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Wall Climbinbg Robot for the Inspection and Maintenance of Buildings

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ABSTRACT

The inspection and maintenance of buildings and other structures constitutes a significant proportion of the workload of the construction industry. Difficulties associated with access, risk of injury and costs, point to the need to reduce human involvement and look for means of automating these activities. In this paper conceptual requirements are identified and robotic devices designed and produced at Bristol Polytechnic for this purpose are discussed. The latest prototype is described including the enabling technologies such as delivery mechanisms, control and communication systems, adhesion mechanisms and the vehicle structure. Tests using the robot are described, including experiments using a cover meter mounted on reciprocating mechanisms to feedback data (computer interfaced) on re-bar cover and position.

1. INTRODUCTION

The Construction Industry is one of the largest in the United Kingdom with a turnover approaching £40 billion per annum. Approximately 40% of this work is concerned with maintenance and refurbishment. The industry generally is labour intensive, tending to place its emphasis on maximising output per employee. This is particularly true of maintenance and refurbishment. Research indicates that the annual investment in maintenance, repairs and refurbishment is in the region of £15 to £18 billion pounds per annum. Buildings generally have a relatively long life and require inspection of both the structure and the fabric on a regular basis, and although it is extremely difficult to determine the actual cost of this function it is estimated to be in the region of £250 to £300 million per annum. It is also difficult to assess the cost of not inspecting buildings. Clearly regular inspection could substantially reduce the annual expenditure on repair and maintenance.

The inspection of the existing stock of buildings and structures is carried out in a hostile and hazardous environment that creates a high level of risk from a safety viewpoint due to difficulties of access particularly to multi-storey buildings and buildings that may be contaminated e.g. nuclear power stations.

A feasibility study[1] undertaken for the UK Department of Trade and Industry by CIRIA - the Construction Industry Research and Information Association between May 1986 and July 1987 identified the inspection of civil engineering and building structures as having the greatest potential for developments in automation and robotics.

Safety statistics[2] for the period 1981 to 1985 showed that maintenance activity accounted for between 34% and 50% of the total number of fatal accidents in construction and that of these 30% were caused by falls from scaffolds with 20% as results of falls from ladders. Apart from the human factor, accidents of this nature have substantial financial consequences for the industry.

2. THE WALL CLIMBING ROBOT, SISYPHUS

2.1 Introduction

The first proto-type wall climbing robot - Sasquatch (Figure 1) - designed at Bristol was reported in Advance[3] and created considerable interest at the Automan Exhibition held 14th to 17th May 1991 at National Exhibition Centre, Birmingham, UK. This paper describes the second proto-type - Sisyphus - and the way it has been used as a test bed for a range of inspection tools.

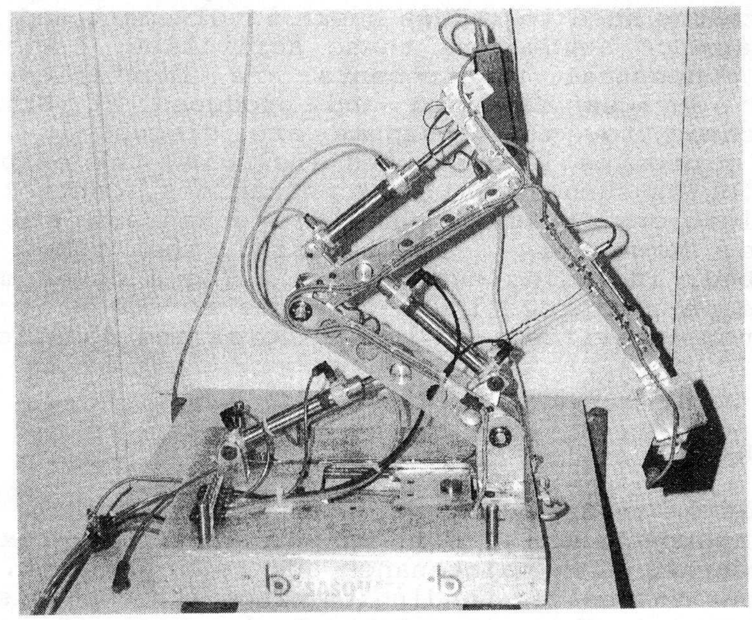

Figure 1.

