18

City-Climber: A New Generation Wall-climbing Robots

Jizhong Xiao and Ali Sadegh
The City College, City University of New York
USA

1. Introduction

1.1 Motivations

An increasing interest in the development of special climbing robots has been witnessed in last decade. Motivations are typically to increase the operation efficiency in dangerous environments or difficult-to-access places, and to protect human health and safety in hazardous tasks. Climbing robots with the ability to maneuver on vertical surfaces are currently being strongly requested by various industries and military authorities in order to perform dangerous operations such as inspection of high-rise buildings, spray painting and sand blasting of gas tanks, maintenance of nuclear facilities, aircraft inspection, surveillance and reconnaissance, assistance in fire fighting and rescue operations, etc. Such capabilities of climbing robots would not only allow them to replace human workers in those dangerous duties but also eliminate costly scaffolding.

1.2 Related Work

One of the most challenging tasks in climbing robot design is to develop a proper adhesion mechanism to ensure that the robot sticks to wall surfaces reliably without sacrificing mobility. So far, four types of adhesion techniques have been investigated: 1) magnetic devices for climbing ferrous surfaces; 2) vacuum suction techniques for smooth and nonporous surfaces; 3) attraction force generators based on aerodynamic principles; 4) bio-mimetic approaches inspired by climbing animals.

Magnetic adhesion devices are most promising for robots moving around on steel structures. Robots using permanent magnets or electromagnets can be found in (Grieco et al., 1998), (Guo et al., 1997), (Hirose et al., 1992), (Wang et al., 1999), (Shen et al., 2005), and (Kalra et al., 2006) for climbing large steel structures and in (Kawaguchi et al., 1995), (Sun et al., 1998) for internal inspection of iron pipes. However, their applications are limited to steel walls due to the nature of magnets.

In applications for non-ferromagnetic wall surfaces, climbing robots most generally use vacuum suctions to produce the adhesion force. Examples of such robots include the ROBUG robots (Luk et al., 1996) at University of Portsmouth, UK, NINJA-1 robot (Nagakubo & Hirose, 1994) at Tokyo Institute of Technology, ROBIN (Pack 1997) at Vanderbilt University, FLIPPER & CRAWLER robots (Tummala et al., 2002) at Michigan

Source: Climbing & Walking Robots, Towards New Applications, Book edited by Houxiang Zhang,
ISBN 978-3-902613-16-5, pp.546, October 2007, Itech Education and Publishing, Vienna, Austria

State University, and ALICIA robots (Longo & Muscato, 2006) developed at the Univ. of Catania, Italy. Besides those robots built in academic institutes, some robots have been put into practical use. For example, MACS robots (Backes et al., 1997) at the Jet Propulsion Laboratory (JPL) use suction cups for surface adherence when inspecting the exterior of large military aircraft; Robicen robots (Briones et al., 1994) use pneumatic actuators and suction pads for remote inspection in nuclear power plants; SADIE robots (White et al., 1998) use a sliding frame mechanism and vacuum gripper feet for weld inspection of gas duct internals at nuclear power stations. A wall climbing robot with scanning type suction cups is reported in (Yano et al, 1998). Other examples include (Rosa et al., 2002) and (Zhu et al., 2002). More recently, some robots using vacuum suction cups for glass-wall cleaning are reported in (Elkmann et al., 2002), (Zhang et al., 2004) and (Qian et al., 2006). The common defects of the suction-based climbing robots lie in the facts that the suction cup requires perfect sealing and it takes time to generate vacuum and to release the suction for locomotion. Thus they can only operate on smooth and non-porous surfaces (e.g., glass, metal walls, or painted walls) with low speed. These constraints greatly limit the application of the robots.

The third choice is to create attraction force based on aerodynamic principles including the use of propeller (Nishi & Miyagi, 1991) (Nishi & Miyagi, 1994) and recent innovative robots such as vortex climber (Illingworth & Reinfeld, 2003) and City-Climber (Xiao et al., 2005) (Elliott et al., 2007) robots. The vortex climber is based on a so-called "tornado in a cup" technology, while the City-Climber combines the suction and aerodynamic attraction to achieve good balance between strong adhesion force and high mobility. Both robots have demonstrated the capability moving on brick and concrete walls with considerable success. However, the power consumption and noise are two issues need to be addressed for some surveillance tasks.

Apart from the aforementioned adhesion mechanisms, significant progress has been made to mimic the behavior of climbing animals (e.g., geckos and cockroaches). The investigation on gecko foot (Autumn et al., 2000), (Sitti & Fearing, 2003) has resulted in many gecko inspired climbing robots including the early version of Mecho-Gecko developed by iRobot in collaboration with UC Berkeley’s Poly-PEDA lab, Waalbot (Murphy & Sitti, 2007) developed at Carnegie Mellon University, and more recent work of StickyBot (Kim et al., 2007) (Santos et al., 2007) at Stanford University. These robots draw inspiration from the dry adhesive properties of gecko foot and achieved certain success in climbing applications. However, it is a challenging work to synthesize gecko foot hair which should be rugged, self-cleaning and can produce dry adhesive force strong enough for practical use, especially when large payload is desired. Other successful bio-inspired climbing robots are based on microspines observed on insects, which lead to the SpinyBot (Kim et al., 2005) (Asbeck et al., 2006) and RiSE platform (Clark et al., 2007) developed by Stanford University and other RiSE (Robotics in Scansorial Environments) consortium members. The robots are used to climb rough surfaces such as brick and concrete. A novel spider-like rock-climbing robot (Bretl et al., 2003) has been developed at Stanford University and JPL which uses claws at the end of limbs to meticulously climb cliffs. However, this robot cannot move on even surfaces without footholds.

1.3 City-Climber Features

A multi-disciplinary robotics team at the City College of New York (CCNY) has developed a new generation wall-climbing robot named as City-Climber, which has the capabilities to climb walls, walk on ceilings, and transit between different surfaces. Unlike the traditional climbing robots using magnetic devices, vacuum suction techniques, and the recent novel vortex-climber and gecko inspired robots, the City-Climber robots use aerodynamic rotor package which achieves good balance between strong adhesion force and high mobility. Since the City-Climber robots do not require perfect sealing as the vacuum suction technique does, the robots can move on virtually any kinds of smooth or rough surfaces. The other salient features of the City-Climber robots are the modular design, high-payload, and high-performance on-board processing unit. The City-Climber robots can achieve both fast motion of each module on planar surfaces and smooth transition between surfaces by a set of two modules. Experimental test showed that the City-Climber robots can carry 4.2kg (10 pound) payload in addition to 1kg self-weight, which record the highest payload capacity among climbing robots of similar size. The City-Climber robots are self-contained embedded systems carrying their own power source, sensors, control system, and associated hardware. With one 9V lithium-polymer battery, the robot can operate continuously for half hours. DSP-based control system was adopted for on-board perception and motion control. This chapter provides detailed description of City-Climber prototypes, including the adhesion mechanism, mechanical design, and control system. A video which illustrates the main areas of functionality and key experimental results (e.g., payload test, operation on brick walls, locomotion over surface gaps, and inverted operation on ceiling) can be downloaded from website http://robotics.ccny.cuny.edu

