City-Climber: Development of a Novel Wall-Climbing Robot

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ABSTRACT
This article describes a novel mobile wall-climbing robot named City-Climber that has the capabilities to move on the ground, climb walls, walk on ceilings, and transit between different surfaces. Unlike the traditional climbing robots using magnetic devices and vacuum suction techniques, and the robots inspired by the gecko foot, the City-Climber robot is based on aerodynamic attraction which achieves good balance between strong adhesion force and high mobility, and can carry a large payload. Since our robots do not require perfect sealing as the vacuum suction technique does, the City-Climber robots can move on virtually any kind of smooth or rough surfaces. We envision that the City-Climber robots will be used in urban environments with potential applications in inspection of high-rise buildings, search and rescue operations, reconnaissance and surveillance.

KEYWORDS: Mobile robots, suction, wall-climbing robot, aerodynamic attraction

INTRODUCTION
In the last few decades, the field of mobile robotics has developed from theoretical research to practical applications. Consumers can now buy a Roomba robotic vacuum cleaner from iRobot Inc. to clean their floors or a Robomow from Friendly Robotics Inc. to mow their lawn. Hospitals have started using mobile robots to deliver lab specimens and the oil industry uses mobile robots to inspect oil pipelines. The military also uses mobile robots to perform various dangerous tasks such as disarming improvised explosive devices and landmines. All of these robots have one thing in common—they all operate in a 2-D space.

The City-Climber is part of a new generation of mobile robots that are capable of operating in three dimensions. The ability to move up walls and across ceilings allows these robots to operate in areas that would otherwise be inaccessible and perform tasks that would otherwise be expensive or impossible. These robots can be used for building, aircraft and bridge inspections, tasks which would otherwise require expensive scaffolding and place human workers at risk. Consumer applications of wall-climbing robots include window cleaning and painting; public safety and military applications include surveillance, search and rescue.

The Biomimetics Dextrous Manipulation Laboratory at Stanford University has developed a gecko-like wall climbing robot, “Stickybot,” which uses the van der Waals force to adhere to surfaces. Stickybot moves quickly on smooth surfaces, but its current design appears to have a limited payload and the directional adhesive may have trouble operating on dirty or rough surfaces. Michigan State University has produced two wall climbing robots, Flipper and Crawler, which adhere to the walls using micro-pumps to generate suction. The articulated design of these robots allows them to transition easily between two planar surfaces with relatively heavy payload. The downside of the design of these robots is their slow speed and inability to work on rough surfaces such as brick walls. The wall-climbing robot manufactured by Clarifying Technologies Inc. is a commercially available four-wheeled robot capable of quickly driving up rough surfaces; it uses a vortex suction mechanism to adhere to walls. The payload for this robot, however, is limited to about one pound.

The goal of our research is to overcome the limitation of these robots by producing the City-Climber robot which is small, lightweight, and be capable of non-destructive adhesion on both smooth and rough surfaces, with strong attraction force to carry a significant payload and sufficient mobility for travel on various planar surfaces and the ability to transit between them.

MECHANICAL DESIGN
The mechanical design of the City-Climber is divided into three main areas; the adhesion mechanism, the drive system and the
After working in industry for a few years, William Morris has re-entered the academic realm and is a Mechanical Engineering senior at the Grove School of Engineering. He has been performing research at the CCNY Robotics Lab where he has been collaborating with a team developing a wall climbing robot under the mentorship of Professor Jizhong Xiao. One lesson William has learned on the project is that of perseverance: “On the wall climbing robot project, the most interesting work was finding out all of the ways not to make a wall climbing robot that works.” Through his research experience, William has found that he was better able to connect the theoretical class work with real world applications.

William is also the founding President of the CCNY Robotics Club which has been working on several research and outreach projects. The club’s biggest project will be working to develop an autonomous helicopter for the Association for Unmanned Vehicle Systems International (AUVSI) International Aerial Robotics Competition (IARC). He has also led the club to participate in educational outreach by mentoring high school students in the FIRST (For Inspiration and Recognition of Science and Technology) Robotics Competition. William plans to attend graduate school with an emphasis in the field of robotics and to continue working in a research environment.