2.2 Design Concept

Sisphus was designed to carry instrumentation for measuring defects in structures and tools for carrying out remedial work. To achieve this the following criteria were established. The robot should:

- be able to travel quickly to the points requiring inspection using the long stroking piston
- be able to move in smaller steps with the short stroking pistons when using the measuring equipment
- turn, incrementally, on it's own axis
- have as high a power to weight ratio as possible so that reasonable payloads can be carried and to ensure that the robot is as stable as possible when using the tools and end effectors fitted to it
- enable the tools and measuring equipment to be easily fitted and interchanged
- be able to check the feet for vacuum so that if any foot cannot get a grip, a decision can be made to either short stroke it to another position, or to assess the possibility of making the foot redundant for that particular move

- carry the pneumatic controllers on the robot so that pressure losses are kept to a minimum and the weight of the umbilical, which can be significant on tall structures, kept as light as possible.

3. HARDWARE

3.1 Configuration Vehicle Structure

The robot (Figure 2) is built on a framework of 12mm steel tube, the overall dimensions being 790mm x 440mm x 155mm. There are a total of 8 short stroke vacuum feet, 4 on each side, each foot being able to move laterally 20mm and vertically 25mm. The movements for all feet are independently operable with pneumatic cylinders. There is a central assembly consisting of 4 vacuum feet. A pair of air cylinders are used to move the central foot assembly forward and backwards with a stroke of 200mm. A subsidiary piston is also fitted which will rotate the central foot assembly. Control of the pneumatic system and ejectors used to create the vacuum for the vacuum feet is from 12v solenoid valves mounted on the chassis.

It was decided to have this number of independently movable feet so that, various climbing strategies could be investigated and used. The robot can climb a structure by long stepping - using the 200mm pistons, or short stepping - using the 20mm pistons. There is also the option of making feet redundant where a grip cannot be obtained i.e. over a crack or defect in the cladding. A step over mode has also been designed but this has not been incorporated in this robot to date.

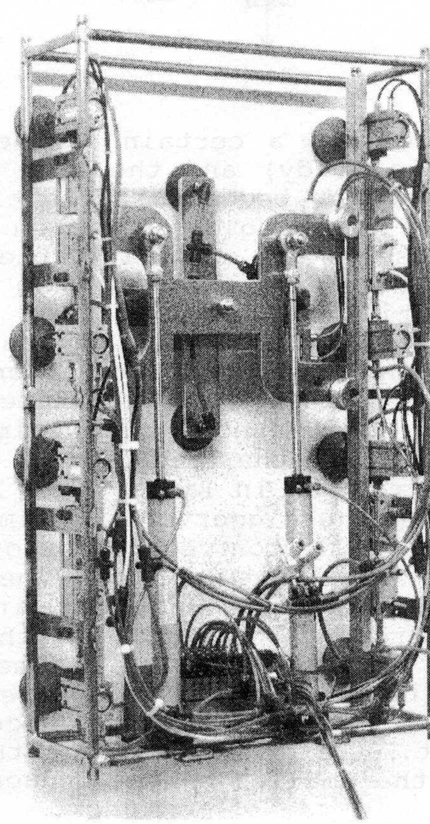

Figure 2.

The vacuum feet used are silicon rubber, 54mm Diameter, with 1½ bellows, initial tests showed that they would adhere to the target surface, which was precast concrete, and would form around defects in the surface of approximately 4mm deep. A vacuum sucker is currently being developed at Bristol Polytechnic which uses pressure to give a better form around defects.

3.2 Assessment of Sustainable Vertical Loads on a Vacuum Foot

In order to assess the vertical loads which might be sustained by a single sucker of 50mm diameter, the set up shown in (Figure 3) was used. It consists of a metal crank of certain crank distance (only two distances were attempted: 52mm and 71mm). The top end of the crank was clamped between the upper jaws of the test machine, and the bottom end was clamped using an angle mounted on the surface of the concrete cube.