2. Adhesion System

2.1 Adhesion Mechanism

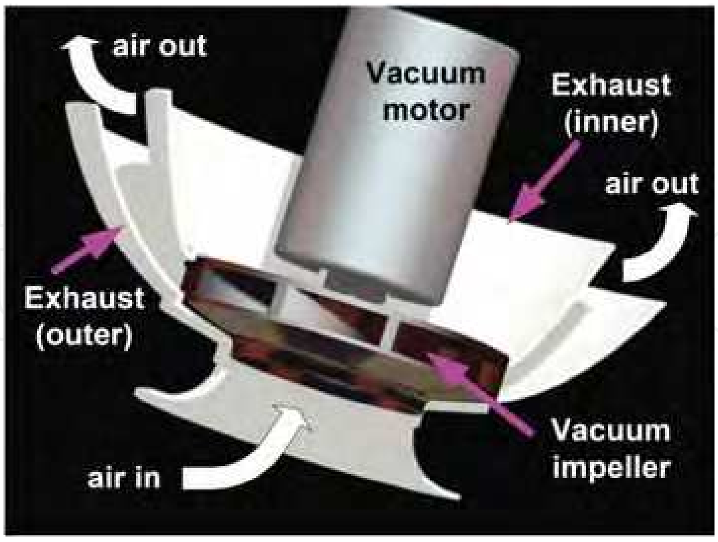


Fig. 1. Vacuum rotor package to generate aerodynamic attraction

The adhesion device we designed for City-Climber is based on the aerodynamic attraction produced by a vacuum rotor package which generates a low pressure zone enclosed by a chamber. The vacuum rotor package consists of a vacuum motor with impeller and exhaust cowling to direct air flow as shown in Fig. 1. It is essentially a radial flow device which combines two types of air flow. The high speed rotation of the impeller causes the air to be accelerated toward the outer perimeter of the rotor, away from the center radically. Air is then pulled along the spin axis toward the device creating a low-pressure region, or partial vacuum region if sealed adequately, in front of the device. With the exhaust cowling, the resultant exhaust of air is directed toward the rear of the device, actually helping to increase the adhesion force by thrusting the device forward.

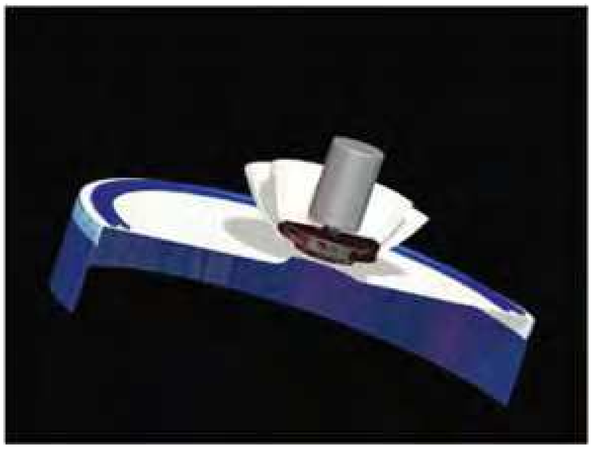


Fig. 2. Exploded view of the vacuum chamber with flexible bristle skirt seal.

In order to generate and maintain attraction force due to the pressure difference, a vacuum chamber is needed to enclose the low pressure zone. Fig. 2 shows a vacuum rotor package installed on a plate, and a vacuum chamber with flexible bristle skirt seal. When the air is evacuated through the hole on the plate by the vacuum rotor, the larger volume of the chamber, and the smaller gaps between the seal and contact surface, the lower steady state pressure we can obtain, thus increase the attraction force and load capacity. Two low pressure containment methods were investigated: inflated tube skirt seal and the flexible bristle skirt seal. The inflated tube seal is very successful, generating attraction force which is so strong that it anchored the device to wall surfaces. In order to make a trade-off between sealing and mobility, we designed a flexible bristle skirt seal, which the bristle surface is covered in a thin sheet of plastic to keep a good sealing, while the flexing of bristle allows the device to slide on rough surfaces. A novel pressure force isolation rim connecting the vacuum plate and the bristle skirt seal is designed. The rim is made of re-foam which improves the robot mobility, and also enhances sealing by reducing the deformation of the skirt as shown in Fig. 3. When the vacuum is on, the rim helps reducing the pressure force exerted directly on the skirt, thus reduce the deformation of the skirt. We select internal differential drive system which adopts two drive wheel and one castor wheel inside the chamber. Since the locomotion system and the payload are mounted on the plate, thus the re-foam makes the skirt and the robot system flexible and adaptable to uneven surfaces such as stone walls.

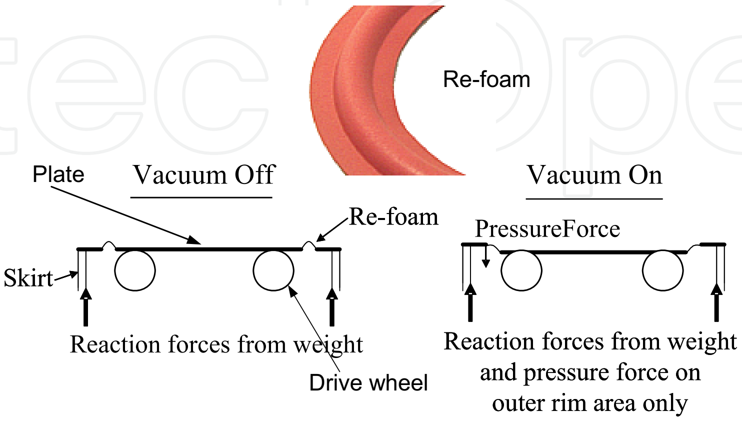


Fig. 3. The pressure force isolation rim is made of re-foam. When the vacuum is on, the rim helps reducing the pressure force exerted directly on the skirt, thus reduce the deformation of the skirt.

2.2 Aerodynamic Study

We studied the aerodynamic behavior of the adhesion mechanism by means of computational fluid dynamics (CFD) simulation using Fluent 6.2 software. The simulation results provide directions to optimize some design factors (e.g., the shape and distribution of impeller vanes, the volume of chamber, etc.) to generate stronger attraction force. Gambit 4.0 was utilized as pre-processor software for Fluent where the geometry of the rotors and the impellers were generated. In the gambit software the volume of the fluid (space within the impellers and inside the chambers) were meshed and proper boundary conditions were applied. This file was read into Fluent for the aerodynamics analysis. In Fluent, the solver was defined as “Steady State” and the type of flow was defined as a “K-Epsilon”, and the material as air.

Fig. 4 and 5 (static and total pressure) show the pressure distribution inside the chamber when the impeller rotates in a constant speed of 600 rpm. It indicates that the most low-pressure region (shown in blue) is at the entrance of the curved region of the impeller which caused by the rotational flow due to the rotation velocity of the rotor. This low pressure sucks the air from the inlet and pushes it to the outlet. This has been reflected by the high-pressure region at the most outer boundary area of the rotor (shown as orange to red regions). As shown in Fig. 6, the velocity is low at the entrance and it is high at the outlet, which corresponds with the pressures at these locations. It reveals that the rotor package can generate negative pressure around the axial, and the higher the rotation speed, the lower pressure it can create inside the rotor cylinder. Note that total pressure is the sum of the static and dynamic pressure of air.

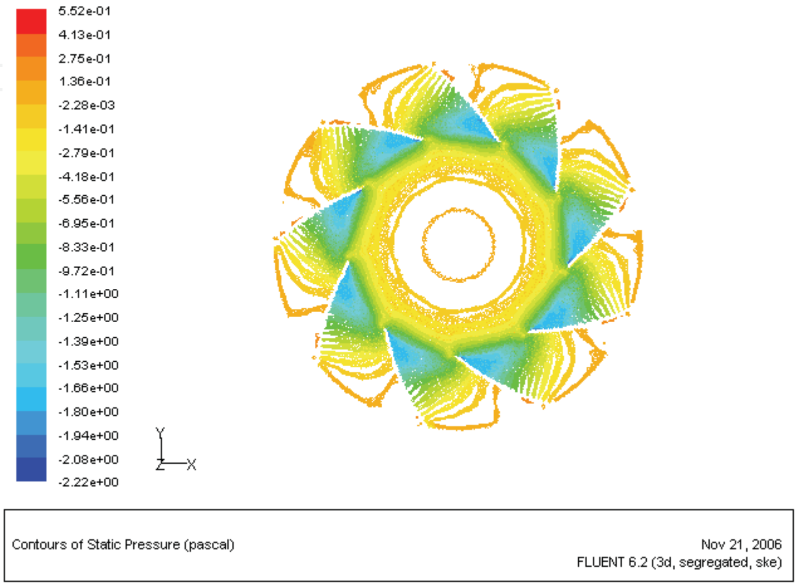


Fig. 4. Aerodynamic simulation, static pressure distribution inside the rotor cylinder (Pascal)