Transition system. The adhesion mechanism is the most critical of these as it allows the robot to adhere to the surface on which it climbs. The drive system is designed to transmit power to four wheels of the robot and to provide maximum traction as it climbs. The transition system has been designed to allow the City-Climber to move from a vertical wall to a ceiling.

**Adhesion Mechanism**

The City-Climber uses a vacuum rotor package that generates a low pressure zone enclosed by a flexible vacuum chamber to adhere to a variety of surfaces as shown in Figures 1 and 2. This adhesion mechanism is based on aerodynamic attraction and works in many ways like a hovercraft lift system in reverse. By considering the Navier-Stokes equations the pressure differential between the inside of the vacuum chamber and atmospheric pressure are shown to be generated by the velocity of the airflow and the mass flow rate of the impeller.

The main considerations for the design of the vacuum chamber include the radistance between the flexible skirt...
around the edge of the chamber, the surface being adhered to, and determination of the optimal speed and required torque of the motor. These parameters have been determined empirically and the results of our experiments will be used for future analytical and numerical optimization. The aerodynamics of the fluid flow inside the chamber and possible separation of flow at the impeller exhaust will also be considered; this will require further testing and experimental data to generate a model for computational fluid dynamics.

**Drive System**  The design of the drive system has proven to be surprisingly critical to the performance of the City-Climber. While climbing a wall, the adhesion mechanism provides a pressure differential which pushes the robot against the wall. A normal force at each wheel is created in reaction to the suction force created by the pressure differential.

To counter the force of gravity the static friction of the wheels must be considered. In the two-wheel drive case, half most by accident, simply by often thinking about the problems of static suction and happening to see information on tornadoes used for air contaminant removal and vortex propulsion.

He says that the path to discoveries is often accidental and much of the work is simply being highly interested in the target issue and thinking about it even outside the lab.

One of Dr. Xiao’s successes has been in using robotics in the teaching of engineering and technology to students. His establishment of a pipeline of students that spans from high school to undergraduate to graduate has given these students the opportunity for academic growth as well as a creative outlet.

He believes that robotic engineering allows for a diverse set of minds to come together to solve practical problems as well as serving as a way to improve the pipeline of students with an interest in robotics into the field of engineering.

\[
\sum N = F_{suction} \\
F_{suction} = 4N_{wheel} \\
F_{fwheel} = \mu N_{wheel} \\
mg = 4F_{fwheel}
\]

Where,

- \( N \) = Normal force
- \( F_{suction} \) = Friction of suction
- \( N_{wheel} \) = Normal force per wheel
- \( F_{fwheel} \) = Force of friction per wheel
- \( \mu \) = coefficient of friction
- \( m \) = mass
- \( g \) = gravity

**DR. JIZHONG XIAO** joined the Department of Electrical Engineering (EE) in September 2002, after receiving a Ph.D. from Michigan State University. He established the robotics research program at CCNY and is the founding director of the CCNY Robotics Lab and the Center for Perceptual Robotics, Intelligent Sensors and Machines (PRISM Center). He has received several grants to support robotics research and education at CCNY, including the prestigious CAREER grant award from the National Science Foundation. Under Dr. Xiao’s leadership, robotics research has become one of the most active and well-funded research directions in the EE department of the Grove School of Engineering.

Dr. Xiao began investigating wall-climbing robots as a Ph.D. student and developed a new prototype of single-module wall-climbing robots, the City-Climber, at CCNY. The robot uses a circular air current inside its vacuum chamber to attach to the wall, and the suction strength can be varied by adjusting the air current. As a result the robot can remain attached to even the most difficult surfaces, but can decrease attachment strength and “walk” on the wall when necessary. Sensors attached to the robot help it regulate the air current to remain attached to vertical surfaces, and video cameras aid in navigation. This is a revolutionary switch from the long-used approach of attachment through static suction, which cannot be regulated and which often fails on uneven or moist surfaces. The City-Climber is poised to be the prototype of a new generation of wall-climbing robots, which would be used in previously impossible settings.

