RISE-ROVER: A WALL-CLIMBING ROBOT WITH HIGH RELIABILITY AND LOAD-CARRYING CAPACITY*

JIZHONG XIAO, BING LI

Electrical Engineering Department
The City College, City University of New York
160 Convent Avenue, New York, NY 10031, United States
{jxiao, bli}@ccny.cuny.edu

KENSHIN USHIRODA, QIANG SONG

InnovBot LLC, Zahn Center for Entrepreneurship at Grove School of Engineering
The City College, City University of New York
160 Convent Avenue, New York, NY 10031, United States
{kenshinushiroda, songqiangty}@gmail.com

This paper presents Rise-Rover, a new generation wall-climbing robot with high reliability and load-carrying capacity on vertical surfaces for Non-Destructive Testing (NDT) of concrete and steel infrastructure. One Rise-Rover drivetrain module can operate on both smooth and rough vertical/inclined surfaces independently. The on-board electronics and PID controller monitor the pressure reading and adjust impeller speed to provide stable suction force for the wall-climbing robot. The use of duct fan and tether further increase the operation reliability. Rise-Rover is remotely controlled by Android smartphone via Wifi, and the User Interface (UI) provides good usability and convenience. The experimental test verified the good performance of the Rise-Rover prototype.

1. Introduction

The civil infrastructure (e.g., buildings, bridges, tunnels, dams, concrete towers) that was built in the mid-20th century or earlier in the United States and across the world is reaching its life expectancy, leaving questions about their structural integrity and deterioration levels, thus have strong needs for routine inspection and maintenance to ensure sustainability. In addition to visual inspection of surface flaws, the inspectors need to detect subsurface defects (i.e., cracks, delamination, and voids) using NDT instruments such as ground penetration radar (GPR) or impact echo device to inspect the structural integrity of concrete

* This work is supported by U.S National Science Foundation I-Corps program and STTR Phase-1 grant: “Wall-climbing robots for nondestructive inspection to ensure sustainable infrastructure”.

and steel structures. It is a very challenging job to inspect vertical surfaces and other difficult to access places. The current practice of manual inspections is time consuming, expensive and often requires the use of extensive scaffolding, leading to human safety concerns. Climbing robots with the ability to maneuver on vertical surfaces are needed to automate the inspection process, which will provide vertical mobility and allow inspections to be performed significantly faster, safer and more thorough, at a lower cost, by eliminating the costly scaffolding.

2. Related Work

To successfully accomplish NDT inspection task, the climbing robots should have reliable adhesion, high maneuverability, large payload/weight ratio, and adaptability on a variety of wall surfaces. The most challenging work in climbing robot design is the adhesion method to ensure that the robots grip the target surface firmly and without sacrifice of maneuverability. So far, researchers around the world have developed adhesion mechanisms that mainly fall in six categories: 1) magnetic adhesion devices for climbing ferrous surfaces [3]; 2) vacuum suction techniques for operation on smooth and nonporous surfaces [4]; 3) attraction force generators based on aerodynamic principles [1, 2, 5]; 4) grippers; 5) bio-mimetic approaches inspired by climbing animals [6]; and 6) other emerging techniques such as compliant electroadhesion. The book chapter [7] by Dr. Jizhong Xiao provides a comprehensive review on the climbing robot technologies.

The immediate competitor comes from International Climbing Machines (ICM) which produces a large robot platform using an AC vacuum pump to generate strong suction and using rolling tread with thick foam to create perfect seal perimeter as shown in Figure 1. It is so far the most mature robot prototype that has the potential to be used in NDT inspection of civil infrastructure [8]. The ICM robot can generate very strong adhesion on smooth and rough surfaces and overcome small surface irregularities thanks to the conformable thick form. However, the major weakness of this robot is that it has one vacuum chamber that requires perfect sealing enclosed by the thick foam tread. The robot falls when the vacuum breaks, and it happened when the robot crosses a ditch or deep groove/crack -- which are very common on brick/concrete walls.

Figure 1. ICM robot uses rolling seal and AC suction pump for strong adhesion.

3. Mechanical System of Rise-Rover

3.1. *Mechanism*

Figure 2 shows the innovative design of Rise-Rover climbing robot prototype. The robot uses two drivetrain modules on each side, and two ducted fans in the middle of the chassis. Each drivetrain module can operate on wall surface independently and two modules can carry payload in the middle payload area.

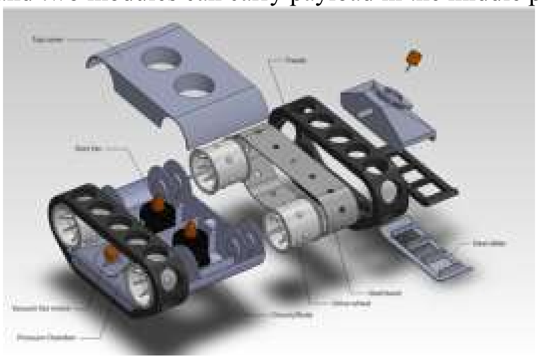

Figure 2. Exploded view of the Rise-Rover robot.