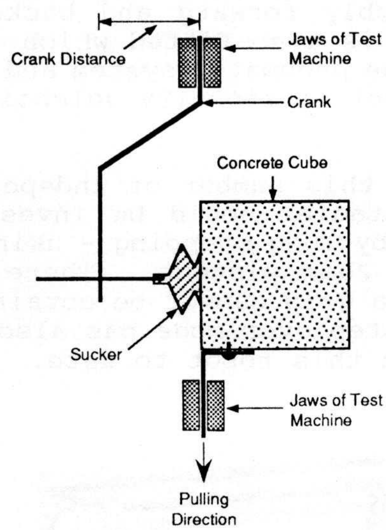

Figure 3. Test Setup

The sucker was first subjected to a certain degree of vacuum (which is taken as a parameter in this study) and the cube moved downward. The ultimate load at which the sucker becomes ineffective is recorded. For comparison purposes, the test was also conducted on a metal plate instead of the concrete cube. The results are shown in Tables 1 and 2 for 52mm and 71mm crank respectively. It can be seen that on the metal plate, the vacuum remains unchanged until the ultimate load is attained. On the concrete cube, the vacuum remains unchanged until a load of a value less than the ultimate load of 5 Newtons is reached. Then the vacuum decreases by almost 100mmhg, the load fluctuates for a minute or so, then both the vacuum and the load pick up again until the ultimate load is reached. Therefore, it is advisable to limit the load figures on concrete to a value 5 Newton less than the values shown in Table 1 and 2.

Table 2 shows that using the bigger crank (71mm) there is a maximum limit on the vertical load of 39 Newton regardless of the amount of vacuum used on concrete. Obviously this limit decreases when using a crank bigger than 71mm. This is because of the movement induced at the sucker interface. This distance represents the length of the grippers in the wall climbing robot. This limit did not apply on the metal plate because the vacuum remains intact which is not the case on concrete, perhaps due to its porosity. This porosity effect is more critical under the combined action of vertical load and moment. It did not affect the results in table 1 (smaller crank) because of the smaller moment induced.

VACUUM (mm hg)	ULTIMATE VERTICAL LOAD (52mm crank)	
	METAL PLATE (Newton)	CONCRETE (Newton)
600	55	50
500	49	45
400	45	41
300	43	36
200	34	30

Table (1) Ultimate vertical loads sustained by a sucker of 50mm diameter using 52mm crank.

VACUUM (mm hg)	ULTIMATE VERTICAL LOAD (71mm crank)	
	METAL PLATE (Newton)	CONCRETE (Newton)
600	49	39
500	42	39
400	37	39
300	31	32
200	27	25

Table (2) Ultimate vertical loads sustained by a sucker of 50mm diameter crank.

In general, at any vacuum level, the load on the concrete was slightly less than that on metal plate due to the porosity of concrete. Smooth surfaced concrete will however yield loads equivalent to those obtained for the metal plate.

4. CONTROL SYSTEM

This is based on a system assembled at Bristol, using the STE bus. This was used to develop the control system on a PC using Basic or C, then down loading a compiled version to the STE controller.

STE bus systems are easily configured using standard boards, these are simply plugged into a STE bus back plate, with a power supply and peripheral devices such as keyboards and the system is then ready to run. The system configured for the robot incorporates

SC88T	Processor Board
DRAM	Dynamic RAM board, up to 512 KB
SPINC	Parallel 1/0, timers and interrupt controller
SADC 12/6	High speed, High resolution, A/D converter
SCB18	opto isolator input board
SCB16	Solenoid driver output
SCB2C	4-20 mA current input board

The programmes used are usually in the form of macro's, each built to perform the various moves required to monitor position sensors, operate traversing mechanisms for inspection tools and read the values from the sensors. The programme operates the I/O hierarchically so that safety monitoring ie checking the vacuum in the feet and the power supplies are the top priorities. It is anticipated that in the future this system will be interfaced to a CAD system for autonomous guidance.

5. SAFETY CONSIDERATIONS

If the power supply fails, then the solenoid valves go to a preset failsafe condition in which the side feet are in the up position with no vacuum, the centre feet are down with the vacuum on, so that the robot will stay on the wall. If the air compressor fails then the operator would retrieve the robot using the reservoir air in the compressor's receiver. As it is assumed that a lot of work could be carried out from the top down, the umbilical will incorporate a Bowden Cable which supports the robot if all the systems fail.

6. APPLICATION OF THE ROBOT TO INSPECTION WORK

6.1 Testing Techniques

There are, primarily, two methods of testing - destructive and non-destructive used in construction work. The first takes small samples of the component for further testing, for example, core sampling. The second method uses techniques which will not subject the surface being inspected to any deformation or mechanical damage. Non-destructive testing (NDT) is therefore more popular as the integrity of the surface of the structure is kept intact.