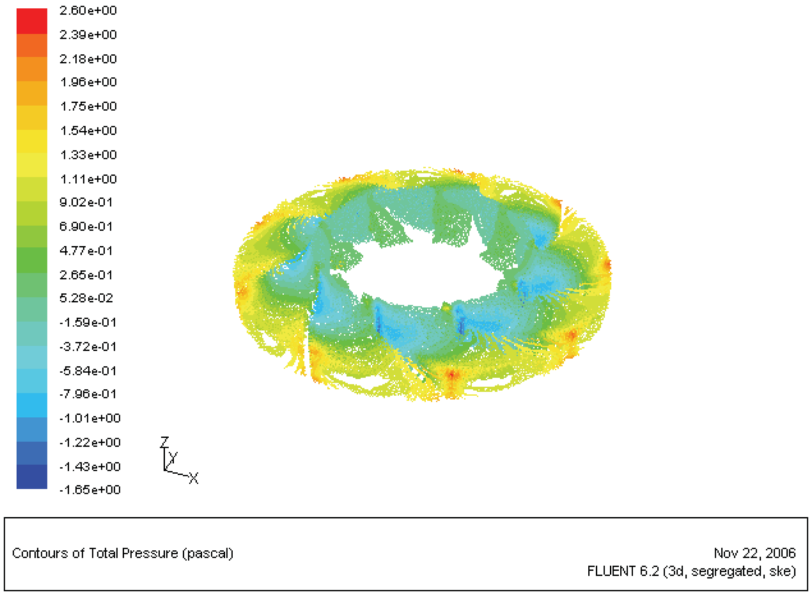


Fig. 5. Aerodynamic simulation, total pressure distribution inside the rotor cylinder (Pascal)

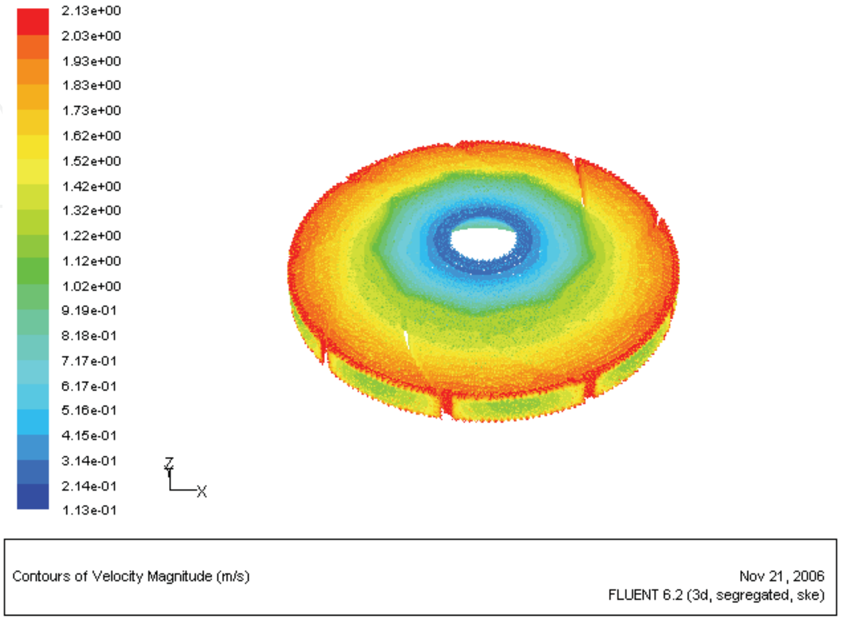


Fig. 6. Aerodynamic simulation with Fluent 6.1, velocity distribution

We compare the original design (Fig. 7, impeller diameter is 8cm) with scale two design , i.e., we left all the conditions the same and just double the size of impeller. As shown in Fig. 7 the minimum total static pressure in original design is -2.22e^{+00} Pascal, but with increasing the size of impeller, Fig. 8 indicates that the minimum static pressure decreases to -1.24e^{+03} Pascal.

We also compare the areodynamic behavior with chamber diameter as 28cm in three conditions when the chamber is: 1) fully open, 2) has 1cm gap between wall and chamber, and 3) fully sealed. Simulation results show that in the case of fully open (Fig. 9) we have minimum suction pressure of -4.54e^{+00} Pascal; in case 2 (Fig. 10, 1cm gap between wall and chamber) we have minimum suction pressure of -3.80e^{+02} Pascal but it is not uniformly distributed; in the case of fully sealed (Fig.11) we have minimum suction pressure -2.43e^{+02} Pascal and it is evenly distributed compared with case 2. The total attraction force generated by the adhesion mechanism can be calculated by integrating the pressure distribution within the the chamber. It is apparent that the attraction force will be the highest when the chamber is fully sealed because of the evenly distributed large low pressue area in Fig. 11. It also reveals that the rotor package can generate negative pressure around the axial even if there are gaps between wall and the chamber. Our simulation shows that for getting stronger suction force we need to increase the size of impeller, rotation speed, and the volume of chamber, and decrease the gaps between wall and chamber. However, these design factors have physical constraints, and balance between suction force and mobility shall be made. We use pressure sensors to monitor the pressure change inside the chamber and adjust the impeller speed to keep a constant pressure value for strong suction and smooth motion.

