CROMSCI - A CLIMBING ROBOT WITH MULTIPLE SUCKING CHAMBERS FOR INSPECTION TASKS

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The non-destructive inspection of large concrete walls via robotic systems is no longer an unsolved problem. This paper will present first results with the climbing prototype CROMSCI which uses a vacuum system of seven controllable vacuum chambers and an omnidirectional drive to move and cling to vertical concrete surfaces. This platform is able to move and inspect vertical surfaces safely, fast and cost-efficient. The technician can check the building more safe without any telescopic crane or other complex access devices via remote control or semi-autonomously.

Keywords: Climbing Robot, Adhesion System, Negative Pressure, Sealings.

1. Motivation and state of the art

Service robots are a suitable way to fulfill inspection tasks of concrete buildings more safely. These systems should be able to inspect the building area-wide and semi-autonomously under survey of a technician.

In literature multiple kinds of climbing robots can be found using different propulsion and a mass of adhesion techniques like passive suction cups, magnetic adhesion [1] [2], van-der-Waals molecular adhesion or kind of claws [3] [4]. The most confident technology for our application is the negative pressure adhesion [5] [6] [7] [8] [9]. Some of these systems are suitable only for smooth surfaces or use legs for locomotion, which will result in slow movement. For climbing on concrete surfaces an active vacuum system driven by wheels seems to be the best solution because of fast continuous motion and a simple mechanical structure.

2. Climbing Robot CROMSCI

CROMSCI[a] is equipped with three single unsprung, steerable and driven wheels as shown in figure 1 which provide best characteristics for maneuverability and adhesion [10]. Each wheel is able to generate continuously $182N$ to assure sufficient reserves for critical situations by a maximum speed of $9.63m/min$. Each wheel is equipped with an integrated load cell using strain gauges for indirect measuring forces at the wheel's contact point. On an outer ring lies a movable manipulator arm which carries the sensors for inspection like a cover meter or a high-resolution camera. The round shape with a complete diameter of $80cm$ is devided into seven single vacuum chambers. The overall weight is at about $50kg$ with an additional payload of up to $10kg$, the height is $50cm$. Because of the high energy consumption of the three suction engines (each $1.200W$) and for communication purposes the robot has to be connected via an umbilical cord to a ground station. From there the technical staff can control the robot, survey its measurements and supply it with power.

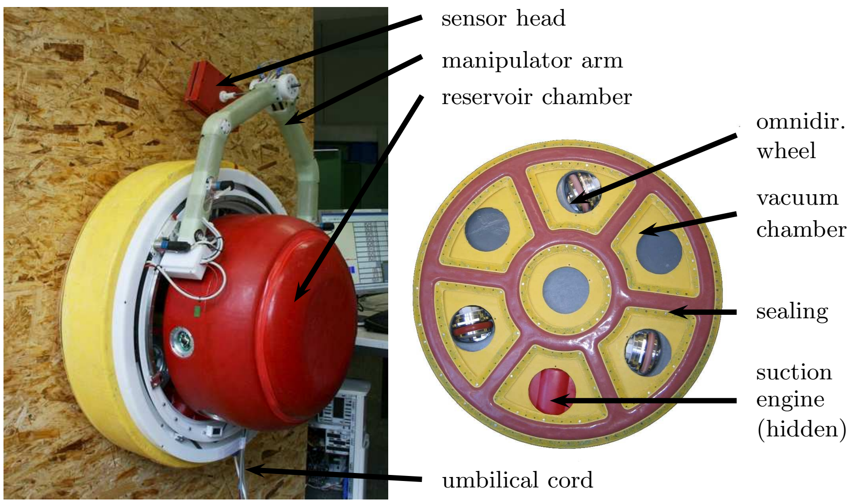

Fig. 1. CROMSCI stucking to a wall (left, view on top) and its sealing system (right, bottom view)