There are many NDT tests available, however it was decided to concentrate on the following test methods:

Test	Test Method
Presence, location, depth and diameter of re-bars	Covermeter
Compression Strength	UPV
Quality	UPV
Uniformity	UPV
Density	UPV
Sub-surface Voids	UPV
Honey-combing	UPV
Location of cracks	UPV
Moisture	Protimeter
Surface Profile	Distance Sensor
Visual Inspection	TV

Table 3: Test Methods

6.2 Mounting of Test Equipment

Most testing techniques require a mechanism to carry the inspection heads which produces a motion parallel to the surface being measured. A lightweight mechanism operated by a pneumatic piston has been produced which is mounted on a supplementary frame to give this motion.

(Figure 4) shows this mechanism and the arrangement used for mounting the UPV Transducers.

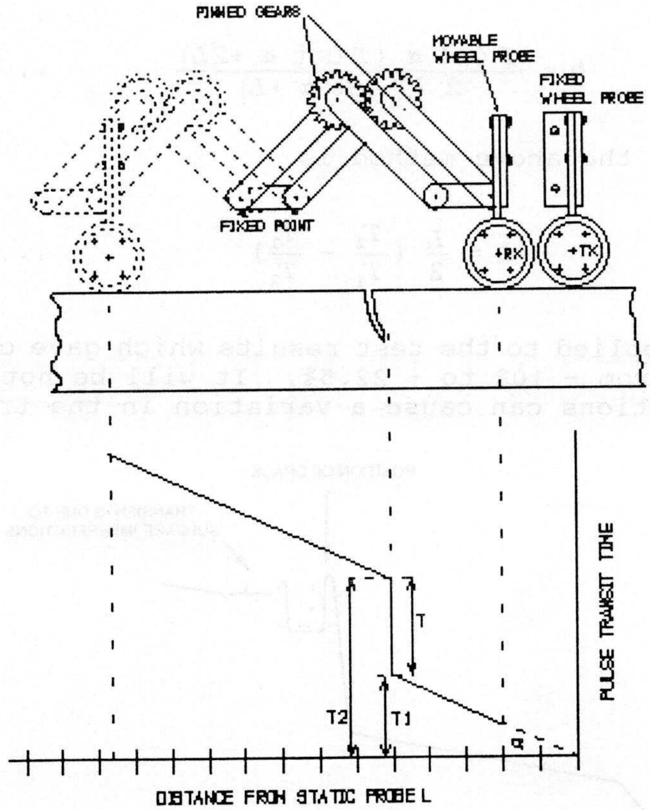

Figure 4. Parallel Mechanism

7. TEST METHODS

7.1 Ultra Pulse Velocity (UPV) Testing

UPV testing can be used to determine;

(i) The homogeneity of the Concrete
(ii) The position of cracks, voids and other imperfections
(iii) Changes in the concrete which may occur with time (ie due to the cement hydration) or though the action of fire, frost or chemical attack.
(iv) The quality of the concrete in relation to specified standard requirements ie. its strength.

For the purpose of this research (i) and (ii) were considered the most appropriate.

In order to automate the process of UPV testing 80mm dia wheel probes, operating at a frequency of 78khz, were used. These allow the transmitter to be at a fixed position and the receiver to track along a 400mm length. Trials were carried out on a concrete test piece with a crack 300mm along its length. The crack was progressively cut deeper after each run.

7.2 RESULTS

(Figure 5) shows a typical profile of a chart recording for a test piece with a crack depth of 78mm. It can be seen that a steep rise in the transit time occurs at the position of the crack.

When standard transducers are being used in the indirect mode for crack detection the following equations can be applied to determine the crack depth.

$$h = \frac{T \cot \alpha \; (T \cot \alpha + 2L)}{2 \; (T \cot \alpha + L)} \quad \ldots\ldots\ldots \; 1$$

a simpler formula for the above method is

$$h = \frac{L}{2} \left(\frac{T_2}{T_1} - \frac{T_1}{T_2} \right) \quad \ldots\ldots\ldots \; 2$$

Equation 2 was applied to the test results which gave calculated crack depth error varying from - 10% to + 22.5%. It will be noticed from Fig 5 that surface imperfections can cause a variation in the transit time.

