Developments in Wall Climbing Robots: A Review

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ABSTRACT – The purpose of wall climbing robots is climbing mainly on the vertical surfaces like that of walls. The robots are required to have high, maneuverability and robust & efficient attachment and detachment. The robot can automate tasks which are done manually with an extra degreed of human safety in a cost effective manner. The robot can move in all the four directions forward, backward, left and right. The other locomotion capabilities include linear movement, turning movement, lateral movement, rotating and rolling movement. Apart from the reliable attachment principal the robot should have low self weight and high payload capacity. The design and control of robot should be such that it can be operated from any place. A wireless communication link is used for high performance robotic system. Regarding the adhesion to the surface the robots should be able to produce secure griping force. The robots should adopt to different surface environlments from steel, glass, ceramic, wood, concrete etc. with low energy consumption and cost. This paper presents a survey of different proposed and adopted climbing robots developed on the recent technologies to fulfill the objective

Keywords: robot, climbing, adhesion, suction, magnetic. Electrostatic.

1 INTRODUCTION

Wall climbing robots (WCR) are special mobile robots that can be used in a variety of application like inspection and maintenance of surfaces of sea vessels; oil tanks, glass slabs of high rise building etc. To increase the operational efficiency and to protect human health and safety in hazardous tasks make the wall climbing robot a useful device. These systems are mainly adopted in such conditions where direct access by human operator is very expensive due to hazardous environment or need of scaffolding. During navigation wall climbing robots carry instrument hence they should have the capability to bear high payload with lower self weight. Researchers have developed various types of wall climbing robot models after the very first wall climbing robot dated back to 60's,developed by Nishi based on single vacuum suction cup. Basically these are design factors for developing the mobile robots, their adhesion and locomotion. Based on locomotion the robots can be differentiated into three types viz. crawler, wheeled and legged type. Although the crawler type is able to move relatively faster, it cannot be applied in rough environments. On the other hand legged type easily copes with obstacle found in the environments. Generally its speed is lower and requires complex control system. The wheeled robots can have relatively high speed except they cannot be used for surfaces with higher obstruction. Based on the adhesion method the robots can be classified into magnetic, vacuum or suction, grasping grippers, Electrostatic and biologically inspired robots. The magnetic type robots are heavy due to weight of magnets and can only be used on ferromagnetic surface. Vacuum based robots are lightweight and easy to control but they cannot be used on cracked surfaces due to leakage of compressed air. The biologically inspired robots are still in the development stage as newer material is tested and to be improved. The technology based on electrostatic adhesion is lightweight and have high flexibility to be used on different type of walls is in the developing stage.

2 CLIMBING ROBOTS DESIGN CONCEPT AND APPLICATIONS

The paper by Shigeo Hirose and Keisuke A.Rikawa describes seemingly two opposite design and control concepts based on coupled and decoupled actuation of robotic mechanism. From the viewpoint of controllability, decoupled actuation is better than coupled actuation.[5]

Manual F. Silva's paper presents the survey of different technologies proposed and adopted for climbing robots adhesion to surfaces, focusing on the new technologies that are developed recently to fulfill these objectives.[15]

The paper by H.X.Zhang presents a novel modular caterpillar named ZC-I featuring fast building mechanical structure and low frequency vibrating passive attachment principle.[20]

Shanging Wu proposes wireless distributed wall climbing robotic system for reconnaissance purpose.[2]
The solution for inspection of marine vessels is proposed in design and control of a lightweight magnetic climbing robot for vessel inspection by Markus Eich and Thomas Vogele.[4]
A paper by Hao Yangand Rong Liu Proposes the vibration suction method(VSM) which is a new kind of suction strategy for wall climbing robots.[6]
Stephen Paul Linder have designed a handhold based low cost robot to climb a near vertical indoor climbing wall using computer vision.[10]
The paper by Jason Gu presents a proposed research on wall climbing robot with permanent magnetic tracks. The mechanical system architecture is described in the paper.[11]
The inspection of large concrete walls with autonomous system to overcome small obstacles and cracks are described by K.Berns.[16]
Gecko, climbing robot for wall climbing vertical surfaces and ceiling is presented by F.Cepolina.[24]
Climbing service robots for improving safety by Bing L.Luk describes how to overcome the traditional manual inspection and maintenance of tall building, normally require scaffolding and gondolas in which human operator need to work in mid air and life threatening environment.[25]
Houxiang Zhang's paper describes three different kinds of robots for cleaning the curtain walls of high rise building.[26]