[a] CROMSCI: Climbing RObot with Multiple Sucking Chambers for Inspection tasks

3. Negative Pressure System

The adhesion system of our climbing robot Cromsci consists of seven single vacuum chambers which are supported by one large reservoir chamber at the top of the robot. The number of working chambers is a good compromise between realization simplicity (best: only one chamber) and operation safety (best: as much chambers as possible). Each chamber with a volume of about $4.5l$ receives its negative pressure from the reservoir ($\approx 20l$) which is evacuated by three strong suction engines as shown in figure 2. The air-pressure in each chamber and the reservoir is measured by sensors. These informations are given to a close-loop controller which opens and closes valves to evacuate the chambers separately depending on the actual leak tightness. The total effective suction area of Cromsci is $0.4m^2$, the pressure difference of the chambers is between $-50mbar$ and $-100mbar$ compared to ambient pressure. If one or more working chambers are loosing negative pressure they can be isolated from the vacuum system by closing the valve to avoid the propagation of normal pressure to the other chambers. Beside the real adhesion mechanism a thermodynamical model has been created both to set up a close-loop controller and to simulate the airflow and pressure variations with modelled leakages.

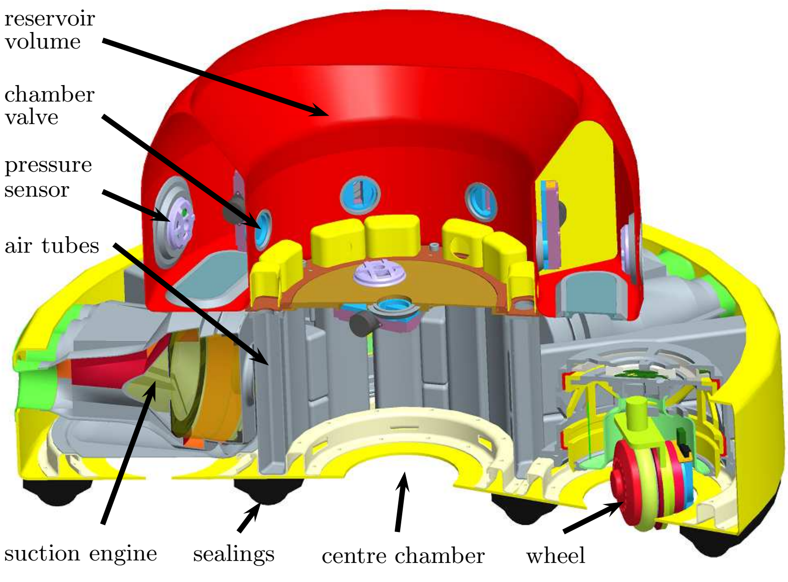

Fig. 2. Cromsci's negative pressure system

An important aspect is the interaction between adhesion system and drive due to the fact that the robot should neither stuck to the wall (soft sealings) nor fall down (hard and robust sealings). We have to allow controlled leakages for good sliding characteristics and to develop special sealings which are wear-resistant, leak-proof and easy sliding. To minimize losses of negative pressure the sealing's border to ambient air has been reduced by creating a cascaded system of suction chambers which share borders. The centre chamber has no direct contact to ambient air and can be used with higher negative pressure.

An optimized sealing system produces a constant force to the sliding areas independent of the ground shape. This force influences the leak tightness of the sealing which makes it possible to seal the system in cases of emergency. CROMSCI has an air filled tube in the shape of spokes, where the pressure is regulated by a closed loop controller. Unfortunately the characteristics confirm not with the optimized sealing system but are similar and good enough for this application. The system is able to select between a more sealing or more sliding strip. This mechanism will be used to build a safety system if any critical situation is detected.

4. Control System

The overall control system of CROMSCI consists of different layers, which differ in the level of abstraction and importance concerning safety aspects. As shown in figure 3 the lowest control layer is occupied by circuit boards containing a DSP, a CPLD and additional electronics. These are used for *higly critical* systems like close-loop control of pressure and motor control. If one of these components fails or does not satisfy the requirements the whole system may crash. These circuit boards are connected via canbus to the embedded onboard-pc which executes different cooperating programs.

The security level of the lowest software layers is *critical* due to important hardware link to the canbus and a cascaded close-loop controller for the chamber pressure and robot's downforce. Additionally it is also possible to replace hardware elements by simulated ones without any influence on higher program routines.

The next software level is an abstraction layer which is responsible for transformation of abstract values to robot specific ones, for kinematic calculations and localization. Coupled with the basic motion and safety behaviors these two software elements are responsible for *less critical* tasks like obstacle avoidance. For this they get information from a sensor processing part, which receives measurements via firewire, usb or serial port from a variety of sensors (infrared sensor, ultrasonic sensor, laserscanner, gps, ins, camera).