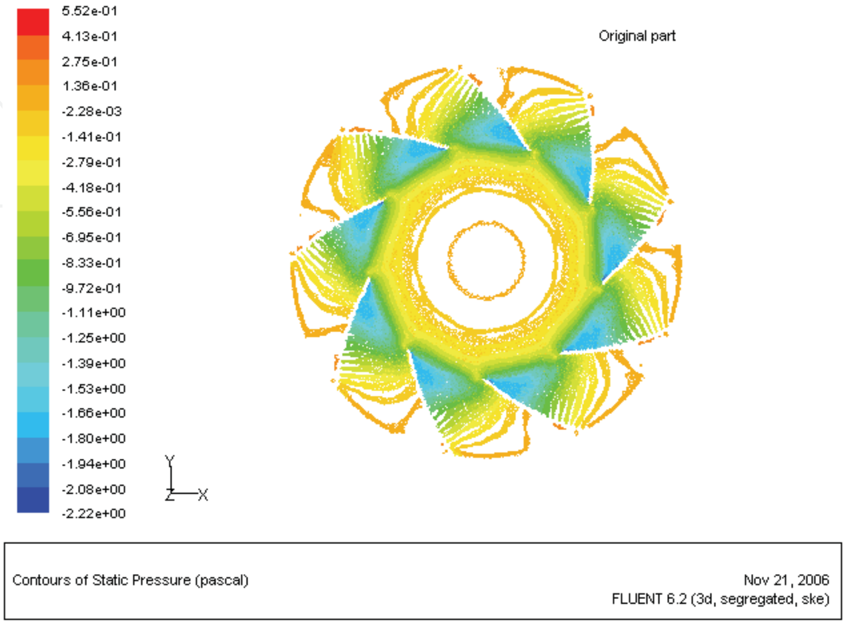


Fig. 7. Simulation of suction pressure in original design

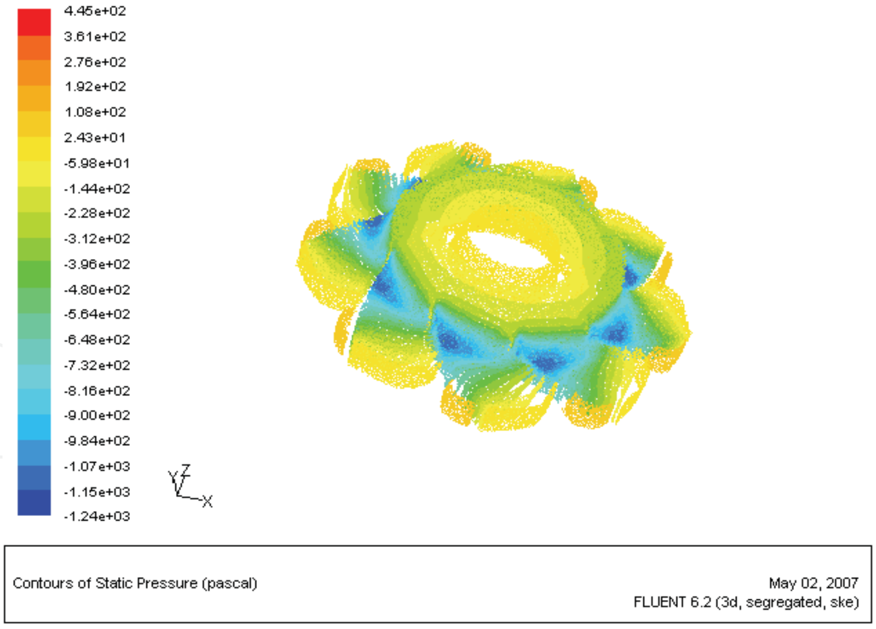


Fig. 8. Simulation of suction pressure in Scale 2

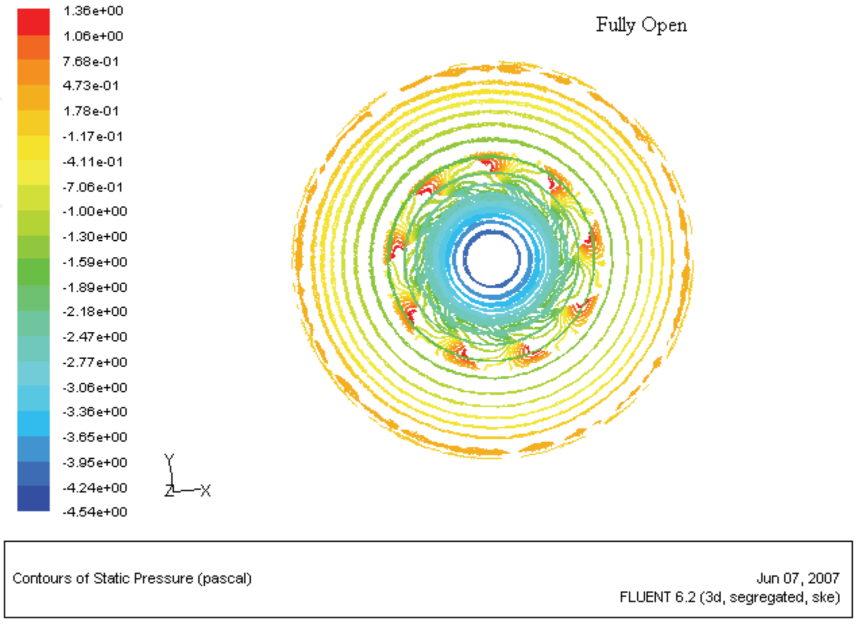


Fig. 9. Simulation of suction pressure: fully open

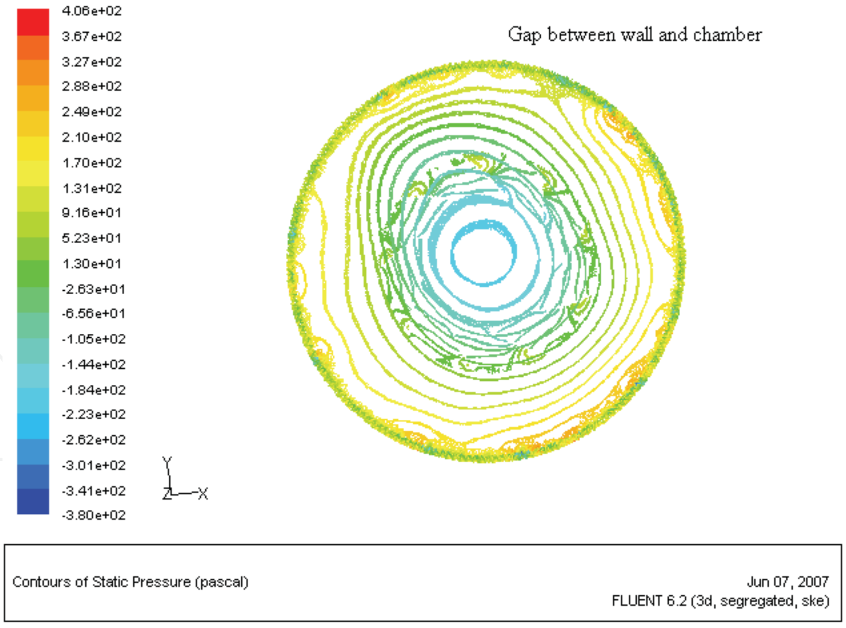


Fig. 10. Simulation of suction pressure: 1cm gap between wall and chamber

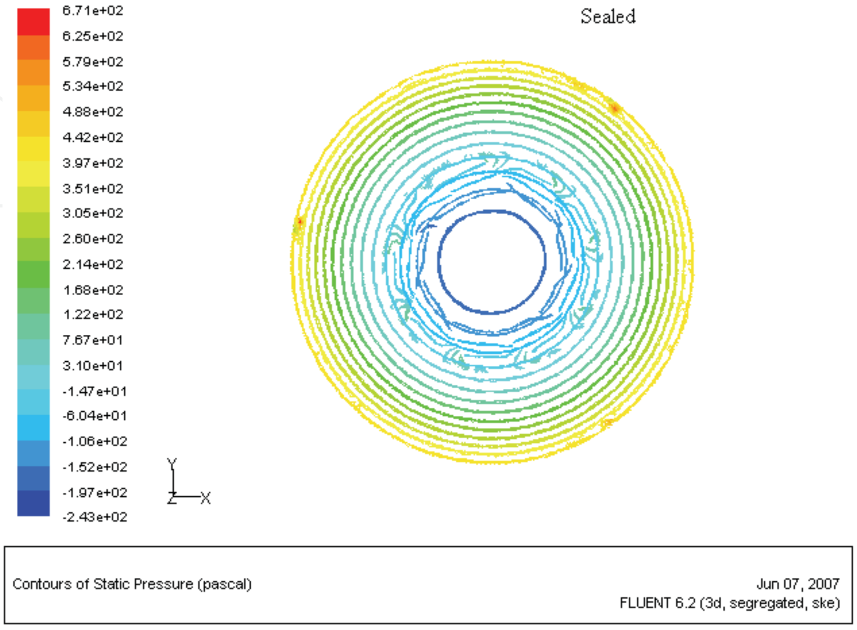


Fig. 11. Simulation of suction pressure: fully sealed

3. City-Climber Prototypes

3.1 City-Climber Prototype-I

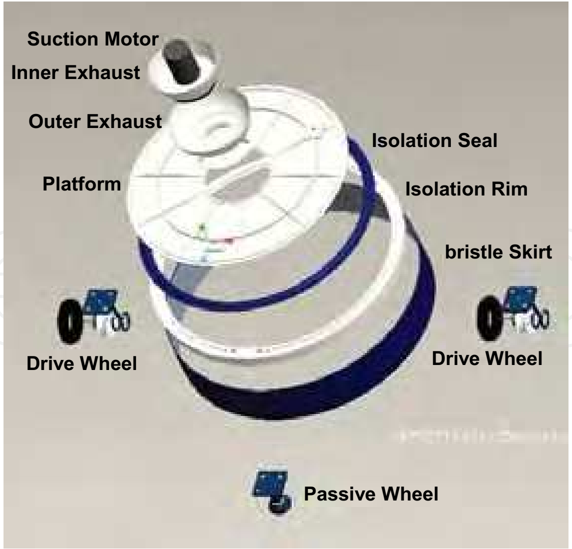


Fig. 12. Exploded view of City-Climber prototype-I.