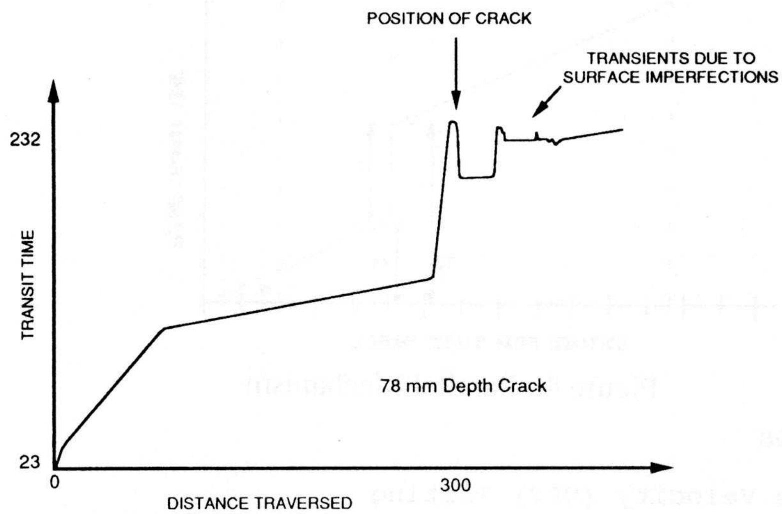

Figure 5. Output from UVP Unit

It is concluded that using roller transducers as a qualitative test, cracks can be readily detected in structures. However more work is required to determine crack depth using quantative methods.

7.3 Cover Meter

The cover meter was used to (a) locate the position of reinforced bars in concrete and b) accurately measure the depth of concrete cover to the bar.

To carry out (a) the measuring head, a directional search coil, is moved over the surface until a peak signal is obtained. (b) is measured by setting the cover meter to a known (or estimated) bar diameter, zeroing the instrument, setting it to depth and then, having placed the head directly over the bar, reading off the depth directly in mm.

For use with the robot the head was mounted on a subsidiary frame. Two methods of reciprocation have been tried, the first used a ball reversing unit, the second was the parallel motion unit described previously. It was decided that the parallel motion mechanism was the most appropriate for use with the cover meter. This mechanism can be easily built, it is adaptable, can be made 'in house' and was cheap and most importantly, light.

The cover meter has an analogue output socket so that the readings can be either output to a chart recorder or can be fed to an A/D converter for storage in the robot's control computer. It should be noted that as the sensing head will detect any metallic object in its immediate vicinity eg.

the robot frame and traversing mechanism. It was necessary to produce a 'look up table' of such readings, these are stored in memory and automatically deducted from the test measurements, in order to obtain reliable data from the concrete covered re-bars. It should also be noted that it is not necessary to have the head rubbing against the concrete, it can be held above the surface at a known height. This measurement can be deducted from the reading to give the actual cover.

To give maximum adaptability, the head should also be able to rotate around its centre point. Trials have been carried out on test sections with various configurations of Re-bar.

Typical data logger outputs are shown in table 4.

Typical output values:

Cover mm	**Output mV**
(117)	(280)
100	328
90	364
85	384
82	400
80	410
70	468
66	500
64	512
60	546
55	600
50	655
47	700
43	768
41	800
40	819
36	900
33	1000
32	1024
30	1092
26	1270
(25)	(1311)

Table 4: Data Logger Outputs

(nb: the first and last entries are for guidance only)

The (dc) output voltage ranges from 300mV to 1.27V. This voltage increases with a signal strength (bar proximity) and is directly related to cover by the equations 3 or 4

$$\text{signal (in mV)} \times \text{cover (in mm)} - 32768 \qquad \ldots\ldots \; 3$$

or

$$\text{cover (in mm)} - 32768 : \text{signal (in mV)} \qquad \ldots\ldots \; 4$$

Preliminary trials indicate that this method of scanning can be undertaken using the wall climber producing reliable measurement readings of both concrete cover depth and position of re-bars within the matrix, ultimately achieving a three dimensional 'image' of the test area.

CONCLUSIONS

Clearly the inspection of buildings is a hazardous and a costly process and providing access has been identified as the major component in the total cost of inspection[4]. It is considered that considerable savings in cost and the risk of accidents can be achieved by automating the inspection process.

The development of the wall climbing robot described in this paper at Bristol confirms that it is technically feasible to access buildings and obtain reliable inspection data in this way. Further work is continuing on the further development of the robot and its suitability for activities other than the inspection of buildings.

References:

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4. Radevisky RA, Garas FK, "Advanced Robotics in the field of Survey/Inspection Maintenance and Repair of Buildings and Structures", 5th International Symposium on Robotics and Construction, 6 - 8 June 1988, Japan.