On top lies the behavior based control structure for driving and inspection strategies, which interacts via lan with the input devices of the human operator. These elements do have no critical aspects concerning robot's safety, although a foresighted strategy can help avoiding crucial situations.

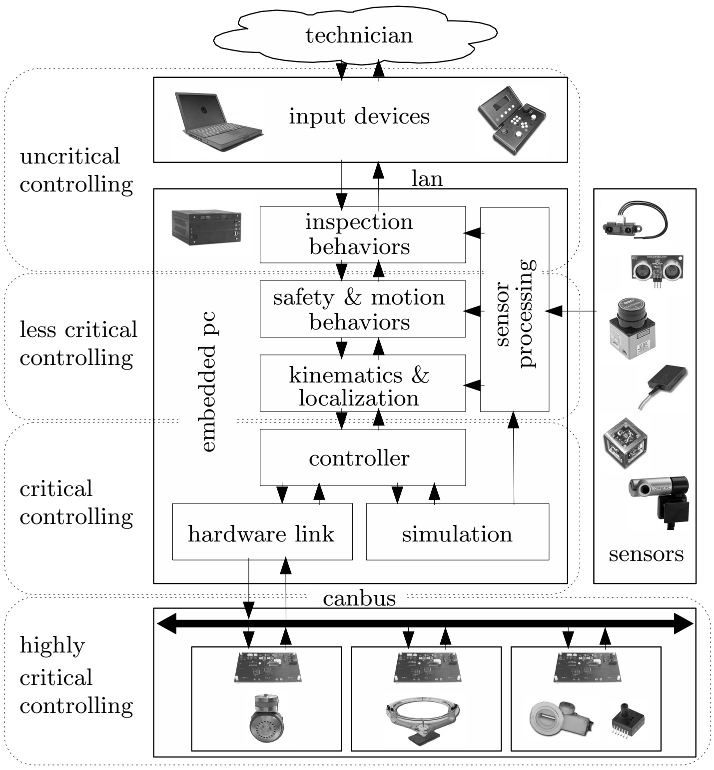

Fig. 3. Control structure of CROMSCI

5. Experimental Results With Seven-Chamber Prototype

The presented seven chambers have been tested extensively both inside of a simulation environment and on the presented prototype. By using a thermodynamic modell the air flows and pressure changes inside the whole system can be simulated and the close-loop controller could be adapted to system parameters [11]. Real-life experiments with the seven-chamber prototype prove that two sealed and evacuated chambers are sufficient for safe robot adhesion.

5.1. *Generated Forces*

Our first experiments with CROMSCI are very satisfying concerning forces. Measurements of load cells show that the negative pressure system is able to produce up to $1500N$ downforce at each wheel if all chambers have only a base leakage dependend on the sealing's facing. That implies sufficient reserves for crucial situations as shown in figure 4 where the robot is using only two chambers for adhesion. While reducing the valve openings of these two chambers the downforce of the front wheel decreases from $300N$ to only $50N$. Now the forces are too low to let the robot stick to the wall which is indicated by the decreasing robot height (measured by a laser scanner). The robot slips down the wall but does not fall off and can be rescued by increasing the vacuum again - the slipping stops.

