneumatic actuator and is moved along the guide rails by the second pneumatic actuator.

As well as advancing in a straight line, the robot can rotate around its vertical axis and change direction of movement. To change direction, the internal body of the robot consists of two telescopic cylinders, which can rotate with respect to each other (using an electric motor mounted on the lower cylinder and with the axis integral with the upper cylinder). When the lower part of the internal body is anchored to the surface and the external body is raised, the upper cylinder of the internal body is rotated with respect to the lower cylinder, so that the whole of the external body rotates (since it is integral with the upper cylinder of the internal body through the guide rails). Once the external body has been rotated it is lowered and anchored to the surface, the lower cylinder is then raised and realigned with the external body (again by means of the electric motor). At the end of this sequence of operations, the robot can advance in the new direction. The desired speed was one step every 2 s, corresponding to 100 mm/s, being a step of about 200 mm, in order to reach the top of a storage tank in few minutes and to limit the power of the pneumatic actuator.

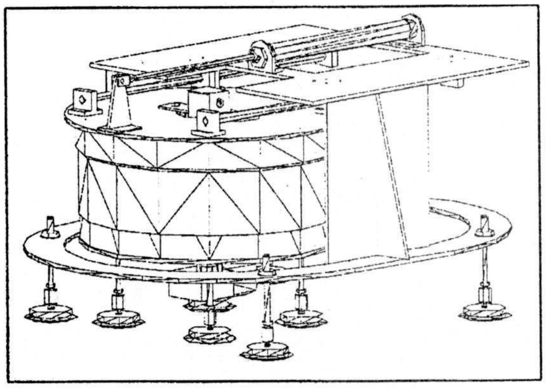

Figure 1. Rising Robot

Plexiglas (density 1,200 kg/m^3) was chosen for the construction of most parts of the robot, in order to obtain a lightweight structure. Before establishing the dimensions of the various parts, some test pieces of the Plexiglas were produced. A test machine and strain gauge techniques were used to verify their mechanical characteristics, given the considerable variability in materials of this type. The mean values found were: elastic modulus E = 3040 MPa, UTS = 57 MPa.

The suction cup was made to adhere to the surface of a painted steel plate. The suction cups were tested using a pneumatic circuit consisting of a mini vacuum pump, delivering a maximum vacuum of 210 mbar, an air-filter and the suction cup. Three different trials were performed (Figure 2):

1. horizontal plane of attachment with a force of vertical traction F_3 applied;
2. vertical plane of attachment with a vertical shear force F_1 applied;
3. vertical plane of attachment with a couple (F_2*a) applied.

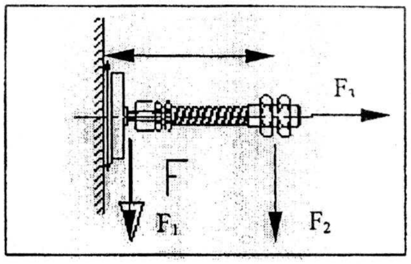

Figure 2. Suction cup tests.

The forces and the couples to be applied to each single suction cup were calculated as a function of the real weight of the robot, of the payload, and of the weight of the electric and pneumatic cables connecting the robot to the ground control station. Particularly, the torques were calculated in the two following cases:

1. upper part rotating around the inner part constrained to the surface ($M_t = 3.32$ Nm)
2. inner part rotating when the upper part is constrained to the surface ($M_t = 5.53$ Nm).

The great difference between the values depends mainly by the position of the electric and pneumatic cables.

The dimensions of the most critical elements of the robot were optimised using a finite element programme, so that the weight of the robot could be optimised without compromising a reliable degree of safety. Principally, the plates and the telescopic cylinders were calculated, basing on the maximum deformation allowed to avoid the gripping.

The final weight of the structure is 6.5 kg; the weight of the pneumatic actuators and electric motor with reduction gear is about 5 kg. Considering about 3.5 kg for accessories (compressed air pipes, power cables, electronic boards, etc.), the total weight of the robot is about 15 kg, with a platform for the pay-load (max. 5 kg).

3. CONTROL SYSTEM.

A block diagram of the control system is reported in Figure 3.

The system is composed by two main parts: a remote station and a local controller that communicate by using a serial interface. The remote station is based on a normal personal computer which constitutes the user interface with the robot. Using this interface, the operator can control the motion of the robot and carry out the required remote measurements.

The local controller is the subsystem devoted to the communication with the user interface, the control of the pneumatic valves for the pistons, the control of the valves for the suction cups, the measurement of the vacuum sensors, and the control of the position of the DC motor for the rotation of the internal body with respect to the external body.