The design of a drivetrain module is shown in Figure 3. The drivetrain consists of two driving wheels, a foam tread, a rotor package with air chamber and impeller, and a perforated spring steel band (belt). The backside of the foam tread is lined with the belt which acts to provide structure and prevent deformation to the tread. The holes in the belt allow the driving wheels to pull the belt with matching teeth, and also serve as ports for the air to be evacuated from the circular openings in the foam. The ultra-high-density foam is adaptable to surface irregularity and provide a rolling seal to the chamber. The chamber is evacuated by a 2.75-inch diameter vacuum impeller powered by an ultra-fast and highly efficient brushless motor. The chamber is divided into three sections and contains two pressure valves which close upon the break of a seal, virtually increasing the number of independent chamber seals to three.

Figure 3. A drivetrain with foam tread and vacuum rotor package.

The rotor package is an improved design variance of the one used at City-Climber robot (our old generation wall-climbing robot). The rotor package produces adhesion for the drivetrain to scale vertical walls while the high-density foam is conformable to surface irregularity and helps to muffle the impeller noise. The design has been undergo several iterations of improvement with multiple validation tests. We evaluated the relationship between impeller speed and adhesion force, and the improvement in noise/disturbance reduction, etc. The most critical test is to determine if the track can rotate when it is pushed against the wall with maximum suction force. The experiment comes out that the driving motor, when powerful enough, is able to overcome the friction on the track and provide adequate mobility. We also tested the valves function well in dividing the chamber into multiple sections for independent sealing effects.

3.2. *Design for Reliability*

For any wall-climbing robots working on the vertical surfaces, reliability is a very critical factor. The climbing robots must be able to supply necessary adhesion to operate on various wall surfaces, attach to a wiring harness for safety, and implement fault tolerance features to deal with deep cracks/ditches, ledges/overhangs on wall surfaces.

Since our Rise-Rover robot has three individual chamber seals on each tread, any straight-line gaps cannot cross all six chamber seals at any given time. Thus, the robot is able to cross over ditches, which our previous version City-Climber failed to cross over.

Another novel design for reliability is duct fans to push the robot in contact with the wall when suspended in midair as shown in Figure 4. The thick foam tread is deformable to cope with surface irregularities that may exist. The propellers of two duct fans generate push force to allow re-attachment of the robot to vertical walls when it loses contact with the surface.

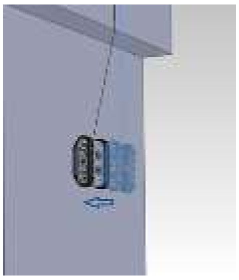

Figure 4. Duct fans push the robot in contact with wall surface.

4. Electronics and Software

4.1. *Electronics Design*

The Rise-Rover platform was designed to initially use minimal control and sensing to reduce the weight of the overall system and simplify the electronics configuration. The requirements of the system called for a programmable controller capable of driving two brushed dc motor, and four DC brushed wheel motors, as well as the onboard Live-Camera or NDT devices to be installed in the middle payload compartment. The integrated controllers onboard are the ATmega32u4 running Arduino Leonardo, and Atheros AR9331 running Linux with the OpenWrt wireless stack. The board has built-in Ethernet and Wifi support, a USB-A port, micro-SD card slot, 20 digital input/output pins (of which 7 can be used as PWM outputs and 12 as analog inputs), a 16 MHz crystal oscillator, a micro USB connection, an ICSP header, and a 3 reset buttons. This microcontroller incorporates all of these specifications into a board that is 73 mm × 53 mm and weighs 32 g. The suction motors are powered by 6 cells of 3.7 V battery, and wheel motors are driven by 3 cells of 3.7 V battery.

The electrical system diagram of Rise-Rover is shown in Figure 5. The user level control is running on Android platform, and it provides the user interface (UI) and data transmission from the climbing robot, also further transfer to the data server. The middle level control is based on the embedded Linux system which handles on-board peripheral devices (surveillance camera, extended NDT device, etc.), and the data transmission. The lower level control is based on the Arduino, which process the real-time motor control, and odometry calculation for left/right wheel motors, left/right vacuum motors and monitor pressure sensor reading.

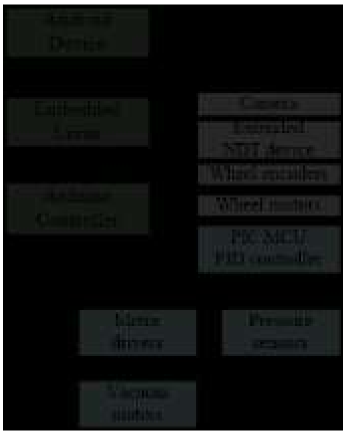

Figure 5. Electrical System Diagram.

