Title: Wireless Controlled Pneumatically Operated Wall Climbing Robot

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ABSTRACT

A wall climbing robot is a robot with the capability of climbing in vertical as well as horizontal direction with efficient attachment and detachment. The bot is designed to replace the activities carried out along the wall at high heights which would risk the human life. This paper describes the fabrication of a pneumatically operated wall climbing bot which uses suction cups as a mean of sticking to the wall. Each vacuum generator will operate two suction cups on either vertical or horizontal limb of robot. Linear movements are achieved through double acting pneumatic cylinders. A wireless communication link can be interfaced to the electric circuit of solenoid operated DCV's making bot operation semi-autonomous and autonomous also. The bot is adaptable to various wall materials such as metal, ceramic, glass, concrete, wood. Currently the robot is designed only for linear movement. Further scope of development in this prototype includes imparting other locomotion capabilities such as turning movements, angular movements shifting bot from one plane to another thus, making it omnidirectional.

Keywords*: Arduino, Bluetooth module, DCV's , Suction cups, Vacuum generator.*

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1. INTRODUCTION

Wall climbing bots 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 task make the wall climbing robot a useful device. Robots have been created to assist or replace humans in various dangerous and difficult tasks[1]. Robots have been used in construction, manufacturing, security etc. This is because they are able to adapt to different environment conditions and situations. They have conquered nearly all environments that humans have put them through. Climbing robots can be used on artificial surfaces like a wall, or on natural surfaces like trees or cave walls. They are desirable for several applications such as search and rescue. [13]

1.1 Adhesion Principle

1. Magnetic adhesion: This principle is very reliable on ferromagnetic surfaces and it is able to create strong adhesion forces on small area. Adhesion can also be created without energy consumption using rare earth magnet, keeping the magnet within a certain distance from wall to limit magnetic forces and friction. The main drawback of this adhesion technique is that it is applicable for only metallic surfaces and also residual eddy current stresses are generated in wall surfaces which are not desirable[7].

2. Mechanical gripping : Mechanical adhesion is based on claws (or spines) used for gripping the surfaces which are either sufficiently rough so that the spine find enough contact points for attraction. But, these systems are slow and have restricted maneuverability and they have low payload capacity.
3. Electrostatic Adhesion : This method comprises of electroadhesive pads having electrodes and insulation substrate are utilised for generation of electrostatic or van der waals forces[2]. It is safe, energy efficient and robust. Unfortunately this technology has opaque understanding and still is at indormant stage of development and also it has low payload capacity.
4. Pneumatic adhesion : This is the another technique also called as negative pressure adhesion which can be distinguished between three different types: passive suction cups, active suction chambers and vortex or thrust systems. Passive suction cups are suitable only on very flat surfaces like glass but can be combined with different types of locomotion like Tracked Racoon or the Dexter robot having two articulated fits. In active suction chambers, suction cups are used along with electrical vacuum generators which produces a large through flow volume or high negative pressure. They can be used on rough ground in comparison with passive cups as they produces high attraction forces and can be combined with nearly every locomotion system e.g. WallWalker[9], Bitclimber[9], LARVA[9].

1.2 Locomotive Principle

In literature various combinations exist combining different types of locomotion with different adhesion principles [10]. During robot development a question has to be considered: What kind of locomotion principle is the optimum for the given task and the environment? In general, one can distinguish three classes of locomotion with their individual assets and drawbacks:
1. Arms and Legs : This locomotion principle resembles the movement of lizard on a wall which includes alternate forward movement of one of the arms or legs and by pivoting the other at the same time. The main advantage of this locomotion principle is that the robot is highly adaptable to wall surface structure which includes overcoming obstacles, small steps, etc and translation of robot from ground to wall. However, high degree of freedom leads to complicated mechanical structure and control system which ultimately results in higher weights, larger torques and slow movement.
2. Wheels and Chains : Wheeled or tracked locomotion is the fast and continuous movement and the simplest mechanism to employ. Magnetic or pneumatic adhesion system can be used in combination with this locomotion system, but it has a limitation of lifting load capacity since the power input of motors driving the wheels is insufficient at high carrying load. Also, motors of wheels must be mounted on robot which results in increase in dead load of robot.
3. Pneumatic actuators : Pneumatic actuators with sliding frame are very commonly used locomotive principle. The main purpose of using this system is that it provides wide range of lifting load capacity from 0.25 kg to 100 kg on varying the supply pressure of compressed air. Regulation of air flow rate to actuators enables us a great control on climbing velocity in case of precise motion applications. The drawbacks of this principle are again a low speed compared to wheeled or tracked vehicles, a discontinuous movement due to the stick-move-stick-move cycle.
By considering precision and payload capacity, pneumatic actuators with sliding frame is selected as locomotive principle for wall climbing robot.

