A Climbing Robot based on Under Pressure Adhesion for the Inspection of Concrete Walls

K. Berns , C. Hillenbrand,
Robotics Research Lab, Department of Computer Science, Technical University of Kaiserslautern
P.O. Box 3049 Kaiserslautern, Germany – http//agrosy.informatik.uni-kl..de
Email berns@informatik.uni-kl.de

Abstract-- **The inspection of large concrete walls with autonomous systems is still an unsolved problem. One of the main difficulties is the development of a very flexible platform, which is able to move at horizontal and vertical surfaces. The platform also has to overcome small obstacles and cracks. In this paper a prototype of a climbing robot will be presented.**

Keywords-- **Climbing robot, mechatronics concept, concrete wall inspection**

I. MOTIVATION

A very interesting application area for climbing robots is the inspection of concrete walls like bridges, cooling towers or dams. E.g. almost 90% of all motorway bridges in Germany are made from reinforced concrete or prestressed concrete. The total number of these bridges is 32 300, the total length is 1197 km. The averaged age is 33 years. To maintain the stability, safety of traffic and durability of these bridges regular inspections are prescribed by law.

In Germany the test procedures and inspection intervals are fixed in the German standard DIN 1076. According to this standard inspections have to be performed every three years, main inspections have to be performed every six years and inspections after special occurrences have to be performed after earthquakes, crashes with vehicles, fires and other unusual stresses. To perform the inspection tasks complicated access devices are needed at the moment (see fig.1).

When scanning literature for these kinds of applications one can find different types of climbing robots with different adhesion principles. The 3 main classes which can be distinguished by their locomotion ability are [1]:

- wheeled-driven or chain-driven machines,
- legged locomotion,
- locomotion based on arms and grippers.

As adhesion principles for the locomotion on a concrete wall only under pressure can be used.

In the following the requirements imposed on a climbing robot for the inspection of concrete walls are given. Then based a thermo dynamical model of adhesion principles rules for the mechatronic design of such a machine are derived. The sensor system necessary to support the locomotion and the basic control behaviour is introduced. At the end of the paper first tests with the machine are described.

Figure 1: Device to access undersides of bridges.

II. REQUIREMENTS FOR A CLIMBING ROBOT

For applications as described above, the vehicle should be able to move horizontally, vertically and over side on slightly bended surfaces (radius 5 m). For the inspection task it is necessary to move continuously (not possible with sliding frame mechanisms). The machine should also be able to drive over steps of up to 2cm and a width of 2 cm. It should carry a maximum payload of 10kg and reach a speed of 10 m/min. The total weight of the machine should not exceed 30kg. Based on the required mobility the robot should have a turning cycle of less than 0.5 m and the diameter should not exceed 0.8m. For the use of such a machine a safety cable must be fixed on the robot. This safety cable can also be used for energy supply. Because normally an operator is not able to drive the machine from a base station using a joystick the machine must be autonomous in a way that the selection of control behaviors is done by itself.

III. THEORETICAL BACKGROUND FOR THE DESIGN

Based on the first law of thermodynamics we derivate the following equation which describes the relation between the change of pressure in a chamber and the volume of the chamber, the area of leakage and the flow rate area to the system which generates the under pressure. In the equation p represents the pressure, A_L is the area of the leakage, A_V is the area of flow rate, and V is the volume of the chamber. The terms p_a-p is the difference between the pressure outside the chamber; p-p_R is the difference between the chamber pressure and the pressure generated by the under pressure system.

$$\dot{p} = \frac{\kappa RT}{V}\sqrt{2\rho}\left[A_L\sqrt{p_a - p} \; - A_V\sqrt{p - p_R}\right]$$

It was calculated that for our above described robot an under pressure of 100 mbar is adequate to hold the machine on vertical walls as well as upside down. With the help of thermodynamics simulation it was shown that the under pressure is changed during 10ms to normal pressure when a crack is crossed with a leakage area of 2cm^2. Therefore "a one chamber system is not adequate for such type of climbing robot".

More chambers make the robot more robust regarding the roughness of the surface but at the same time increase the technical effort for its construction. As a compromise a 7 chamber system as shown in fig. 2 is selected.

