A Novel Wall Climbing Robot Based on Bernoulli Effect

XiaoQi Chen, *Senior Member, IEEE,* Matthias Wager, Mostafa Nayyerloo, Wenhui Wang, *Member, IEEE,* and J. Geoffrey Chase

***Abstract*—It is a challenge for mobile robots to climb a vertical wall primarily due to requirements for reliable locomotion, high manoeuvrability, and robust and efficient attachment and detachment. Such robots have immense potential to automate tasks which are currently accomplished manually, offering an extra degree of human safety in a cost effective manner. In contrast to vacuum suction, magnetic adhesion, and dry techniques used existing wall climbing robots, Canterbury's research effort focuses on a novel approach which achieves attachment and detachment based on Bernoulli Effect. The adhesion force is achieved on a variety of surfaces, independent on the material of the wall and surface conditions. Such ubiquitous mobility with a force / weight ratio as high as 5 is nearly impossible to be achieved by other adhesion methods.**

***Index Terms*—Bernoulli Effect, wall climbing robot, attraction force, adhesion, attachment mechanism**

I. Introduction

Wall Climbing Robots can replace human beings to perform dangerous operations on vertical surfaces like cleaning high-rise buildings. Another large application domain is automatic Non-Destructive Testing (NDT) of large vessels, storage tanks or silos, which is required by dairy, petrochemical, mining industry. Integrated with process tools and sensors, wall climbing robots can carry out more complex operations like tank welding. Generally speaking, three main types of attachment mechanisms are used: suction, magnetic and dry adhesion mechanisms. In the former, the robot carries an onboard pump or vibration mechanism to create vacuum inside cups which are pressed against the wall or ceiling [1 -5]. This effect is dependent on a smooth impermeable surface to create enough force to hold the robot. Magnetic adhesion has been implemented in wall climbing robots for specific applications such as nuclear facilities or oil and gas tanks inspection [6 - 9]. In specific cases where the surface allows, magnetic attachment can be highly desirable for its inherent reliability. Other novel adhesion mechanisms like bio-inspired dry adhesion using synthetic fibrillar adhesives have been reported, but are very sensitive to contaminants on wall surface [10, 11].

XiaoQi Chen is with the Department of Mechanical Engineering Department, the University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand (phone: +64-3-364 2987 Ext.: 7221; fax: +64-3-364 2087; e-mail: xiaoqi.chen@canterbury.ac.nz).

Matthias Wager is with the University of Munich. He was an intern with the Department of Mechanical Engineering, the University of Canterbury in 2007. (e-mail: matze.wagner@mytum.de).

Mostafa Nayyerloo, Wenhui Wang and J. Geoffrey Chase are with the Department of Mechanical Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand. (e-mails: mna16@student.canterbury.ac.nz, wenhui.wang@canterbury.ac.nz, geoff.chase@canterbury.ac.nz).

Existing wall climbing robots are often limited to selected surfaces. Magnetic adhesion only works on ferromagnetic metals. Suction pads may encounter problems on the surface with high permeability. A crack in a wall would cause unreliable functioning of the attachment mechanisms, and cause the robot to fall off the wall. For this reasons, a wall climbing robot independent of wall materials and surface conditions is desirable. To this end, the University of Canterbury has embarked on a research program to develop novel wall climbing robots which offer reliable adhesion, manoeuvrability, high payload/weight ratio, and adaptability on a variety of wall materials and surface conditions. The research has led to the development of a novel wall climbing robot based on the Bernoulli Effect.

As a standard Bernoulli device only offers a small attraction force, special attachment mechanisms have to be designed to enhance effectiveness of mechanical force generation. The mechanisms are designed to create the force without any contact to the surface. They literally float on an air cushion close to the wall. The contact between the robot and the wall lies in wheels with tires made of a high friction material which avoids sliding. The non-contact mechanisms provide a continuous and relatively constant suction force as the robot manoeuvres. The locomotion through the motorised wheels ensures smooth motion of the robot, which is paramount for continuous 3D curvature surface operation.