Fig. 12 shows the exploded view of the City-Climber prototype-I that consists of the vacuum rotor package, an isolation rim, a vacuum chamber with flexible bristle skirt seal, and internal 3-wheel drive. The entire bristle surface is covered in a thin sheet of plastic to keep a good sealing, while the flexing of bristle allows the device to slide on rough surfaces. A pressure force isolation rim connecting the platform and the bristle skirt seal is made of re-foam. The rim improves the robot mobility, and also enhances sealing by reducing the deformation of the skirt. The driving system and the payload are mounted on the platform, thus the re-foam makes the skirt and the robot system adaptable to the curve of rough surfaces. Fig. 13 shows a City-Climber prototype-I operating on brick wall.

Fig. 13. City-Climber prototype-I approaching a window on brick wall, a CMU-camera is installed on a pan-tilt structure for inspection purpose.

3.2 City-Climber Prototype-II

The City-Climber prototype-II adopts the modular design which combines wheeled locomotion and articulated structure to achieve both quick motion of individual modules on planar surfaces and smooth wall-to-wall transition by a set of two modules. Fig. 14 shows the exploded view of one climbing module which can operate independently and is designed with triangle shape to reduce the torque needed by the hinge assembly to lift up the other module. To traverse between planar surfaces two climbing modules are operated in gang mode connected by a lift hinge assembly that positions one module relative to the other into three useful configurations: inline, +90°, and -90°. Responding the electronic controls, a sequence of translation and tilting actions can be executed that would result in the pair of modules navigating as a unit between two tangent planar surfaces; an example of this is going around a corner, or from a wall to the ceiling. Fig. 15 shows a conceptual drawing of two City-Climber modules operating in gang mode that allow the unit to make wall-to-wall and wall-to-ceiling transitions. Fig. 16 shows the City-Climber prototype-II resting on a brick wall and ceiling respectively. The experimental test demonstrated that the City-Climber with the module weight of 1kg, can handle 4.2kg additional payload when moving on brick walls, which double the payload capability of the commercial vortex climber.

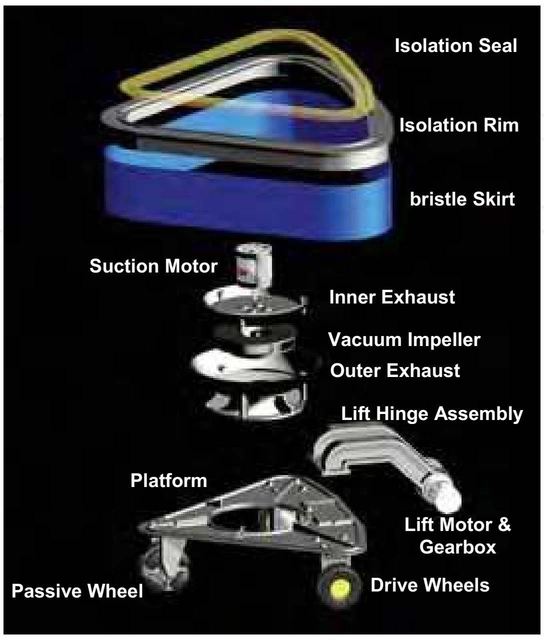


Fig. 14. Exploded view of City-Climber prototype-II

Fig. 15. Two robot modules connecting by a hinge in +90°, and -90° configurations, being able to make wall-to-wall, and wall-to-ceiling transitions

Fig. 16. The City-Climber prototype-II rests on a brick wall and sticks on a ceiling respectively

3.3 City-Climber Prototype-III

The most important improvements in City-Climber prototype-III are the redesign of transition mechanism and the adoption of 6-wheel driving system to increase the contact friction and avoid wheel slippage while climbing vertical walls. Note that the wheels are outside of the robot frame, making it possible for each module to make ground to wall transition with ease (see video demonstration on http://robotics.ccny.cuny.edu). The two modules are closely coupled to reduce the torque required to lift up other module, as shown in Fig. 17. Due to efficient placement of the driving system the robot is still capable of +/- 90 degree transitions, similar to prototype-II. Fig. 18 shows the robot prototype III and Fig. 19 shows the exploded view with each module consists of a vacuum rotor package and is closely coupled by shared center axel and transition motor. Same as the prototype-II, the new design still uses one motor for lift/transition and two motors for driving. The two driving motors drive the two center wheels (left and right) independently, and via the right and left belts, drive the front and rear wheels. Additional multiple modules could be linked together in the future to a form snake-like version.

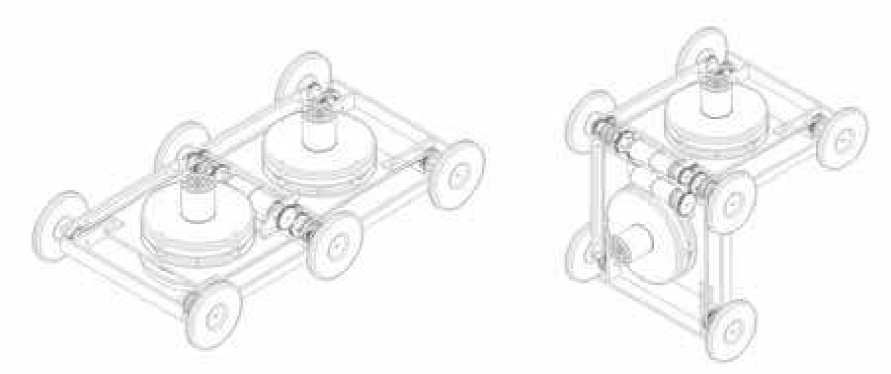


Fig. 17. City-Climber prototype-III, two modules are closely coupled with one transition motor placed in the middle and two other motors drive the two center wheels (left and right), and via the driving belts drive the front and rear wheels

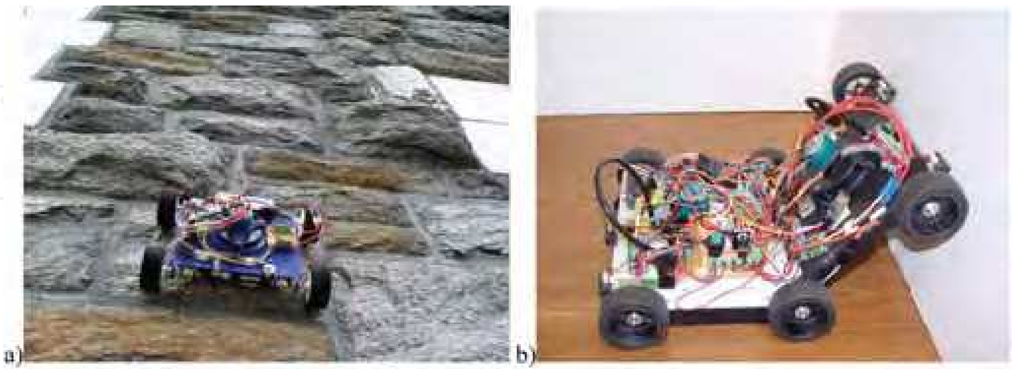


Fig. 18. City-Climber prototype-III: a) One module resting on a brick wall; b) two module