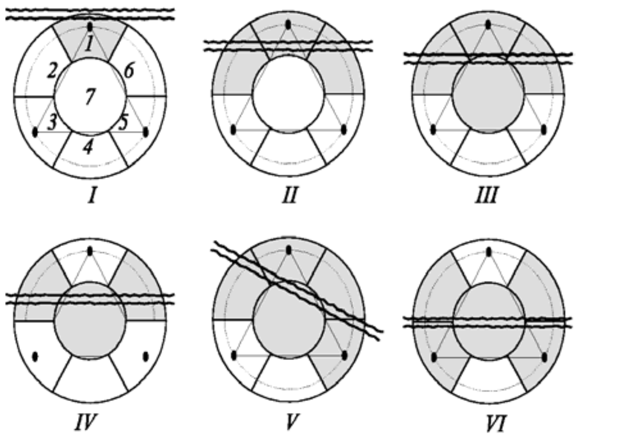

Figure 2: Simulation of the 7 chamber system climbing robot when moving on a vertical wall over a crack. The gray areas show those chambers which lost under pressure. It was calculated that in situation III, V and VI the robot is falling down.

The 7 chambers are connected to a under pressure reservoir, in which the vacuum engine is installed. As vacuum engine a vacuum cleaner motor is used, which is able generate a maximum under pressure of 250 mbar and maximum volume flow of 0.05m^3/s (see fig.3).

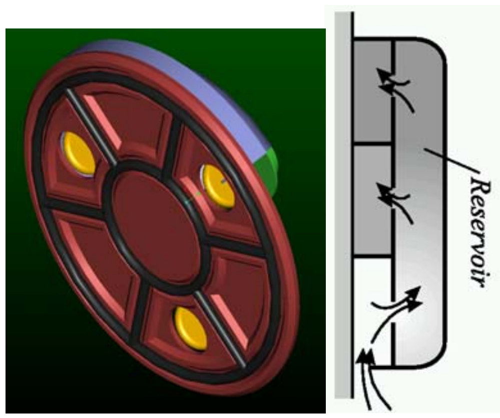

Figure 3: Mechanical design of the under pressure system. The 7 chambers are connected to a reservoir of 50l volume.

In fig. 4 we calculate the necessary under pressure of the reservoir in 4 different simulations. The calculations are done based on the estimation that the robot has a weight of 20 kg (no payload is considered), and the given dimensions of the robot. The robot is moving over a crack. Those chambers which are over the crack loose under pressure. In situation III the under pressure which is necessary to hold the machine on the wall, can not be generated by the under pressure system.

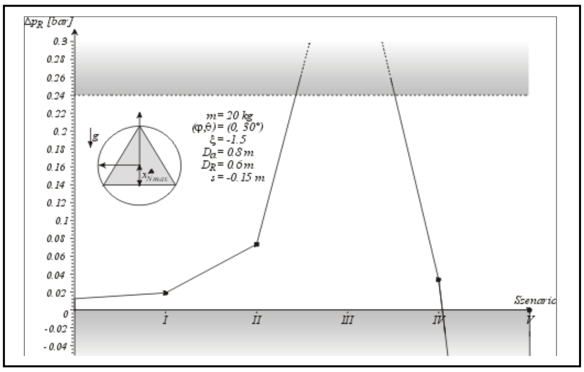

Figure 4: The necessary reservoir under pressure when moving over a crack in the direction shown above. The situations I to IV are those shown in figure 2.

Up to now a testbed is constructed (see fig.5) to verify the results which are calculated in our dynamic simulation.

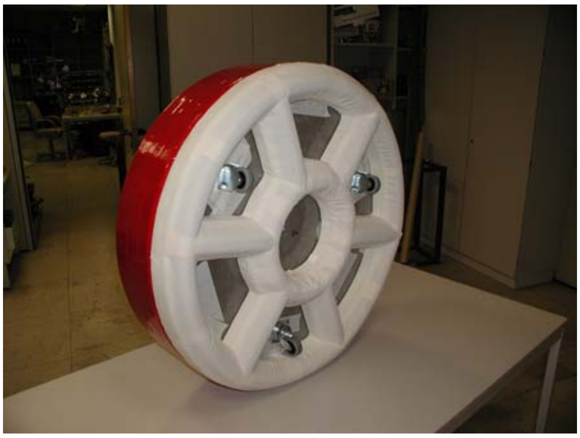

Figure 5: The testbed to examine the under pressure systems and the seals of the climbing robot.