The advantage of our novel approach is that the adhesion force is largely independent of the type of materials and surface conditions. High attraction forces can be achieved on a broad range of surface materials with varying roughness. The device accommodates wall permeability to air to a certain degree, which means that gaps and cracks, which would pose a hazard to conventional suction methods, can be tolerated by the novel device. Furthermore, the robot is easy to setup using a standard pressure supply readily available industry wide.

This paper firstly explains the principle of attraction force due to Bernoulli Effect, and considers some design factors. It then discusses the design of the attachment mechanisms. Experimental results on adhesion and prototyping of wall climbing robot are presented and discussed. Finally some concluding remarks are made.

II. Attraction Force due to Bernoulli Effect

Bernoulli Effect dictates a relationship between pressure, velocity, and position or elevation in a flow field. The original equations are very complex and can only be solved in very special conditions. Therefore, in most problems assumptions are made to simplify the equations which are omitted in this paper. These assumptions are applicable to experiments involving the wall climbing robot. The Bernoulli principle states that in an ideal fluid (low speed air being a good approximation) with no work being performed on the fluid, an increase in velocity occurs simultaneously with a decrease in pressure. This principle is a simplification of Bernoulli equation, which states that the sum of all forms of energy in a fluid flowing along an enclosed path (a streamline) is the same at any point in that path.

$$\frac{v^2}{2} + \frac{p}{\rho} + gh = const$$

where g is acceleration of gravity [m/s²], p static pressure [N/m^2], v velocity of the air along the streamline [m/s], ρ density of the fluid [kg/m^3], and h elevation or height of the point of consideration in the streamline [m].

The constant value can be different for different streamlines. Comparing two points on one streamline, the following equation is obtained:

$$\frac{v_1^{\ 2}}{2} + \frac{p_1}{\rho} + gh_1 = \frac{v_2^{\ 2}}{2} + \frac{p_2}{\rho} + gh_2$$

If there is no height difference between the two points, the following equation stands:

$$\rho\frac{v^2}{2} + p = const$$

This equation shows that for an ideal fluid travelling along a horizontal streamline, the pressure decreases with a simultaneously increasing velocity. Consequently, the pressure drop leads to an attraction force. This principle has been used in some industrial applications such as non-contact wafer transportation and food handling.

A non-contact end effector for robot handling of non-rigid materials has been developed by F. Erzincanli and J.M. Sharp in 1998 [12]. They studied the radial outflow between two disks and considered laminar as well as turbulent. The air pressure distribution between two disks, upper one with a perpendicular hole and lower disk plain, starts with a high pressure in the middle which creates a force against the second disk and lowers the total adhesion force of the device before it decreases under the ambient pressure, as shown in Fig. 1.

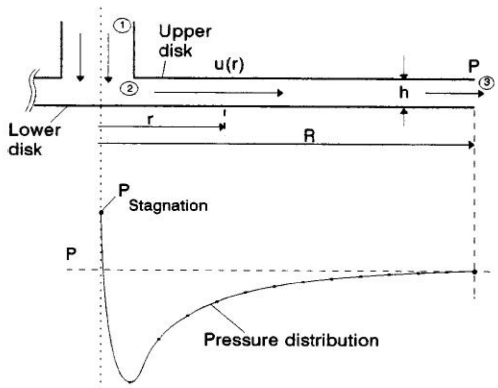

Fig. 1. Radial pressure distribution on a disk

The stronger one of their devices was built out of nine radial nozzles with 10.8 mm outer diameter and an orifice diameter of 2.7 mm. This device can only lift jelly blocks up to 175 grams at a gauge pressure of 100 kPa with an air flow rate around 200 l/min.

Another interesting device which delivers a more satisfying force is the Bosch Rexroth non-contact transport system (NCT) [13, 14]. The advantage over Erzincanli's and Sharp's end effector is the deflection of the air stream to the sides of the device as shown in Fig. 2.

The NCT series consists of four different devices with their diameter as the main attribute. The stroke force F depending on the input pressure p is shown in Fig. 3. The number in the device's name (after NCT) gives the outer diameter in millimetre. The force of 6 N of NCT60 at a normal supply pressure around 5 bars can be considered as sufficient for one device of a light weight wall climbing robot which should be able to carry a certain payload. But the device with 60 mm outer diameter weighs 0.12 kg. As the robot has to carry the device, the effective force would only be around 4.8 N. Furthermore, it needs a very high air flow of 210 l/min which already reaches the borders of some pressure supply systems. For this reason, the devices of the NCT series could not be effectively used as a robot end effector for general material handling.