Climbing robots are useful devices that can be adopted in a variety of application such as Non Destructive Evaluation (NDE), diagnosis in hazardous environments, welding, construction, cleaning and maintenance of high rise buildings, reconnaissance purpose, visual inspection of manmade structures. They are also used for inspection and maintenance of ground storage tanks and can be used in any type of surveying process including inspection of marine vessels, to detect damaged areas, cracks and corrosion on large cargo hold tanks and other parts of ships. Small sized wall climbing robots can be used for anti terror and rescue scout tasks. Firefighting, inspection and maintenance of storage tanks in nuclear power plants, airplanes and petrochemical enterprise etc.

Application of some of the wall climbing robots is given in the table below.

SR. NO	AUTHOR	YEAR	APPLICATION
1	Young Kouk Song, Chang Min Lee	2008	Inspection purpose
2	Love P. Kalra, Weimin Shen, Jason Gu	2006	Non destructive inspection
3	Shanqiang Wu, Mantian Li, Shu	2006	Reconnaissance purpose
4	Markus Eich And Thomas Vogele	2011	Vessel inspection
5	shuyan liu, xueshan gao, kejie li, jun li	2007	Anti terror scout
6	Juan Carlos Grieco, Manuel Prieto.	1998	Industrial application
7	K. Berns, C.Hillenbrand	-	Inspection of concrete walls
8	F. Cepolina, R.C. Michelini,	2003	Wall cleaning
9	Bing L. Luk, Louis K. P. Liu	2007	Improve safety in building maintenance
10	Houxiang Zhang , Daniel Westhoff	-	Glass curtain walls cleaning

Table No. 1

3 PRINCIPAL OF LOCOMOTION

The wall climbing robots are based on the following three types of locomotion

a) Wheeled

b) Legged and

c) Suction cups

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The following robots comes under this category

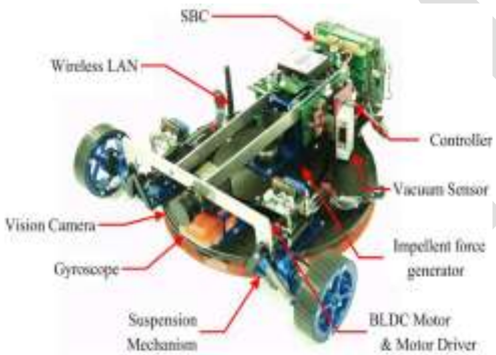
Wheeled wall climbing robots

This section describe, the hardware platform of a wall climbing robot ,called LARVA as shown in Fig. 1 and its control method. LARVA is the robot containing all the components except the power, when is supplied via a tether cable. Total weight of system is 3.3 kg. Its dimensions are 40.0cm width, 34.5cm length, and 11.0 cm height. Impellent force generator can evacuate the chamber to 5kpa. It is same 300M approximately. Finally, it can move on the wall in 10cm/s as a maximum speed[1]

The mechanical design of the proposed WCR is shown in Fig 2. The robot consists of aluminum frame, motors and drive train, and tracked wheels with permanent magnets plate in evenly spaced steel channels.[3]

A differential drive mechanism has been selected for this robot in which the wheels or tracks on each side of the robot are driven by two independent motors, allowing great maneuverability and the ability to rotate the robot on its own axis. The tracks provide a greater surface area for permanent magnets near the contact surface than moral wheels, creating enough attraction force to keep the robot on the wall and enough flexibility to cross over small obstacles like welding seams resulting in a more stable locomotion.

The mechanical design of the city-Climber is divided into three main areas; the adhesion mechanism , the drive system and the 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 to move from a vertical wall to the ceiling.[22]



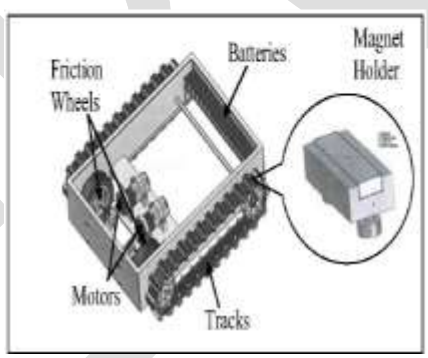


Fig. No. 1 WCR LARVA **Fig. No. 2 Magnetic Wheel WCR** **Fig. No. 3 TheCity Climber WCR**