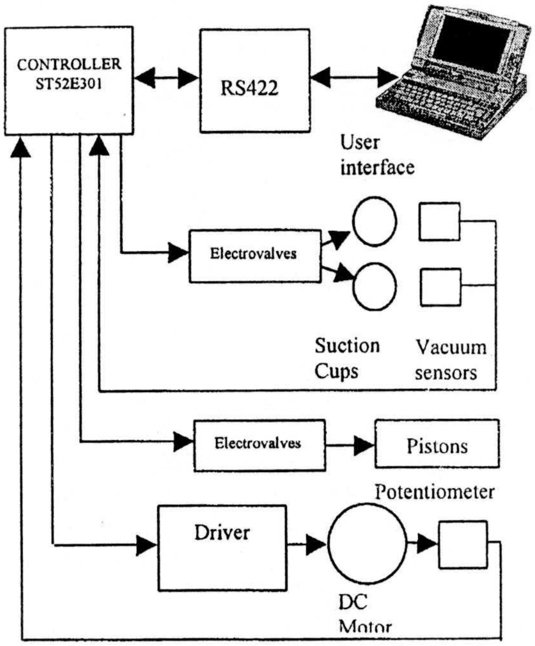

Figure 3. Block diagram of the control system.

The control of the pneumatic part is performed by digital valves, but the vacuum pressure is measured each time a group of suction cups is attached to the surface, in order to be sure that adhesion is guaranteed. The control of the position of the DC motor is achieved by using a Fuzzy PD controller that controls the rotation on the basis of the error between a reference transmitted from the remote station and the measurement of the position by means of a potentiometer.

An ST-Microelectronics micro-controller ST52E301 (formerly WARP3) was adopted for the hardware implementation of the local controller. The processor is a mixed digital/fuzzy micro-controller which directly acquires analog signals, processes them following fuzzy or digital rules and gives a PWM control signal with the required duty-cycle or a digital output. Table I summarises some of the particular characteristics of this processor. The micro-controller can be programmed in a graphical manner using the software tool FUZZYSTUDIO 3, without the need to write code.

4. ROBOT ASSEMBLY.

In order to perform the experimental trials, it was necessary to assemble the robot, from the mechanical point of view, and to complete it by installing the electronic hardware. The completed robot weighs about 15 kg with a useful pay-load of 5 kg. The dimensions are 300 mm x 600 mm x 400 mm. Subsequently the ground station for pneumatic control (compressor, pressure regulators, manometers and vacuum pump) was set up.

High speed dedicated structures for Fuzzy Logic (3.5 s to compute a 4IN X 1OUT rule)
Up to 4 Input, 2 output Configurable Variables for each fuzzy algorithm and up to 300 rules.
Up to 16 Triangular and Trapezoidal Membership functions for each input variable.
Up to 256 Singleton Membership functions for all consequents.
Program and data EPROM 2 Kbytes.
16 general-purpose registers.
Capability to perform simple Boolean and arithmetic operations.
Working Clock Frequencies 5, 10, 20 MHz.
On-Chip Clock Oscillator.
One External Interrupt.
Standard TTL inputs.
CMOS compatible output
4 Channel 8 bit Analog to Digital converter.
Digital 8 bit I/O port independently programmable.
Serial Communication Interface with Asynchronous protocol (UART).
Programmable Timer with internal prescaler.
Internal Power Fuzzy Control to drive external TRIAC.
Internal Fuzzy controlled PWM to drive an external power device.

Table I. Main features of ST52E301 processor.

Finally the robot was connected to this pneumatic control unit and to a personal computer. Software, written in visual basic, was installed on the PC so that the robot could be commanded stepwise or be made to execute a complete series of steps. Once the final designs had been drawn up, the various parts were manufactured by companies specialising in working materials such as Plexiglas and PVC. At the same time, the necessary components for the robot's movement (electrovalves, suction cups, suction cup holders, vacuum pump, manometers, pressure regulators, etc.) and the actuators defined during the first design phase (pneumatic micro-cylinder, tandem pneumatic cylinder, electric motor and reduction gear) were purchased from commercial suppliers.

In Figure 4 it is possible to observe (from the bottom towards the top) the steel guides for longitudinal movement, the pneumatic micro-cylinder, the tandem pneumatic cylinder, three electrovalves mounted on a pneumatic distribution junction block, the electric motor with the mounted reduction gear.