Dr. Xiao developed the idea of air-current suction from considering the mechanism of tornadoes, which “attach” themselves to the ground through the suction created by their high-speed circular winds. The idea came to him almost by accident, simply by often thinking about the problems of static suction and happening to see information on tornadoes used for air contaminant removal and vortex propulsion.

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of the normal force is distributed across the driven wheels. For four-wheel drive the normal force is applied fully to the driven wheels.

The static or rolling coefficient of friction is specific to the particular wheel and wall combination. The physics of the system shows that four-wheel drive is superior to two-wheel drive for providing maximum traction. Due to the need to provide four-wheel drive and concerns about the additional weight of adding motors, a mechanical power transmission is required. The power transmission of the drive system needs to be capable of providing power reliably to the front and back wheels of each side of the robot. Several methods of power transmission have been considered and we eventually selected a fine pitch metal roller chain to transmit power between the wheels.

**Transition System**

The transition system of the City-Climber is designed to allow the robot to move quickly from ground to a wall and from a wall to the ceiling. The ground-to-wall transition can be easily accomplished by a single module with four wheels outside of the structure frame (Figure 4). To accomplish the wall-to-ceiling transition, two modules are linked together by servo actuated hinge (Figure 6). The weight of the front module should be small since it creates a moment around the back wheel of the second module when the robot in its folded configuration approaches the ceiling. This moment, combined with the torque applied to the back wheel by the motors, tends to cause the robot to rotate off the wall. The transition mechanism has been tested in static configuration and proven to be feasible; however movement in this configuration has not yet been successful. Current effort focuses on reducing the weight of the front module by producing its components out of low-weight carbon fiber material.

**CONTROL SYSTEM**

As a self-contained system, the City-Climber robot carries its own power source, sensors, control system and associated hardware. To minimize weight and complexity, each City-Climber module uses two drive motors, one lift motor, and one impeller motor. A pressure sensor is installed for monitoring the pressure level inside the vacuum chamber and forms a feedback loop to adjust the impeller speed. Thus, it allows the robot to conserve battery power while moving on smooth, flat surfaces and provides additional airflow when moving over gaps and on rough surfaces. The accelerometer provides the robot, while stationary, with orientation information so that it can determine which direction is down. The motor encoders send a series of
pulses as the drive motor rotates, where each pulse represents a fixed angular increment, typically on the order of radians. Additional sensors can be installed on the robot as payload when requested by specific tasks such as the wireless camera for inspection and reconnaissance purposes and laser range finder for 3-D modeling.

EXPERIMENTAL RESULTS

The City-Climber has been tested on a wide variety of surfaces. One test involved driving three stories up the side of a brick wall. In another experiment the robot was able to drive smoothly on a glass window. The payload capabilities have been tested using a spring scale, and the robot can carry a payload of about four kilograms, which is the highest payload among existing robots of similar size. In other experiments the transition system has been shown to allow the City-Climber to transit quickly and smoothly from the floor to a vertical wall.

The City-Climber was most recently used in conjunction with three mobile ground robots to co-operatively produce 3-D maps.
in indoor environments. The City-Climber was positioned on the ceiling, while the three ground robots were dispersed in the hallway. All of the robots were equipped with 3-D laser scanners and cameras for constructing a 3-D laser map as shown in Figures 7 and 8.

The video [2] illustrates the capabilities of City-Climber robots and shows the results of several key experimental tests. This video is the finalist for the ICRA2006 BEST VIDEO AWARD and can be downloaded from http://robotics.ccny.cuny.edu.

CONCLUSIONS AND FUTURE WORK
The City-Climber has shown to be successful at many tasks that have not previously been possible for mobile robots. It is notable among wall climbing robots for its large payload, and versatile mobility on both smooth and rough surfaces. Future work is to optimize the adhesion mechanism and further improve the performance of the City-Climber and apply it to building inspection tasks.

REFERENCES