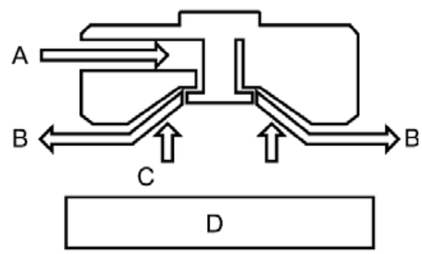

Fig. 2. Functional principle of NCT. A: Supplied pressure, B: Outlet air stream, C: Lifting force, D: Object.

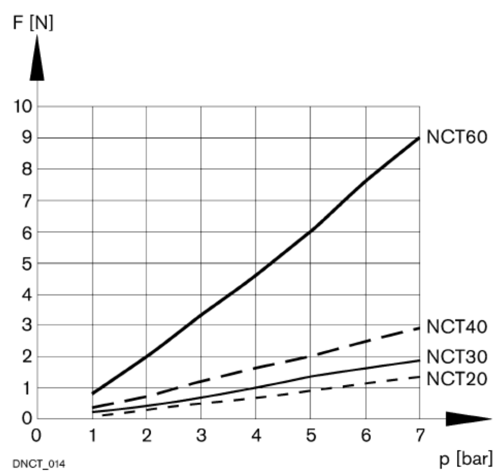

Fig. 3. Lifting force F at pressure p for different NCT devices

III. Design Considerations

A. Pressure and air flow

The experimental device had a nozzle of 10 mm diameter with an outlet for the deflected air and a 50 mm outer diameter. The maximum force of 11.6 N was achieved with a pressure of 6 bars and 110 l/min flow rate. The lifting forces F for the experimental device (d-exp) at different flow rates have been shown in Fig. 4. The force increases linearly with the pressure in different flow rates. The non-linearity of the highest curve (100 l/min) occurs due to reaching the limit of the pressure supply.

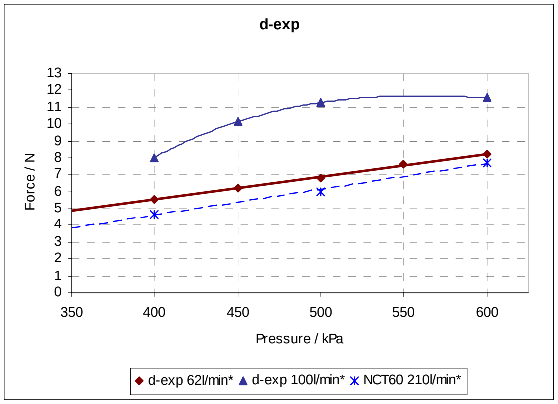

Fig. 4. Force and pressure distribution in experimental device.
(*flow rate at 5 bars)

B. *Outlet design*

According to the Bernoulli principle, an increase in force comes along with an increase in air flow velocity. When the flow is regulated before reaching the nozzle, the gap at the nozzle is not the smallest conduit of the system. The highest velocity of the fluid is reached in the smallest conduit of a pipe system due to the same mass flow in every cross section. Therefore, the velocity at the nozzle decreases because of the flow valve reducing the flow. The highest force is created by the highest air speed between device and wall. To reach the maximum air speed at the nozzle and consequently between device and wall, the Bernoulli device always has to run with the highest possible flow rate in a working pressure. Therefore, the device has to be designed considering the specifications of the pressure supply.

C. *Size and edge design*

The stream velocity slows down with radius, and an increase in size decreases this effect. Thus the achieved force increases slightly with the increase in outer diameter of the device, but the air gap between device and wall becomes thinner, and tilting at raw surfaces becomes more commonly. The robot should be able to climb raw walls, so considerations for size and force have to be made.

A sharp edge also increases tilting. Therefore, a rounded and an angled edge have been tested (Fig. 5.).