Together with the electric motor (E), Figure 5 shows the two Uni-Lat joints (B and C) used to connect, on one side of the reduction gear (D), a potentiometer (A) required to control the rotation of the axis of the reduction gear, and, on the other side, the axis of the tandem micro-cylinder integral with the internal body of the robot. The Uni-Lat joint is a particular type of junction, very similar to the Oldham joint, but with an additional advantage. While the Oldham joint is used to transmit the movement of rotation between two parallel but not coincident axes, the Uni-Lat joint is used to connect two non-coincident skew axes.

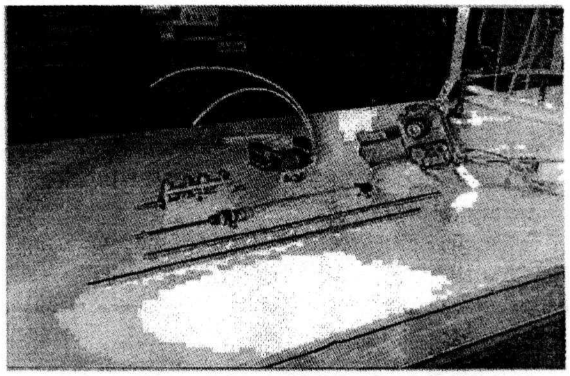

Figure 4. Components utilised in Surfy.

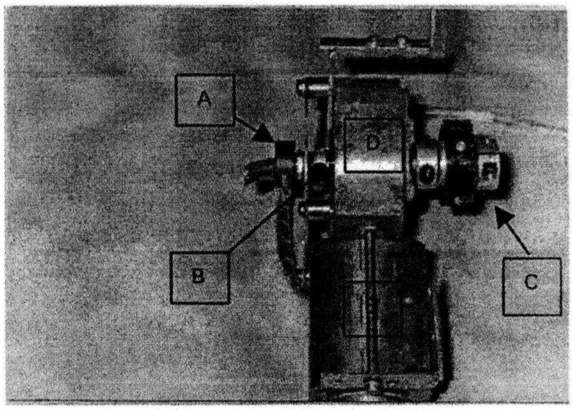

Figure 5. Electrical motor, reduction gear and joints.

The technical characteristics of the actuators are reported below:

Voltage	12 V cc
Nominal velocity	4200 RPM
Nominal couple	28.6 N/cm
Power	20 Watt
Reduction gear	Coupling: Toothed gear - endless screw
Reduction ratio	70:1
Weight (Motor + reduction gear)	1.2 kg

Table II: Electric motor and reducing gear (Lucas Motor)

Feed pressure (bar)	4	5	6
Maximum degree of vacuum (mbar)	350	160	110
Air consumption (l/s)	0,54	0,57	0,6
Air intake (m^3/h)	12	13,5	15
Operating temperature (°C)		-20/+80	
Weight (kg)		0.6	

Table III: Vacuum pump PVP 12M (Vuototecnica)

Micro-cylinder from Pneumax (basic version), with 20 mm stroke, weight 120 g, max feed pressure of 6 bar and magnetic cylinder (for course verification).

Tandem micro-cylinder with opposed pistons from Pneumax, first piston stroke of 10 mm, second piston stroke of 10 mm, weight 160 g, max feed pressure of 6 bar and magnetic cylinder (for course verification).

Particular attention was also paid to the construction of the two telescopic cylinders making up the internal body of the robot. To minimise the friction between the surfaces of the two cylinders under load, a particular construction was implemented. The internal surface of the external cylinder was lined with a 0.2 mm thick steel sheet, while slits were cut in the internal cylinder. These slits were 18 mm wide, almost as long as the entire generatrix of the cylinder and distanced 40 mm apart. Hollow steel cylinders were inserted in the slits, creating a large cage of cylindrical rollers. In this way the two cylinders act as a large roller bearing with a steel-steel contact, providing a friction coefficient considerably lower than that of a PVC-PVC contact.

5. EXPERIMENTAL TESTS.

To verify the effective functioning of the robot, several tests of movement were performed on horizontal, inclined and vertical surfaces. The first trials were successful and at the same time highlighted the need for small adjustments to optimise the machine. The main problems were the friction between the two cylinders that causes grip in the relative motion and the need to insert some a spring on the support of any external suction cup in order to assure the contact to the surface. Once the robot had been assembled and connected to the ground control station, the first movement trials were performed. To test the correct functioning of the robot, the first tests were carried out on a flat surface. The robot was made to move forwards and backwards for several steps, and the rotation necessary to change the direction of movement was tested.