The high-speed blushless DC motor, along with the PID control using pressure measurement as feedback, is designed for the vacuum suction system. To support more than 60K RPM high speed and make it compactable, we design and integrate the controller and driver in one PCB board (50 mm x 30 mm).

4.2. *Software Design*

The software development strategy for Rise-Rover has been to build robust software, incorporating modular code wherever possible. A variety of control schemes were investigated, and the PID control with the pressure feedback is used to adjust the vacuum motor speed to generate reliable suction on wall surfaces.

The Android device is connected directly to the Wifi router on climbing robot, to control the locomotion of the robot, and display the onboard live camera scream wirelessly. The resolution and fps (frames per second) is set smaller as the distance between climbing robot and Android device is bigger. The settings menu for the App includes the settings for locomotion speed, acceleration, camera, Wifi, etc.

5. Experiments

After several design/test iterations, we have successfully developed our Rise-Rover prototype as shown in Figure 6. The innovations are the fault tolerant design using two drivetrain modules with soft/conformable treads to carry a much larger payload of NDT instruments. Each module has multiple suction/chamber seals that allow the robot to cross over gaps/grooves/cracks without loss of adhesion, and the introduction of duct fans allows for re-attachment to the wall surface for increased reliability.

The performance of the Rise-Rover is evaluated and the specs are summarized as follows:

- Dimension of each drivetrain module: 8 inches x21 inches x 5.5 inches
- The maximum normal suction force generated by each module: 30 lbs
- Whole unit self-weight of Rise-Rover (two drivetrain modules + payload chamber): 24 lbs
- Pull-up force of Rise-Rover (i.e., payload carrying on vertical wall): 16 lbs
- Locomotion speed of Rise-Rover: 30 meters/minute
- Power consumption: Peak 4KW

The Rise-Rover test videos can be seen at:

- http://tinyurl.com/Rise-Rover-1
- http://tinyurl.com/Rise-Rover-2
- http://tinyurl.com/Rise-Rover-Android-app

Figure 6 shows Rise-Rover that can operate on both smooth and rough surfaces. The black tread is made from a commercially available high-density thick foam. The custom-designed tread using light-weight foam encapsulated by silicon rubber is soft and conformable to surface irregularities while still allowing the robot to move and maintain strong suction against the surface.

Figure 6. Rise-Rover climbing robot test.

6. Conclusions

This paper presents a novel wall-climbing robot, Rise-Rover, which adopts many fault tolerant features to increase the reliability and has the capability to carry NDT instruments for subsurface flaw detection. We have conducted several design/test iterations and developed a drivetrain module using a rotor package and soft tread. The module not only produces strong adhesion enabling the independent operation on vertical walls but also helps to overcome surface irregularities and reduce the acoustic/vibration interference. The experimental tests show that the Rise-Rover works effectively on the vertical surface with small gaps or ditches. With the self-weight of 24 lbs, the Rise-Rover can carry 16 lbs on vertical wall at the locomotion speed of 30 meters/minute.

Acknowledgments

This work is supported by U.S National Science Foundation I-Corps program grant and STTR Phase-1 program grant: "Wall-climbing robots for nondestructive inspection to ensure sustainable infrastructure".

References

1. J. Z. Xiao, A. Sadegh, M. Elliot, A. Calle, A. Persad, H. M. Chiu. *Design of Mobile Robots with Wall Climbing Capability. Proceedings of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Montery, CA, USA. 2005: 438~443.
2. J. Z. Xiao, A. Sadegh. *City-Climber: a new generation of wall-climbing robots, Chapter 18. In: Climbing and Walking Robots---Towards New Applications*. Vienna, Austria: I-Tech Education and Publishing, 2007. 383~402.
3. S. Hirose and H. Tsutsumitake, *Disk Rover: A Wall-Climbing Robot Using Permanent Magnet Disks, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, USA, 1992, pp. 2074-2079.
4. J. Savall, A. Avello, and L. Briones, *Two Compact Robots for Remote Inspection of Hazardous Areas in Nuclear Power Plants, IEEE International Conference on Robotics and Automation*, pp.1993-1998, 1999.
5. A. Nishi, *Development of Wall-Climbing Robots, Computer and Electrical Engineering*, 22(2), pp.123-149, 1996.
6. M.P. Murphy and M. Sitti, *Waalbot: An Agile Small-Scale Wall-Climbing Robot Utilizing Dry Elastomer Adhesives, IEEE/ASME Transactions on Mechatronics*, 2007, vol. 12(3), pp. 330-338.
7. J. Z. Xiao and H. Wang, *Advances in Climbing Robots, in Chapter 22, Contemporary Issues in Systems Science and Engineering, IEEE Press/Wiley*, Edited by M.C. Zhou, H. X. Li, and M. Weijnen, in press.
8. E. Strickland, *Crawler Bot Could Inspect Nuclear Power Stations, IEEE Spectrum*, September 5, 2013.