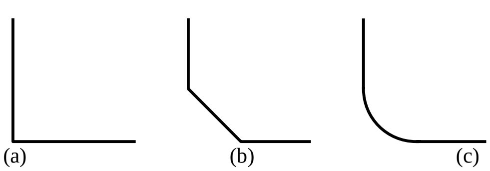

Fig. 5. Edge designs for the outer diameter of the pad: (a) sharp edge, (b) angled edge, and (c) rounded edge

Best performance on raw surfaces was achieved with the rounded edge. Differences in amount of achieved forces were negligible between angled and rounded edges. Compared to the sharp edge, there was a very small force reduction, depending on the dimension of the edge alteration. The air stream noise is also reduced by the rounded edge. Hence, such a small rounded edge was considered for the final device.

IV. Design of Attachment Mechanism

A. *Initial Experimentation*

First experiments were made with a simple disc with an outer diameter of 40 mm and an inlet hole of 1 mm in diameter right in the middle. It was machined out of steel and the vertical hole was directly connected to the pipe system. Fig. 6 shows the simple disc for the first experiments.

Fig. 6. The first test device with its 1 mm hole in the middle

Fig. 7 shows the results of attraction force using a pressure of 5 bars, a 1 mm diameter inlet and a 40 mm outer diameter.

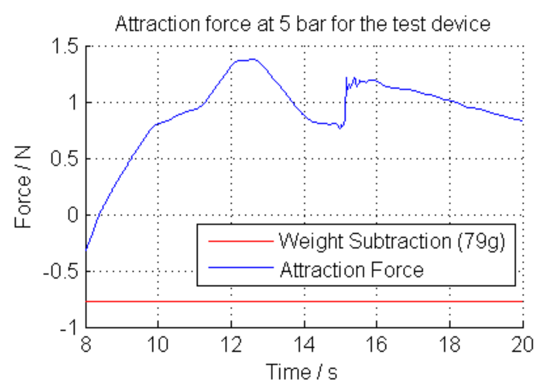

Fig. 7. Force distribution during the lifting process

The force distribution was created by raising the metal disc from the glass surface. The flow rate changed from 11 l/min to 19 l/min, where the second peak was reached. It can be assumed that the full flow through the hole could not be achieved as long as the device was very close to the surface. By raising the device slightly and after reaching the first peak and global maximum of 1.4 N, the clearance gap of approximately 1 mm was large enough for the full flow to pass through the hole and led to a second peak of 1.2 N. It was not as high as the first one because the gap between the disc and the surface was already too large.

The force distribution over the pressure is shown in Fig. 8. The force increases with the pressure linearly. For a 2 mm hole no measurements were recorded because the disc was pushed off the surface so much that there was hardly any attraction force.

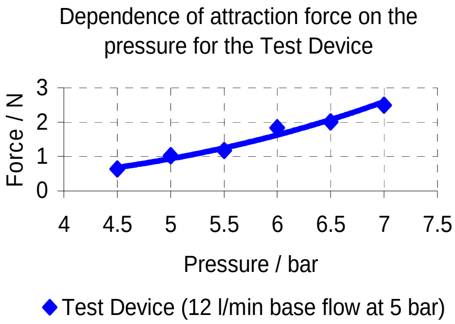

Fig. 8. Maximum adhesion force at a certain pressure

From Fig. 8, a force of 1.5 N was achieved with a pressure of 5 bars under the most favourable condition. This magnitude of attraction force is insufficient to attach a robot to the wall. Deployment of multiple devices would multiply the attraction force, but adds weights to the robot. Nevertheless, the simple device already shows that the Bernoulli Effect leads to an attraction force, but the efficiency in force generation using existing methods is too low to be applicable for walling climbing robots.

All experiments with different layouts and numbers of perpendicular and angled holes did not achieve satisfactory results as the forces were very small compared with the exerted pressure and air flow rate. Best results were achieved with round devices and one outlet in the centre. Our design concept evolved to deflecting the stream to a parallel flow between surface and device so to increase the efficiency force generation. This led to the development of flow regulated attachment mechanism.