The first trials on a surface of painted wood inclined at about 75 degrees were then undertaken (Figure 6). Trials of rotation for the change in direction in movement were then carried out on the same surface placed in a vertical position (Figure 7).

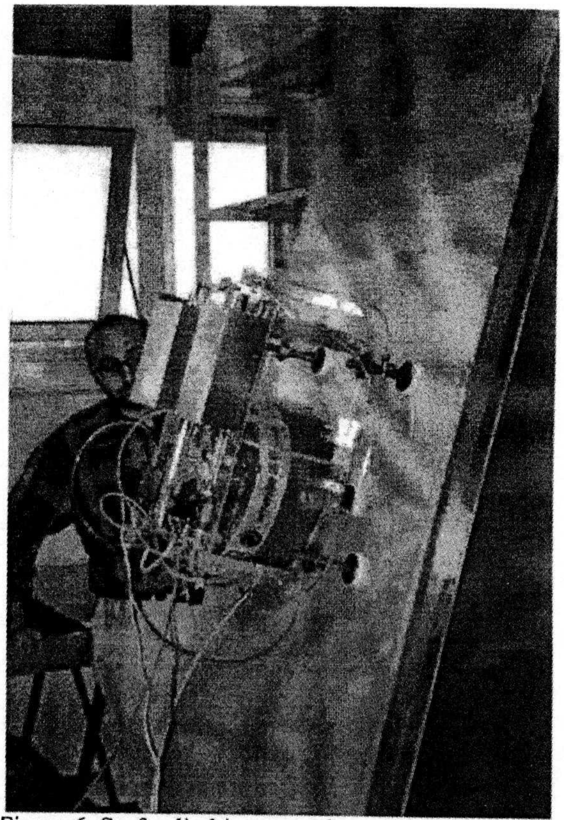

Figure 6. Surfy climbing on a almost vertical painted wood surface (75 degrees).

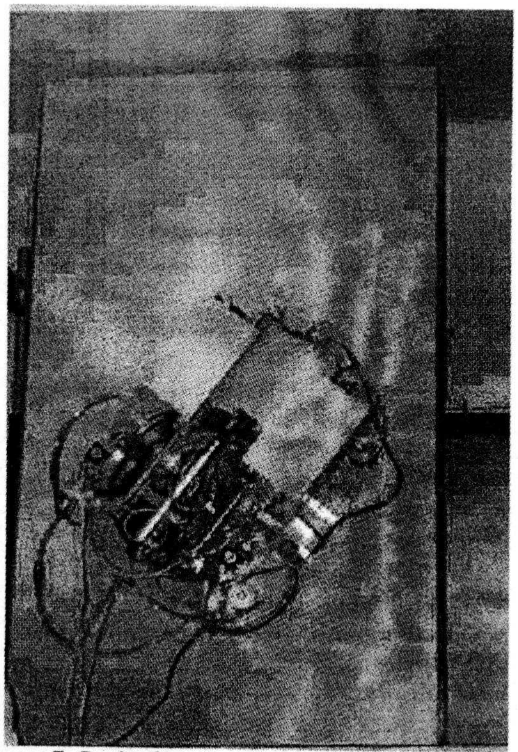

Figure 7. Surfy changing direction of movement on a vertical painted wood surface.

The last trials were performed on a surface of a more rough material, the painted steel panel door of the laboratory (Figure 8) to verify the reliability of the contact in a condition similar to that of a storage tank. All the test performed gave good results, in all cases no suction cup did leave the contact and the programmed motions were accomplished.

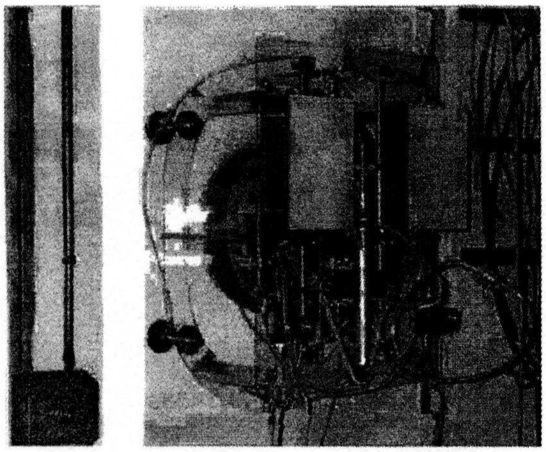

Figure 8. Surfy climbing on a vertical painted steel panel door.

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