As shown in fig. 2 there are several situation in which the under pressure system is not able to generate the necessary under pressure of about 20mbar. Because all chambers are connected to each other via the reservoir chamber the under pressure in the chambers and the reservoir must be control via valves. In situations in which the leakage area is very low the vacuum engine generates a very high under pressure, which makes the movement of the climbing machine impossible. Therefore, one valve is used to adapt the under pressure in the reservoir to the normal pressure. Each individual chamber is equipped with a valve, which is used to close the connection to the reservoir in case the leakage area is large.

In fig. 6 the behaviour of the under pressure of the reservoir and each chambers is shown when the robot moves over a crack and valves of those chambers with a large leakage area are closed. One can see that the under pressure of the reservoir is nearly constant.

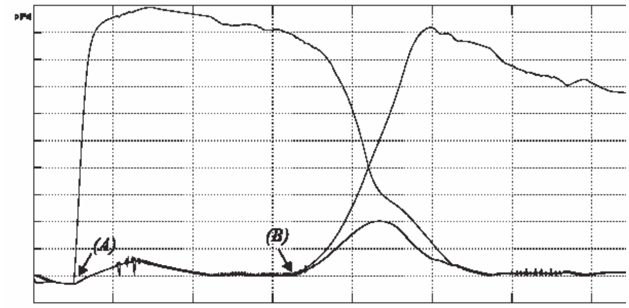

Figure 6: Under pressure over time of the chamber 1, 2 and the reservoir. In (A) a large leakage area crosses chamber 1. The under pressure of the reservoir is decreased till the valve of chamber 1 is nearly closed. Because the valves are not totally closed the control can detect (with the help of an under pressure sensor) if the leakage area is reduced in a way that the under pressure system is able to generate an adequate under pressure (100mbar for the robot described above). In (B) the leakage area crossed chamber 2 and 6. Also in this situation the reservoir under pressure is not changed.

In fig. 7 the closed-loop control is presented for the whole under pressure system. The control considers the information of the system identification unit. This unit estimates the leakage area based on the valve areas and the measured pressures inside the chambers. The strategy of the closed-loop control is to keep the under pressure of each chamber as high as possible under consideration of the maximum power of the vacuum engine. In normal situation (very small leakage areas) the under pressure is set to 100mbar with the help of a PID controller.

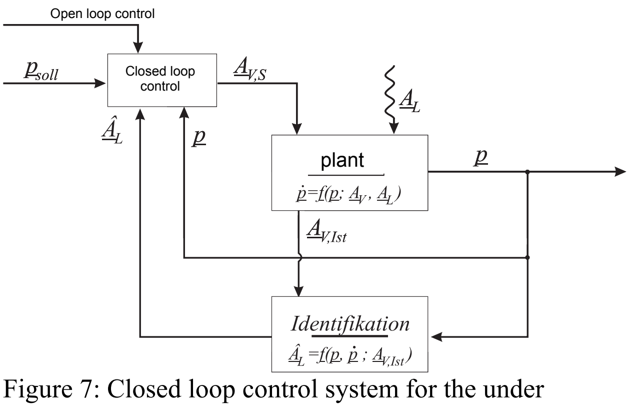

Figure 7: Closed loop control system for the under pressure system.

Based on the strategy of surmounting a crack there exist different situations in which the climbing robot will fall down or remain on the wall. Fig. 8 shows a possible strategy to overcome a crack of a width of 2cm and a depth of 2cm. The driven wheels are placed in the corners of the triangular. The forces which hold the machine on the wall and which are generated by the under pressure in the chambers can be summarized to a force vector in a specific position (red dot in fig.8). In this position there is no torque around the middle axis of the robot. Only if this point is inside the triangular bounded by the driven wheels the robot is able to move over the crack. Therefore, it is necessary to detect cracks or obstacles 1m ahead to select an adequate motion strategy. For more information about the theoretical background see [2].

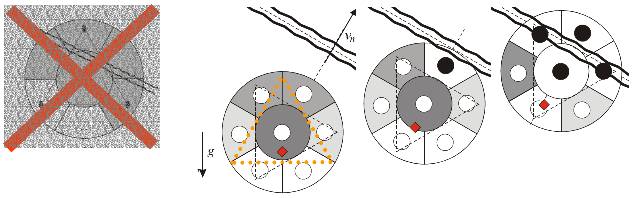

Figure 8: Optimal strategy of motion to overcome a crack. On the left figure only 2 chambers are generating the adhesion. After rotating the robot in the worst case 3 chambers are still generating the under pressure.