B. Flow Regulated Attachment Mechanism

The attachment mechanism was made of two aluminium parts, a top part and a bottom part. The parts were connected with three screws and a sealing ring to avoid loss of air pressure. The top part is connected to air supply, while the bottom part is for the air outlet. The two-part configuration allows fast changes of the bottom plate for different experiments and fine-tuning the airflow to suit a specific application. Furthermore, machining of bottom parts was kept simple; sealing and connection to the pipe system was all linked with the top part. The modular design also allows tailoring attraction force and distribution by changing the bottom attachment, without affecting the top part.

For the bottom part, two types of attachments were designed and built. The first type (Bottom 1) consists of seven symmetrical vertical holes and three angled holes with 60 degrees from the vertical direction, as shown in Fig. 9(a).

The second type of bottom attachment (Bottom 2), shown in Fig. 9 (b), has only one hole in the middle and an angled shape beside the hole to reduce clearance to the surface with an increasing radius. A special pin was placed in the hole and screwed into the top part of the experimental device, which deflected the air flow out of the hole horizontally towards the outer edge of the device. As shown in Fig. 9, the top part is the same for both Bottom 1 and Bottom 2 attachments.

The Bottom 2 attachment provides a smooth conduit for air flow guidance as well as additional flexibility in regulating the air flow via the pin. The airflow rate can be changed by adjusting the pin position, hence the air outlet. This method was adopted in the design of the prototype wall climbing robot. The pad is made of lightweight aluminium to reduce the self-weight of the device.

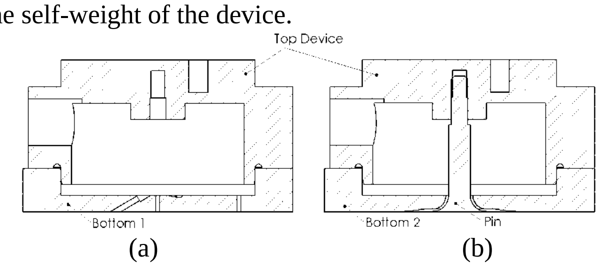

Fig. 9. Cross-section of Experimental Device with mounted Bottom 1 (a) and Bottom 2 (b)

In the final design, the main body is one part with the pin screwed in at the middle. A flat surface with an M5 thread is used for the connection to the pressurised air supply. The device can be mounted to the wall climbing robot with two threads on the top. A cross-section of the body of the pad is shown in Fig. 10(a). The pin, screwed into the pad, stays in the secured position as a result of precise surface tolerances. As such, there is no air flow disturbance at the outlet.

The outer diameter of the nozzle was reduced from 10 mm (Bottom 2) to 6 mm. The reason for this change was the ability to machine tolerances: The resulting nozzle gap between the pin and the main body to achieve the desired flow rate of 50 l/min at 5 bars for a diameter of 6 mm was only 0.10 mm and would have been much smaller with a bigger pin. Furthermore, the whole device should be more compact, and with this change, the attraction force was created closer to the centre of the device.

The gap between the pin and the main body was ensured by a tight tolerance at the pin and pin support in the main body. A flat stopper was included in the construction of the pin which exactly fit into the 5 mm diameter drilling of the body and was stopped by its base exactly at the right position. To meet the tight tolerance with this stopper, a standard M3 thread was used for mounting the pin instead of a high precision thread. The pin with the stopper is shown Fig. 10 (c).

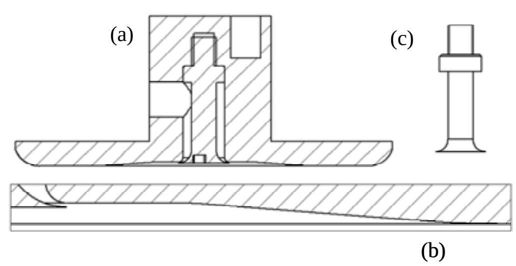

Fig. 10. Cross-sections of (a) the Bernoulli pad, (b) detail of the undercut with the angled ramp, and (c) the pin.

The undercut in Bottom 2 was an important feature that was used in the Bernoulli. It regulates the air outlet air flow rate as well as to safeguard the pin. Because the main body was closer to the surface than the pin, the pin avoids being in contact with the surface. As such, potential scratching of the pin and damage of the nozzle system is prevented.