The Legged wall climbing robots are described below

Distributed inward Gripping (DIG) advances the concept of directional attachment by directing legs on opposite sides of the body to pull tangentially inward toward the body. The shear forces oppose each other rather than the pull of gravity, allowing the robot to climb on surface of any orientation with respect to gravity including ceilings.[12]

REST design was focused on the main specification features , which include :

- Capacity to carry high payloads (up to 100 kg) on vertical walls and ceilings.
- Some degree of adaptation to traverse obstacles and irregularities.
- High safeness for industrial environment operation.
- Semiautonomous behavior.[13]

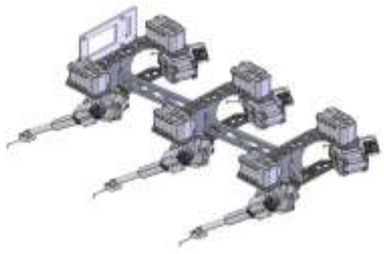


Fig. No. 4 DIGbot WCR

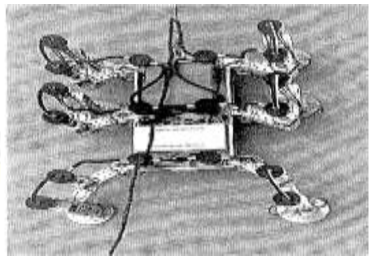


Fig. No. 5 Legged WCR

The basic function of inspired climbing caterpillar include following aspects. The climbing caterpillar has to be safely attached to the slope with different material and has to overcome gravity. The mechanical structure for safe and reliable attachment to the vertical surface is needed. Now our research is focusing on the realization of new passive suckers which will save considerable power. Because of the unique vibrating adsorbing principle, the passive suckers can attach not only to glass, but also to a wall with maximum tiles.[20]

Following table shows robots categorized on the basis of method of climbing

SR. NO	AUTHOR	YEAR	METHOD OF CLIMBING
1	Young Kouk Song, Chang Min Lee	2008	Impellar with sction seal
2	Love P. Kalra, Weimin Shen, Jason Gu	2006	Magnets
3	Shanqiang Wu, Mantian Li, Shu	2006	Distributed wall climbing
4	Hao Yang And Rong Liu,	2008	New vibration suction robotic foot
5	Akio YAMAMOTO, Takumi NAKASHIM	2007	Electrostatic attraction
6	Yu Yoshida And Shugen Ma	2010	Passive suction cups
7	L. R. Palmer Iii, E. D. Lkiller	2009	Distributed inward gripping
8	XiaoQI Chen	2007	Bernoulli effect
9	Sangbae Kim	2008	Geckos
10	Philip Von Guggenberg	2012	Electro adhesion

Table No. 2

4 TECHNOLOGIES FOR ADHERING TO SURFACES

To hold a robot on the wall is the basic concept behind the development of adhesion principal. There are many factors which affect holding especially on all vertical walls and ceiling. Forces, robot movement and mechanical design are such factors.

The Suction force based wall climbing robots are

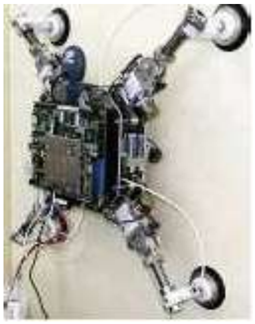


Fig no. 6 Vaccum Cup WCR

Fig. No. 7 Scout Task WCR

This papers proposes the critical suction method (CSM) the method means that the suction force includes two types of forces, one is the negative suction force generated inner suction disc, and the other is the thrust force generated by the propeller . And while the robot is adsorbing on the wall surface, the two forces could push it on the wall safely, and improve its obstacle – overleaping abilities. The robot suction principle mainly composted of suction cup, flexible sealed ring and propeller. Once propeller goes round and round at full speed, the air vents and thrust force produces that pushes the suction cup to the wall. What more air enters into the suction cup through the flexible sealed ring and it makes the cup achieve the negative pressure state. So there is the pressure force for the robot to suck on the wall. By adjusting the gap between the sealed ring and the wall surface, the critical suction would be obtained in the robot suction system. It also meets the demand that the robot can stay on the wall and move smoothly.[9]