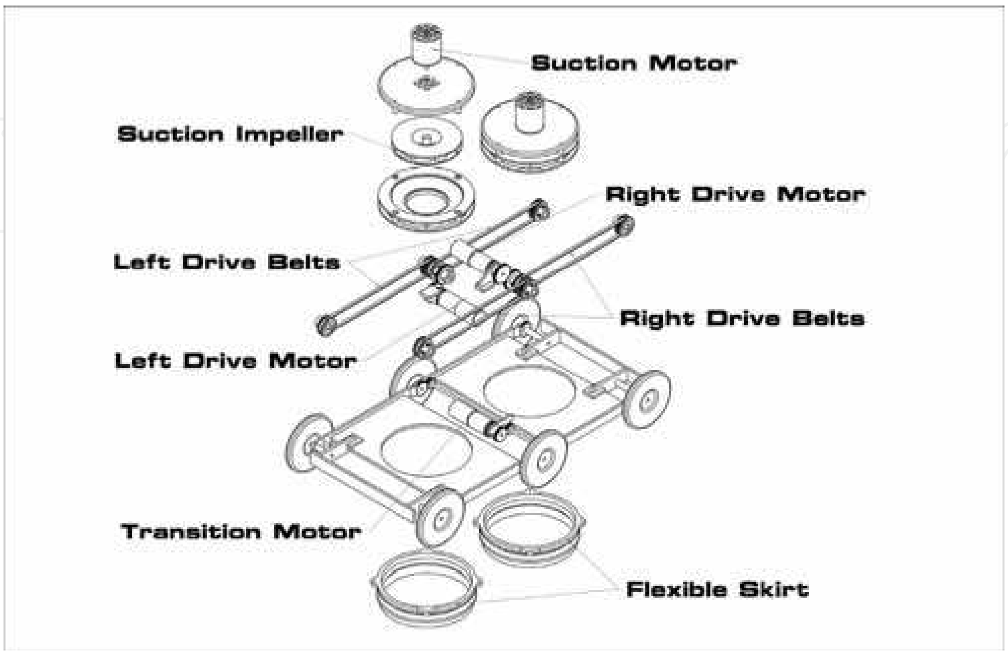


Fig. 19. Exploded view of City-Climber prototype-III

4. Control System

Good mechanical structure cannot guarantee excellent performance. It is crucial to design an effective control system to fully realize the potential of the City-Climber and empower it with intelligence superior to other robots. Resource-constrained miniature robots such as the City-Climber require small but high-performance onboard processing unit to minimize weight and power consumption for prolonged operation. The TMS320F2812 digital signal processing (DSP) chip from Texas Instruments (TI) Inc. is an ideal candidate for an embedded controller because of its high-speed performance, its support for multi-motor control and the low power consumption. This section describes the DSP-based control system design.

4.1 Actuators and Sensor Suite

To minimize weight and complexity, the City-Climber robots use limited number of actuators and sensor components. The actuators in each module include the two drive motors, one lift motor, all of them are DC servo motors with encoder feedback, and one suction motor. The primary sensor components include pressure sensors for monitoring the pressure level inside the vacuum chamber; ultrasonic sensors and infrared (IR) sensors for distance measurement and obstacle avoidance; a MARG (Magnetic, Angular Rate, and Gravity) sensor for tilt angle and orientation detection. For remote control operation the robot has a wireless receiver module, which communicates with the transmitter module in a remote controller. All the signals from those components and sensors need to be processed and integrated into an on-board control system.

Apart from the primary sensors which are critical for operation, additional application sensors can be installed on the robot as payloads when requested by specific tasks. For reconnaissance purpose, a wireless pin-hole camera is always installed and the video images are transmitted to and processed at a host computer.

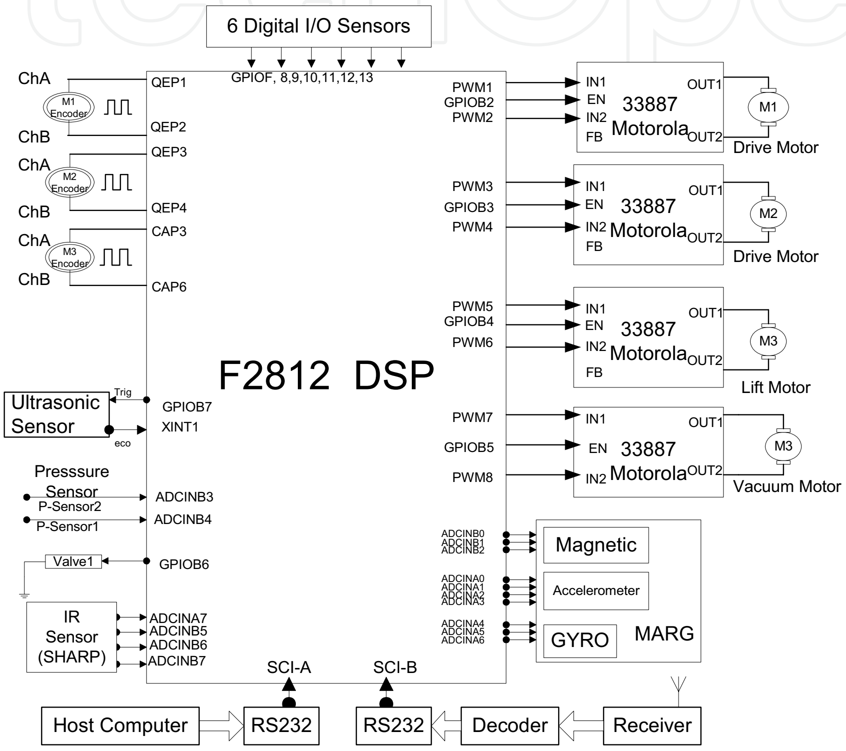


Fig. 20. Hardware design of DSP-based control system

4.2 Hardware Design

The F2812 is a 32-bit DSP controller (TI 2003) targeted to provide single chip solution for control applications. This chip provides all the resources we need to build a self-contained embedded control system. Fig. 20 illustrates the hardware connection based on F2812 DSP. The DSP controller produces pulse width modulation (PWM) signals and drives the motors via 4 Motorola H-bridge chips (Motorola 33887). F2812 DSP has two built-in quadrature encoder pulse (QEP) circuits. The encoder readings of the two drive motors are easily obtained using the QEP channels while a software solution (Xiao et al.; 2000) is implemented to get encoder reading of the lift motor using the Capture units of the DSP. With the encoder feedback, a closed-loop control is formed to generate accurate speed/position control of the drive motors and lift motor. The speed of the vacuum motor is adjusted with the feedback from the pressure sensors. Using Analog to Digital Converter (ADC) the pressure inside the vacuum chamber is monitored continuously. If the pressure reading is higher than a threshold, the vacuum motor increases the speed to generate more suction force. If the pressure drops too low and the suction force prevent the robot from moving, the vacuum motor will slow down to restore the pressure. An ideal pressure will be maintained which keeps the robot sticking to the wall and with certain mobility.

The climbing robot can be operated both manually and semi-autonomously. Infrared sensors are installed to measure distances from close proximity objects, while ultrasonic sensors are used to measure distance from objects that are far away. The infrared sensor has a reliable reading in the range of 10 cm to 80 cm and the ultrasonic sensor has a reliable range between 4 cm to 340 cm. External interrupt (XINT) channel is connected to the ultrasonic sensor to measure the time-of-fly of sound chirp and convert the measurement to distance reading. In order for the climbing robot to understand its orientation and tilt angle, a MARG sensor is integrated into the control system. The MARG sensor (Bachmann et al., 2003) is composed of nine sensor components of three different types affixed in X-Y-Z three axes: the magnetic sensor, accelerometer, and gyro. The magnetic sensors allow the robot to know its orientation with respect to a reference point (i.e., north pole). The accelerometers measure the gravity in three axes and thus provide tilt angle information to the robot. The gyro sensors measure angular rates which are used in the associated filtering algorithm to compensate dynamic effects. The DSP controller processes the inputs from the nigh MARG sensor components via ADC and provides the robot with dynamic estimation of 3D orientation which is very important for robot navigation.