The angled ramp of the undercut serves as an guide for air outlet. It reduces the clearance distance between the surface and the pad so that the air speed reduction due to the increasing radius was slowed down. This results in a slower increase of pressure and likewise a decrease of attraction force. An enlargement of this section is shown in Fig. 10 (b). The outer diameter of the main body was reduced to 45 mm including a rounded edge with a radius of 3 mm. This reduction of diameter was a trade off between attraction force and the ability to compensate for tilting. With the slightly reduced outer diameter and the rounded edge, the Bernoulli pad can also accommodate small tilts which may be encountered when the robot transverses on an uneven surface.

An air supply system delivering a pressure of 5 bars and a permanent flow rate of 120 l/min has been considered. The robot was constructed with two pads. For each pad to reach 50 to 60 l/min flow rate equally, the most important design consideration is the nozzle opening. In the prototype robot, the nozzle with 6 mm diameter and a very precise opening gap of 0.10 mm achieves the desired equal air flow between two pads. The weight of one suction pad, made of Aluminium, is 19 grams. The tube fitting for the pressure supply weighs 4 grams. One pad operates with an air flow of 51 – 52 l/min at a pressure of 5 bars and creates a force of 6.0 N. The attraction force generated is relatively consistent for different surfaces.

V. Results and Discussion

A. Attraction Force

Two pads were constructed and tested. They used the same flow of 51 l/min at 5 bars. As the pads behaved equally thanks to a precise construction, all following experiments were carried out on single Bernoulli pad. Fig. 11 shows the force distribution over the pressure comparing the experimental devices Bernoulli pad with the 3 angled holes in Bottom 1 and a flow rate setting of 50 l/min at Bottom 2. The flow rate behaviour of the final device over the pressure is shown in Fig. 12.

For Bottom 1, the average flow rate during the lifting process has been taken. In all three cases, the attraction forces increase proportionally with the pressure. The device with Bottom 2 attachments offers a higher force than that with Bottom 1 at the same pressure. At the pressure of 5 bars, the maximum force of 6.4 N was achieved on a glass surface.

To use the attachments for wall climbing robots, it was desired to have a reliable adhesion on different surface materials and surface conditions. Therefore, many experiments were carried out on metal, plastic and wooden surfaces, and finally expanded to different grained sandpapers and other materials. Tests were also conducted with simulated cracks on the surface. These results validated the effectiveness of the design of the attachment mechanism, and be reported separately.

B. A Prototype Wall-Climbing Robot

As the Bernoulli pads are non-contact, and flow over an air cushion, the robot needs contact points to adhere to the wall by relying on the friction force. After evaluating various configurations, the design decision fell on two wheels driven by DC motors. The friction force is the multiplication of the attraction force between the pads and the wall and the friction coefficient. With a high friction coefficient wheel material, the friction force is high enough to carry the robot and its onboard tools on the vertical wall. The prototype robot is able to climb on a variety of surfaces.

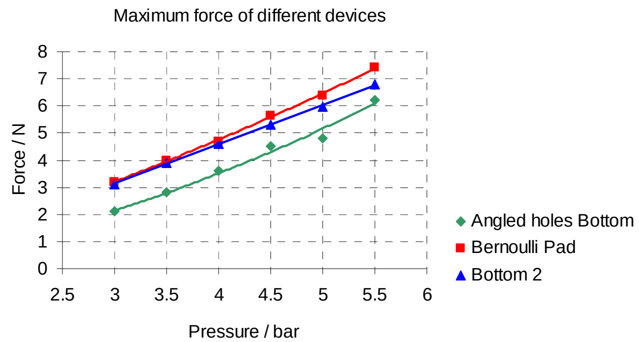

Fig. 11. Maximum force of different device with flow rates.

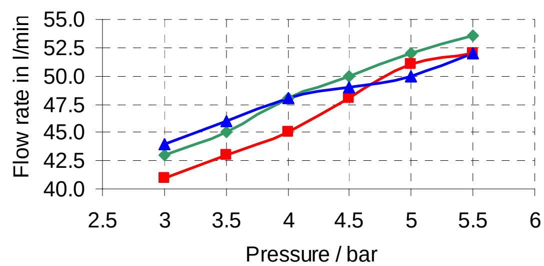

Fig. 12. Flow rate obtained with different pressures.