IV. Basic Sensor System

For the above described closed-loop control of the under pressure of the chambers as well as for the selection of a motion strategy several sensors are used. The under pressure is measured by the pressure sensor FPM-120PGR of the company Fujikura. This sensor has a resolution of 0.1mbar which is sufficient for the control.

Even if there is a good adhesion it possible for the robot to slip or rotate. For the detection of those situations an inertial system and a dead reckoning wheel are developed.

The inertial sensor system consists of three accelerometers and simple piezo gyroscopes [5]. In fig. 9 the three big components are the piezoelectric vibrating gyroscope Series ENV called Gyrostar from Murata, which are placed orthographically. After calibrating the offset and integrating the measure value, the sensor has a deviation of 2 degree per minute.

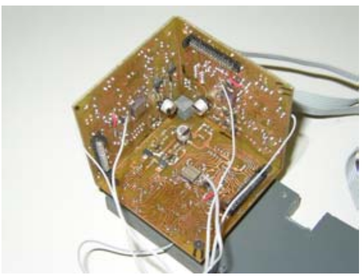

Figure 9: The inertial sensor system

As accelerometers ADXL105 from Analog Device are used. The output of the accelerometer is the sum of different active forces. There are the gravity force, the acceleration of the robot and centrifugal forces. If the robot is not moving, only the gravity force is active. If the robot is moving with a constant velocity the gravity force and the centrifugal force is active. It is very important to detect the correct direction of gravity for a vehicle which is driving at vertical planes as this gives the direction of the locomotion.

Additionally the accelerometer values can be integrated to determine the velocity in the navigation frame. More precise information about the velocity can be calculated from the odometrie measurements.

If the robot is moving on vertical surface the robot can slip in direction of the gravity force. The distance of slipping can be determined by a dead reckoning. The developed dead reckoning wheel is shown in figure 10.

Figure 10: The dead reckoning wheel

The passive wheel consists of a rotation unit inside of the cylinder. The stick pointing out of the cylinder is connected with a linear bearing to adjust rough surface levels. At its end a wheel is mounted on the center of the rotation unit.

The angle of the rotation unit and the rotation of the wheel are measured. The calculation algorithm is based on following equations:

$$x_W = \sum_{i=1}^{n} d_i * \cos(\varphi_i)$$

$$y_W = \sum_{i=1}^{n} d_i * \sin(\varphi_i)$$

These equations are calculating the position of the wheel (Index w - contact point of the wheel to surface). The input is the torsion of the cylinder φ_i and the driven distance of the wheel d_i. This calculation is a sequence based on the last calculated values. This output must be converted to the position of the sensor (Index – s):

$$x_S = x_W * \cos(\varphi_i) * L$$

$$y_S = y_W * \sin(\varphi_i) * L$$

Inside this equation $\boldsymbol{L}$ is the distance between the center of the cylinder and the contact point of the wheel on the surface.

With a build up test assembly experiments were carry out. The path which the sensor had to measure was a rectangle with edge distance of 2 and 2 meter. The measured deviation was less than 10 mm. The results are acceptable for a dead reckoning measure system.

Based on the sensors described above the determination of the position and the orientation with an accuracy of 1cm in each direction and 1° in each rotation axis was possible. Also slipping can be detect by this sensor system.

V. SUMMARY

In this paper the theoretical background for the adhesion of our climbing machine and the control concept is presented. It is shown that a multi-chamber system must be used to ensure safety while climbing on concrete walls. The multi-chamber adhesion system was realized with one reservoir chamber, in which the vacuum engine is installed. The reservoir is connected via valves to the 7 under pressure chambers, which hold the machine on the wall. It was shown that by controlling the valves it is possible even if half of the chambers have normal pressure the machine can still move on a vertical wall. In normal situation (without cracks or obstacles) the under pressure in each chamber can be controlled in a way that on one hand safety and on the other hand a continuous motion with a fixed velocity can be guaranteed.

Also the basic sensor system is introduce which is on one hand side necessary for the close-loop control and on the other side for the determination of the position and the orientation of the robot. It was shown that the knowledge of the orientation of the robot mainly according to the gravity forces can be used for safer navigation. At the moment several tests with our test-platform are done. In parallel an omni-wheel, a manipulator arm and an inspection sensor system are developed [3][4].

At the moment dams and bridges are envisaged to be target structures to be inspected by our robot system. In future several other structures like cooling towers, tunnels and others, preferably the ones made from reinforced and prestressed concrete, could be also inspected by our system.

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