Fig. 6 shows materials handling application where a vacuum cup called a suction cup is used to establish the force capability to lift a flat sheet. The cup is typically made of a flexible material such as rubber so that a seal can be made where its lip contacts the surface of the flat sheet. A vacuum pump is turned on to remove air from the cavity between the inside of the cup and top surface of the flat sheet. As the pressure in the cavity falls below atmosphere pressure, the atmosphere pressure acting on the bottom of the flat sheet pushes the flat sheet up against the lip of the cup. This action result in vacuum pressure in the cavity between the cup and the flat sheet that causes an upward force to be exerted on the flat sheet. [23]

The requirement of the robot is to be self contained i.e. it should be able to operate throughout its task by totally depending upon the on board batteries. This demands on adhesion mechanism that does not require any external power. Permanent magnet makes a great candidate for such a requirement. By carefully selecting the size of the magnets and by introducing an appropriate air gap between the magnet and the wall surface we can have a very efficient adhesion mechanism unlike other alternative like vacuum suction cups which need a continuous supply of negative pressure to stick.[3]

The previous adhesion techniques make the robot suitable for moving on at walls and ceilings. However, it is difficult for them to move on irregular surfaces and surfaces like wire meshes. In order to surfaces this difficulty, some robots climb through manmade structure or through natural environments, by gripping themselves to the surface where they are moving over. These robots typically exhibit grippers.[17]

Fig. No. 8 Grasping WCR

A prototype wall climbing robot was designed and fabricated using flexible electrode panels. The robot was designed to utilize the inchworm walking mechanism. Two square frames made of aluminum were conducted by a linear guide. Their relative position was controlled by two RC Servo motors. Electrode panels were redesigned to fit the frame design. On each square frame, two electrode panels measures 130 mm in which and 75 mm in height. Each panel weighs 12 g and the total weight of the robot is 327 g.[7]

Geckos are renowned for their exceptional ability to stick and run on any vertical and inverter surface. However gecko toes are not sticky in the usual way like duct tape or post it notes. Instead, they can detach from the surface quickly and remain quite clean around everyday contaminates even without grooming. The two front feet of a tokay gecko can withstand 20.1 N of force parallel to the surface with 227 mm^2 of pad area , a force as much as much as 40 times the gecko's weight. Scientists have been investigating the secret of this extraordinary adhesion ever since the 19th century and at least seven possible mechanism for gecko adhesion have been discussed over the past 175 years.. There have been hypotheses of glue, friction, suction, and electrostatics, micro-interlocking and intermolecular forces. . Sticky secretions were rules out first early in the study of gecko adhesion since geckos lack glandular tissue on their toes.[19]

Fig. No. 9 Stickbot WCR

5 NEW ADHESION PRINCIPLES

Climbing robot based on new principal of adhesion: an overview

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 mechanism and cause the robot to fall off the wall materials and surface condition is desirable. To this end, the university of Canterbury has embarked on a research program to develop novel wall climbing robot which offer reliable adhesion, maneuverability, high payload, to weight ratio, and adaptability on a variety of wall material and surface conditions. The research has led to the development of a novel wall climbing robot based on the Bernoulli Effect.[14]

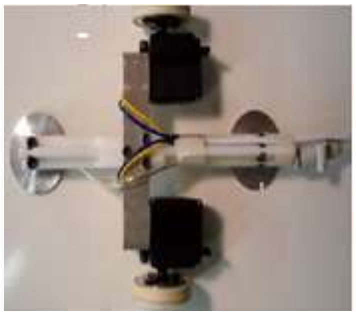


Fig. No. 10 Bernoulli Pad based WCR

The proposed robot moves by crawler driven mechanism and attaches by suction cups. The robot has one motor, which drives the rear pulleys. Several suction cups are installed on the outside surface of the belt with equal intervals as shown in fig. 1 and the cups rotate together with the belt.

The moving process of the robot can be described as follows, firstly the robot is attached to a wall by pushing of the crawler belts makes suction cups contact and attach to the wall at the front pulleys. Then the guide shafts slide into a guide rail as shown in fig. 2 when a suction cup reaches the rear pulley, it is detached from the wall by the rotation of the belts. A sequence of this progress makes the robot move on the wall to keep adhesion[8]

Fig. No. 11 Passive Suction Cup WCR

To develop a robot capable of climbing a wide variety of materials, we have taken design principles adapted from geckos. The result is stickybot (fig. 9), a robot that climbs glass and other smooth surfaces using directional adhesive pads on its toes.