After several tests, the best results were achieved with a combination of a rubber with a friction coefficient of 0.74 on glass with a thin strip of Velcro which supports climbing on cloth and very raw surfaces. Nevertheless, the wheels can be changed easily, so that the best materials can be chosen for each field of application. For a broad range of different surfaces, a set of wheels can be taken along and easily be changed on-site as the wheels are only mounted with one screw each.

Stability of the robot was achieved through two Bernoulli suction pads in the front and at the back of the robot at a distance of 180 mm. These non-contact devices self-place them in a distance of about 0.5 mm of the wall. The whole robot is designed symmetrically in two axes, so that the stability still maintains when the robot is climbing with the head down.

The main body is made out of a plastic bar with a T-profile to reduce the total weight and to achieve high stiffness. The stiffness is needed because the suction pads, which are mounted directly to the bar, have to be placed as parallel as possible to themselves and the wall. To get the best transfer of the suction force to the contact points, a suspension for the wheels is needed. The suspension system has to be lightweight, and the deflection has to be very small. With this consideration, the motors and wheels are mounted on a thin and flexible aluminium beam, which was elastic enough to act as a suspension system.

The prototype wall climbing robot is shown in Fig. 13. Its total length is 224 mm and its width is 156 mm. The robot is driven using two gear-head micro motors. One drive train has a weight of only 38 grams. In total the robot weighs 234 grams and is able to lift an additional weight of 500 grams on a vertical glass surface as well as a concrete ceiling. It can move in all direction: forward, backward, left, right, and upside down.

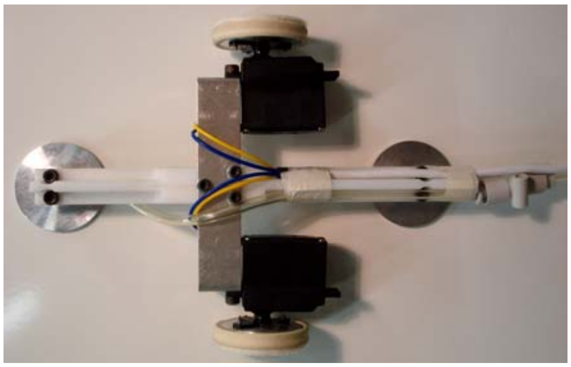

Fig. 13. Top view of the wall climbing robot with two Bernoulli pads and two wheels.

Existing wall climbing robots use vacuum suction cups or magnetic devices to create adhesion to a vertical wall. They are sensitive to types of wall materials and surface conditions such as roughness, permeability, dirt, and cracks. The specially designed attachment mechanisms discussed in this work are less sensitive to these environmental variables. As surface condition deteriorates, the force created by the Bernoulli pads will decrease to a less degree.. Our design achieves 12 N for a robot weighing 234 grams, with the force/weight ratio being as high as 5.

In addition to reliable adhesion on various surface conditions, another advantage of the device is the feature of "self-cleaning". When the robot climbs on a dirty and dusty surface, the air stream cleans the surface and so prepares it for surface inspection using an onboard measuring instrument.

In terms of air supply, a standard high pressure supply or a compressor suffices. Batteries for instruments and motors can be mounted on board. The robot can be steered by a remote control or autonomously navigates using onboard sensors and controllers. Because of the simple but very effective wheeled locomotion and only two suction pads, a simple control system can be employed to steer the movement.

VI. Conclusion

In this paper a new adhesion method for wall climbing robots has been introduced. The adhesion force is created by adhesion pads constructed based on the Bernoulli principle. These non-contact pads generate high attraction forces more effectively in comparison with existing methods. Experiments from the prototype wall climbing robot on glass surface show the effectiveness of the attachment mechanisms. More comprehensive test results on difference materials and different surface conditions have been omitted in this paper.