There are two ways the DSP controller communicates with external sources. Host computer can exchange data with DSP controller via serial communication interface (SCI) using RS232 protocol. Another source that can send commands to the DSP controller is a radio remote controller. This is accomplished by interfacing a receiver with a decoder and then translating the commands into a RS232 protocol compatible with SCI module.

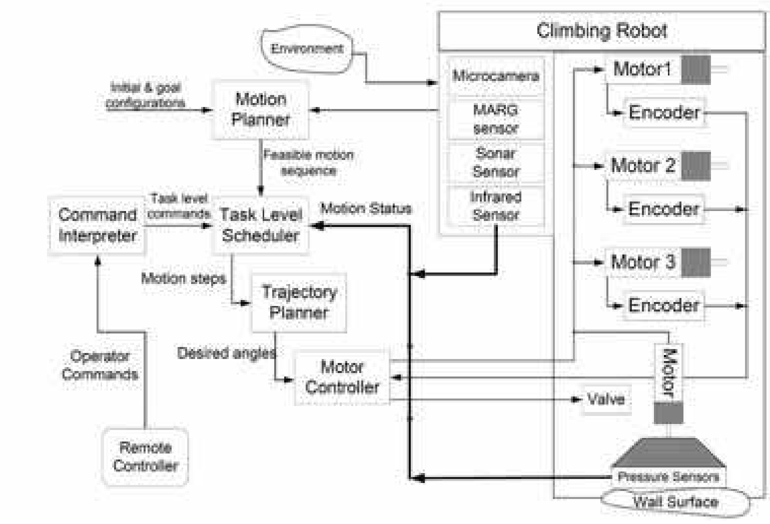


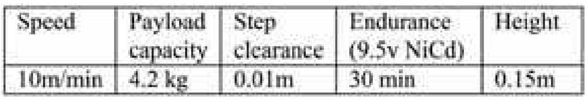
Fig. 21. Control system block diagram

4.3 Software Modules

The control system structure is illustrated in the block diagram as shown in Fig. 21. The physical actuators and sensors are represented in the right block. Other blocks represent the on-board software modules including command interpreter, task level scheduler, trajectory planner, motor controller and motion planner. The operator commands, such as “move forward”, “make left turn”, are transmitted from the remote controller held by a human operator and decoded by the on-board command interpreter. The generated task level commands are then fed into the task level scheduler. The task level scheduler uses a finite state machine to keep track of robot motion status and decompose the command into several motion steps. The trajectory planner interpolates the path to generate a set of desired joint angles. The digital motor controller then drives each motor to the desired set points so that the robot moves to the desired location. The motion planner module generates a feasible motion sequence and transmits it to the task level scheduler. After the motion sequence has been executed, the robot is able to travel from its initial configuration to its goal configuration, while avoiding the obstacles in the environment.

5. Experimental Test

Experiments were conducted to evaluate the performance of City-Climber prototypes. The main areas of functionalities and several key experimental tests are recorded in video which is downloadable from website http://robotics.ccny.cuny.edu/. The specifications of the City-Climber robots are listed in table 1.



Speed	Payload capacity	Step clearance	Endurance (9.5v NiCd)	Height
10m/min	4.2 kg	0.01m	30 min	0.15m

Table1. Physical specifications of the City-Climber robots

It was demonstrated that the City-Climber robots are able to move on various wall surfaces, such as brick, wood, glass, stucco, plaster, gypsum board, and metal. With the module weight of 1kg, the City-Climber can generate enough adhesion force to carry additional 4.2kg payload. The video also shows that the City-Climber can operate on real brick wall, and cross surface gaps without difficulty.

6. Conclusion and Future Work

This chapter highlights some accomplishments of CCNY robotics team in developing novel wall-climbing robots that overcome the limitations of existing technologies, and surpass them in terms of robot capability, modularity, and payload. The performance of several City-Climber prototypes are demonstrated by the experimental results recorded in video. By integrating modular design, high-performance onboard processing unit, the City-Climber robots are expected to exhibit superior intelligence to other small robot in similar caliber.

The next step of the project is to optimize the adhesion mechanism to further increase suction force and robot payload, and to improve the modularity and transition mechanism to allow the robot re-configure its shape to adapt to different missions. Other directions are to increase the robot intelligence by adding new sensors, improving on-board processing unit, and developing software algorithms for autonomous navigation.

7. Acknowledgment

This work was supported in part by the U.S. Army Research Office under grant W911NF-05-1-0011, and the U.S. National Science Foundation under grants ECS-0421159, CNS-0551598, CNS-0619577 and IIS-0644127. The authors would like to thank all the team members for their contributions to the climbing robot project, especially Matt Elliot and William Morris for mechanical design, Parisa Saboori for Fluent simulation, Angel Calle and Ravi Kaushik for control system design.

8. References

Asbeck, A; Kim, S.; Cutkosky, M. R.; Provancher, W. R. & Lanzetta, M. (2006). Scaling Hard Vertical Surfaces with Compliant Microspine Arrays. *International Journal of Robotics Research,* Vol. 15, No. 12, pp. 1165-1180, 2006.

Autumn, K.; Liang, Y; Hsieh, T.; Zesch, W.; Chan, W. P.; Kenny, T.; Fearing, R. & Full R. J. (2000). Adhesive force of a single gecko foot-hair. Nature, 405:681-684, 2000.

Bachmann, E. R.; Yun, X. P.; McKinney, D.; McGhee, R. B. & Zyda, M. J. (2003). Design and implementation of MARG sensors for 3-DOF orientation measurement of rigid bodies, Proceeding of 2003 IEEE International Conference on Robotics and Automation, Taipei, Taiwan, May 2003.

Backes, P. G; Bar-Cohen, Y. & Joffe, B. (1997). The multifunction automated crawling system (MACS), *Proceedings of the 1997 IEEE International Conference on Robotics and Automation,* pp. 335--340, Albuquerque, New Mexico, USA, 1997.

Bretl, T; Rock, S. & Latombe, J. C. (2003). Motion Planning for a Three-Limbed Climbing Robot in Vertical Natural Terrain, In Proceedings of IEEE International Conference on Robotics and Automation, Taipei, Taiwan, Sep 2003.

Briones, L; Bustamante, P.; & Serna, M. A. (1994). Wall-climbing robot for inspection in nuclear power plants, *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, pp. 1409--1414, 1994.

Clark, J; Goldman, D; Lin, P; Lynch, G; Chen, T; Komsuoglu, H; Full, R; Koditschek, D. (2007). Design of a Bio-inspired Dynamical Vertical Climbing Robot, *Proceedings of Robotics: Science and Systems* 2007, Atlanta, Georgia, USA, June, 2007, on line proceedings, http://www.roboticsproceedings.org/rss03/index.html.

Elkmann, N.; Felsch, T.; Sack, M.; Saenz, J. & Hortig, J. (2002). Innovative Service Robot Systems for facade cleaning of Difficult-to-access arears, *Proceedings of 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 756 – 762, Lausanne, Switzerland, Oct. 2002.

Elliott, M; Xiao, J; Morris, W.; Calle, A. (2007). City-Climbers at Work Video Proceeding of the 2007 IEEE International Conference on Robotics and Automation, pp2764-2765, Roma, Italy, April 2007.

Grieco, J. C; Prieto, M; Armada, M; & Santo, P. (1998). A six-legged climbing robot for high payloads, *Proceedings of the 1998 IEEE International Conference on Control Applications*, pp. 446--450, Trieste, Italy, 1998.

Guo, L; Roger, K & Kirkham, R (1997). A climbing robot with continuous motion, *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, pp. 2495--2500, Albuquerque, New Mexico, USA, 1997.

Hirose, S. & Tsutsumitake, H. (1992). Disk rover: A wall-climbing robot using permanent magnet disks, *Proceedings of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2074--2079, Raleigh, NC, 1992.