Geckos are arguable nature's most agile smooth surface climbers. They can run at over 1 m/s , in any direction , over wet and dry surface of varying roughness and of almost any material , with only a few exception like graphite and Teflon . The gecko prowess is due to a combination of "design features" that work together to permit rapid, smooth locomotion. Foremost among this features is hierarchical compliance , which helps the gecko conform to rough and undulating surface over multiple length scales. The result of this conformability is that the gecko achieves intimate contact with surfaces so Waals forces produce sufficient adhesion for climbing. The gecko adhesion is also directional. This characteristic allows the gecko to adhere with negligible preload in the normal direction and to detach with very little pull off force and effect that is enhanced by peeling the toes in digital hyperextension.[18]

The electro adhesion exploits the electrostatic force between the material that serves as a substrate and the electro adhesive pad. The pad is generally made up of polymer coated electrodes or simply by conductive materials. When the charges are induced on the electrodes, the field between the electrodes polarizes the dielectric substrate causing electrostatics adhesion. It is essential to maintain the electro adhesive pad and the surface in close contact. Since the electrostatic forces decrease dramatically with the square of the distance, the basic idea is to create structure with two electrodes that have shape, size and distance requirements that ensure a high electrostatic field and that generate high adhesion forces on different types of material as wood, glass, paper, ceramics, concrete etc.[7]

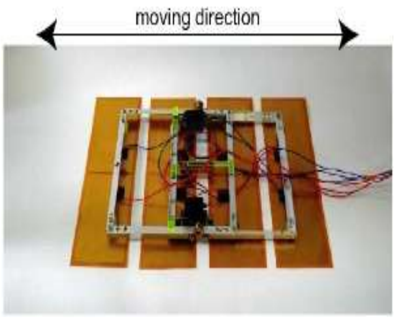


Fig. No. 12 WCR for conductive walls

SRI International is introducing wall climbing robot prototypes for surveillance, inspection , and sensor placement application . Ideal of remote surveillance or inspection of concrete pillars or other structure, this robot uses SRI's patented electro adhesion technology to enable wall climbing. It can also be used to carry payloads such as cameras, wireless network nodes, and other sensors.[27]

Fig. No. 13 SRI's WCR

6 Limitations of WCR

Some of the limitations of different wall climbing robots is given in the following tabular form.

SR. NO	AUTHOR	YEAR	OBJECTIVE OF STUDY	OUT COME	LIMITATION
1	Love P. Kalra, Weimin Shen, Jason Gu	2006	A wireless wall climber	Used magnets for adhesion	Limited to ferrous walls & less battery life
2	Shanqiang Wu, Mantian Li, Shu	2006	Wireless operation	Distributed wall climbing	Mother & child two robots
3	Markus Eich And Thomas Vogele	2006	Light weight robot	Used LED based sensor	Crawler felled if other bright light spot found nearby
4	Akio YAMAMOTO, Takumi NAKASHIMA	2007	To realize Electrostatic adhesion	Improvement of speed	Very low speed
5	Yu Yoshida And Shugen Ma	2010	Passive suction cup based	Prototype fells due to larger power requirements	Mechanism was to be improved
6	Stephen Paul Linder, Edward Wei	2005	Balancing of Hands &legs	Computr vision reliably locates itself	Less flexibility
7	L. R. Palmer Iii, E. D. Lkiller	2009	Design hexapod for advance maneuvering	Leg motion & body balancing	Gripping limited to tangential force
8	Juan Carlos Grieco	1998	High payload carrying	Complexity of design	High self weight
9	Wikipedia	-	Study of bio inspired robots	Climbs smooth walls	Cost/less research on material
10	Jizhong Xiao and Ali Sadegh	-	Modular climbing caterpiller	A highly integrated robotic system	Manufacturing complexity

Table No. 3

7 CONCLUSIONS

During the two last decades, the interest in climbing robotic systems has grown steadily. Their main intended cleaning to inspection of difficult to reach constructions. This paper presented a survey of different technologies proposed and adopted for climbing robots adhesion to surfaces, focusing on the new technologies that are presently being developed to fulfill these objectives. A lot of improvement is expected in the future design of the wall climbing robots depending upon its utility .This paper gives a short review of the existing wall climbing robot

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