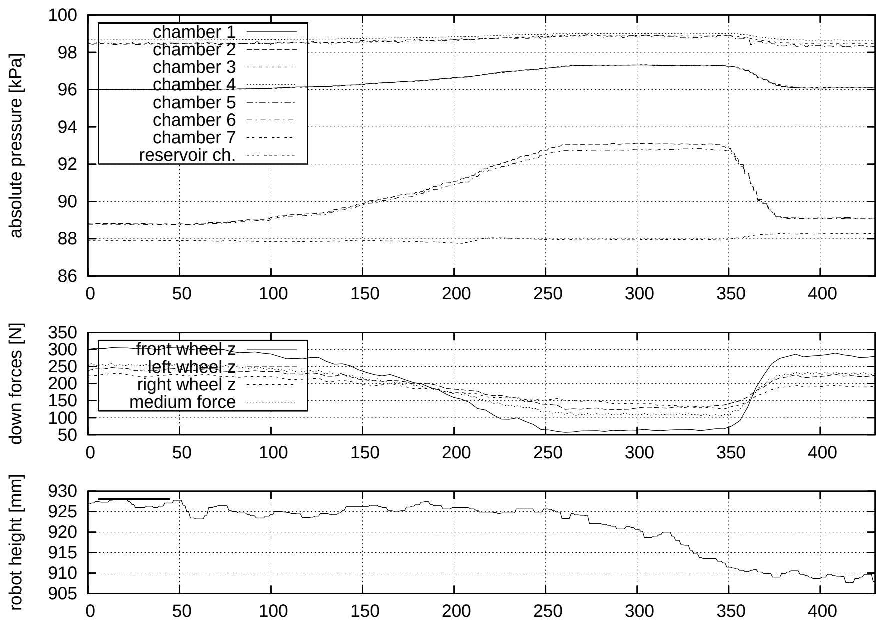

Fig. 4. Correlation of negative pressure, downforces and robot's behavior.

5.2. *Driving Experiments*

Beside the static experiments further test have been made to prove the functionality of the adhesion and movement system. Figure 5 shows the system's behavior while moving over a leakage area of $157mm^2$ (a hole with a diameter of $14mm$). The robot moves backwards, so that at first rear chamber 4 loses negative pressure. This is pointed out in increasing absolute pressure from $92kPa$ up to $95,5kPa$ of that chamber and a lower adhesion force at cycle step 2.500. At 2.800 the hole lies under a sealing and the negative pressure is nearly restored for a short period. After this the centre chamber 7 lies over the hole and loses vacuum. An interesting effect can be seen in the lower figure: Here the medium force of all three wheels stays constant, although the three force values differ stronger. During the first period the robot's tilting has been compensated by the inactive chamber 4 compared to the last period in which tilting is amplified by the inactive frontal chamber 1. At last all chambers are sealed again and the pressure forces reach a maximum of $90kg$ per wheel.

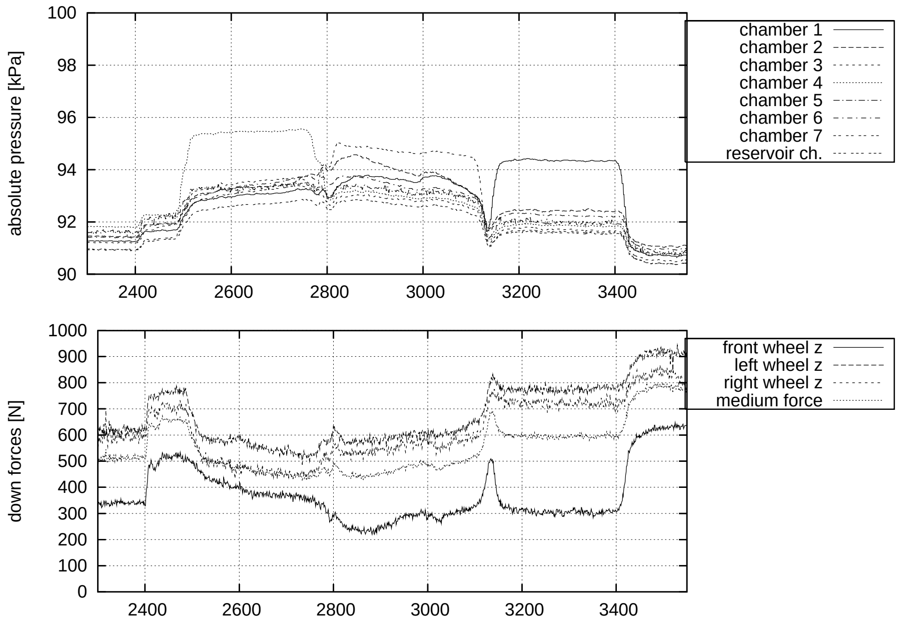

Fig. 5. Correlation of negative pressure and downforces while passing a leakage area.

6. Conclusion

We presented an outline of our climbing robot CROMSCI and first experiments with our seven-chamber prototype. The comparison of simulated results and real experiments indicates that the developed physical model is exact enough to estimate the efficiency of the proposed adhesion mechanism. Future Work mainly consists of technical fine tuning when we are able to validate the system's performance and the simulation model. A critical point in future will be the leak tightness and abrasion of the sealing facings. Here a few more experiments are necessary.

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