Illingworth, L. & Reinfeld, D. (2003). Vortex attractor for planar and non-planar surfaces, US Patents #6619922, Sept. 2003.

Kalra, L. P.; Gu, J.; Max, M. (2006). Wall Climbing Robot for Oil Tank Inspection, *Proceedings of the IEEE International Conference on Robotics and Biomimetics*, pp. 1523 – 1528, Dec. 2006.

Kawaguchi, Y; Yoshida, I; Kurumatani, H.; Kikuta, T. & Yamada, Y. (1995). Internal pipe inspection robot, *Proceedings of the 1995 IEEE International Conference on Robotics and Automation*, pp. 857--862, 1995.

Kim, S., Asbeck, A., Provancher, W. & Cutkosky, M.R. (2005). SpinybotII: Climbing Hard Walls with Compliant Microspines, Proceedings of 12th International Conference on Advanced Robotics, pp. 601-606, July 18-20, 2005.

Kim, S; Spenko, M; Trujillo, S.; Heyneman, B; Mattoli, V. & Cutkosky, M. R. (2007). Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot, *Proceedings of the 2007 IEEE International Conference on Robotics and Automation*, pp. 1268-1273, Rome, Italy, April 2007.

Longo, D. & Muscato, G. (2006). The Alicia 3 Climbing Robot, a Three-Module Robot for Automatic Wall Inspection, IEEE Robotics and Automation Magazine, Vol. 13, No. 1, March 2006.

Luk, B; Collie, A.; Piefort, V. & Virk, G. (1996). Robug III: A tele-operated climbing and walking robot, *Proceedings of UKACC International Conference on Control*, pp. 347--352, 1996.

Murphy, M. P. & Sitti, M. (2007). Waalbot: An Agile Small-Scale Wall-Climbing Robot Utilizing Dry Elastomer Adhesives, IEEE/ASME Transactions on Mechatronics, Vol. 12, Issue 3, pp. 330-338, June 2007.

Nagakubo, A. & Hirose, S. (1994), Walking and running of the quadruped wall-climbing robot, *Proceedings of the 1994 IEEE International Conference on Robotics and Automation,* pp. 1005--1012, 1994.

Nishi, A. & Miyagi, H. (1991). A wall climbing robot using propulsive force of propeller, *Proceedings of the Fifth International Conference on Advanced Robotics*, pp. 320--325, 1991.

Nishi, A. & Miyagi, H. (1994). Mechanism and control of propeller type wall-climbing robot, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1724--1729, 1994.

Pack, R. T.; Christopher, J. L.; & Kawamura, K (1997). A rubbertuator-based structure climbing inspection robot, *Proceedings of the 1997 IEEE International Conference on Robotics and Automation,* pp 1869--1874, Albuquerque, New Mexico, USA, 1997.

Qian, Z. Y.; Zhao, Y. Z.; Fu, Z. (2006). Development of Wall-climbing Robots with Sliding Suction Cups, *Proceedings of 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3417 – 3422, Beijing, China, Oct. 2006.

Rosa, G. L; Messina, M; Muscato, G. & Sinatra, R. (2002). A low-cost lightweight climbing robot for the inspection of vertical surfaces. *Mechatronics*, 12(1):71–96, 2002.

Santos, D.; Kim, S.; Spenko, M.; Parness, A. & Cutkosky, M. R. (2007). Directional Adhesive Structures for Controlled Climbing on Smooth Vertical Surfaces, *Proceedings of the 2007 IEEE International Conference on Robotics and Automation*, pp. 1262-1267, Rome, Italy, April 2007.

Shen, W; Gu, J; and Shen, Yanjun. (2005). Proposed Wall Climbing Robot with Permanent Magnetic Tracks for Inspecting Oil Tanks, *Proceedings of the IEEE International Conference on Mechatronics & Automation,* pp. 2072-2078, Niagara Fall, Canada, July 2005.

Sitti, M. & Fearing, R. S. (2003). Synthetic Gecko Foot-Hair Micro/Nanostructures for Future Wall-Climbing Robots, Proceedings of the IEEE Robotics and Automation Conference , pp. 1164-1170, Sept. 2003.

Sun, L; Sun, P; Qin, X. & Wang, C. (1998). Micro robot in small pipe with electromagnetic actuator, *Proceedings of the International Symposium on Micromechatronics and Human Science*, pp. 243--248, 1998.

TI (2003). TMS320F2812 DSP controllers reference guide, Texas Instruments Inc., January 2003.

Tummala, R. L; Mukherjee, R.; Xi, N; Aslam, D.; Dulimarta, H.; Xiao, J. Z.; Minor, M; Dangi, G. (2002). Climbing the Walls, *IEEE Robotics and Automation Magazine*, Vol. 9, No. 4, pp. 10-19, Dec. 2002.

Wang, Y; Liu, S; Xu, D; Zhao, Y; Shao, H. & Gao, X. (1999). Development and application of wall-climbing robots, *Proceedings of the 1999 IEEE International Conference on Robotics and Automation*, pp. 1207--1212, Detroit, Michigan, USA, 1999.

White, T. S.; Hewer, N.; Luk, B. L. & Hazel, J. (1998). Design and operational performance of a climbing robot used for weld inspection in hazardous environments, *Proceedings of the 1998 IEEE International Conference on Control Applications*, pp. 451--455, Trieste, Italy, 1998.

Xiao, J. Z.; Sadegh, A.; Elliot, M.; Calle, A.; Persad, A.; Chiu, H. M. (2005). Design of Mobile Robots with Wall Climbing Capability, Proceedings of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp438~443, July 2005.

Xiao, J. Z.; Dulimarta, H.; Yu, Z.; Xi, N. & Tummala, R. L. (2000). DSP solution for wall-climber microrobot control using TMS320LF2407 chip, Proceedings of the 43rd IEEE Midwest Symposium on Circuits and Systems, Lansing, Michigan, USA, 2000.

Yano, T; Numao, S. & Kitamura, Y. (1998). Development of a self-contained wall climbing robot with scanning type suction cups, *Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 249--254, Victoria, Canada, 1998.

Zhang, H. X.; Zhang, J. W. & Zong G. H. (2004). Realization of a Service Climbing Robot for Glass-wall Cleaning, Proceedings of the 2004 IEEE International Conference on Robotics & Biomimetics, pp. 395 -400, Shenyang, China, Aug. 2004.

Zhu, J; Sun, D. & Tso, S. K. (2002). Development of a tracked climbing robot. *Journal of Intelligent and Robotic Systems*, 35(4):427–444, 2002.

Climbing and Walking Robots: towards New Applications
Edited by Houxiang Zhang

ISBN 978-3-902613-16-5
Hard cover, 546 pages
Publisher I-Tech Education and Publishing

Published in print edition October, 2007

With the advancement of technology, new exciting approaches enable us to render mobile robotic systems more versatile, robust and cost-efficient. Some researchers combine climbing and walking techniques with a modular approach, a reconfigurable approach, or a swarm approach to realize novel prototypes as flexible mobile robotic platforms featuring all necessary locomotion capabilities. The purpose of this book is to provide an overview of the latest wide-range achievements in climbing and walking robotic technology to researchers, scientists, and engineers throughout the world. Different aspects including control simulation, locomotion realization, methodology, and system integration are presented from the scientific and from the technical point of view. This book consists of two main parts, one dealing with walking robots, the second with climbing robots. The content is also grouped by theoretical research and applicative realization. Every chapter offers a considerable amount of interesting and useful information.

How to reference

Jizhong Xiao and Ali Sadegh (2007). City-Climber: A New Generation Wall-Climbing Robots, Climbing and Walking Robots: towards New Applications, Houxiang Zhang (Ed.), ISBN: 978-3-902613-16-5, InTech, Available from: http://www.intechopen.com/books/climbing_and_walking_robots_towards_new_applications/city-climber__a_new_generation_wall-climbing_robots

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821