The wheeled robot has two contact points (areas) with the wall through two motorised wheels. The robot successfully manoeuvres on different surfaces. The flow-regulated attachment mechanism yields an attraction of 12 N for a robot weighing 234 grams. It has many advantages over existing methods in terms of high force/weight ratio (as high as 5), low cost, ubiquitous mobility under different surface conditions, and modularity. Test results on different surface materials and for gaps simulating surface cracks will be reported separately.

The non-contact adhesion method opens up great potential for wide industrial adoptions such as structural inspection, surveillance, part transporting in bio-medical, inspection, and tank welding. In the future development, scaling up of the robot and non-tethered operation with on-board airflow generation would require more fundamental research, and tackles more challenging and complex applications.

References

[1] Jizhong Xiao, Angel Calle, Ali Sadegh, and Matthew Elliott, "Modular wall climbing robots with transition capability," in *Proc. IEEE Int. Conf. Robotics and Biomimetics*, 2005, pp. 246-250.

[2] Zhi-yuan Qian, Yan-zheng Zhao, and Zhuang Fu, "Development of wall-climbing robots with sliding suction cups," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Beijing, China, Oct 9-15, 2006, pp. 3417-3422.

[3] Tao Zhu, Rong Liu, Xu D. Wang, and Kun Wang, "Principle and application of vibrating suction method," in *Proc. IEEE Int. Conf. Robotics and Biomimetics*, Kunming, China, Dec 17-20, 2006, pp. 491-495.

[4] Daijun Xu, Xueshan Gao, Xiaobing Wu, Ningjun Fan, Kejie Li, and Koki Kikuchi, "Suction ability analysis of a novel wall climbing robot," in *Proc. IEEE Int. Conf. Robotics and Biomimetics*, Kunming, China, Dec 17-20, 2006, pp. 1506-1511.

[5] Yang Li, Man-tian Li, and Li-ning Sun, "Design and passable ability of transitions analysis of a six legged wall-climbing robot," in *Proc. IEEE Int. Conf. Mechatronics and Automation*, Harbin, China, August 5-8, 2007, pp. 800-804.

[6] Masataka Suzuki, Shinya Kitai, and Shigeo Hirose, "New types child units of anchor climber: Swarm type wall climbing robot system," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, San Diego, CA, USA, Oct 29-Nov 2, 2007, pp. 1781-1786.

[7] W. Fischer, F. Tâche, and R. Siegwart, "Inspection system for very thin and fragile surfaces, based on a pair of wall climbing robots with magnetic wheels," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, San Diego, CA, USA, Oct 29-Nov 2, 2007, pp. 1216-1221.

[8] Weimin Shen, Jason Gu, and Yanjun Shen, "Proposed wall climbing robot with permanent magnetic tracks for inspecting oil tanks," in *Proc. IEEE Int. Conf. Mechatronics and Automation*, Niagara Falls, Canada, July 2005, pp. 2072-2077.

[9] Love P. Kalra, Weimin Shen, and Jason Gu, "A wall climbing robotic system for non-destructive inspection of above ground tanks," in *Proc. IEEE CCECE/CCGEI*, Ottawa, Canada, May 2006, pp. 402-405.

[10] Kathryn A. Daltorio, Andrew D. Horchler, Stanislav Gorb, Roy E. Ritzmann, and Roger D. Quinn, "A small wall-walking robot with compliant, adhesive feet," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2005, pp. 4018-4023.

[11] Michael P. Murphy and Metin Sitti, "Waalbot: An agile small-scale wall-climbing robot utilizing dry elastomer adhesives," *IEEE Trans. Mechatronics*, vol. 12, No. 3, June 2007, pp. 330–338.

[12] F. Erzincanli and J.M. Sharp, "Development of a non-contact end-effector for robotic handling of non-rigid materials," *International Journal of Machine Tools and Manufacture*, vol. 38, No. 4, April 1998, pp. 353-361.

[13] Bosch Rexroth AG, "Pneumatic Non-Contact Transfer Unit Series NCT" Order no. 000-120-840-1 EN/2003-01, www.boschrexroth.com/pneumatics

[14] Bosch Rexroth AG, "Series NCT Brochure" Order no. 000-000-000-0/JJJJ-MM/EN, www.boschrexroth.com/pneumatics