2. CONSTRUCTION AND WORKING

Wall climbing robot is made from assembling following parts:

Components	Specifications
Suction cups	Material - polyurethrene Diameter - 80 mm flat round shape , single step, G1/4 connections. max suction force 260 N weight 75g
Direction controlled valve	5x2 spring return solenoid actuated DCV for actuators 3x2 spring return solenoid actuated DCV for vacuum generators 24 V dc coil

Vacuum generator	SBP 07 S01 SDA (Schmalz Company product) Nozzle size-0.7mm Degree of Evacuation - 85%
	Suction rate(max) - 16 l/min Air consumption (during evacuation) - 22 l/min
Microcontroller	ATMEGA 2560 Operating voltage- 5V Digital i/o pins-54 PWM outputs- 15 Analog inputs- 16 each of 10 bits Crystal oscillator- 16MHz
Bluetooth module	HC-06 Build-in 2.4GHz antenna External 8Mb FLASH Low voltage(3.1V~4.2V) Current in pairing (30~40mA) 2.4GHz digital wireless transceiver
Cylinders	Double acting ;Bore diameter-20 mm; Stroke length-150 mm
Teflon pieces	100 mm x 10 mm x 20 mm block having 2 drills of 7 mm for sliding rods and 1 center drill of 8 mm dia. for piston rod end fastening.
sliding rods	Stainless steel rod; diameter 7 mm; M8 threading at both ends.
L-plates	112 mm x 40 mm x 40 mm; 22 mm center drill; 2 drills of 7 mm for sliding rods
Pneumatic Hoses	6 mm

Table-1: Components used in wall climbing bot and their specifications

2.1 Robot Assembly

Assembly of both limbs of robot i.e. vertical and horizontal limb is done separately. It begins with insertion of both threaded ends of cylinders in 22 mm drill of L-plate and tighten it firmly with the help of locknuts. Piston rod end is fixed to center drill of teflon piece. Then, sliding rods are inserted in 7 mm drills of teflon piece through which it can slide freely. Rear ends of sliding rods are fixed rigidly in 7 mm drilled holes of L-plate mounted on piston rod side of cylinder. Front ends of sliding rod are fixed to the L-plate on opposite end as shown in fig. In this way, assembly of one limb is complete. Similarly, other limb is assembled and Teflon pieces of both limbs are kept over each other. Both limbs are fixed to each other permanently by inserting blue rod through teflon pieces as shown.

Fig-1: Assembled robot and Teflon joint

2.2 Pneumatic Circuit

The block diagram for pneumatic circuit of wall climbing bot is shown in Fig.2.

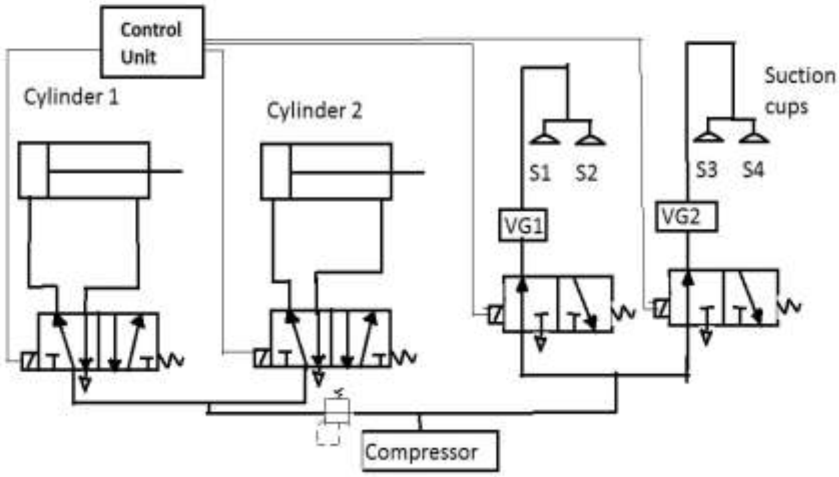


Fig.2 Pneumatic circuit of wall climbing robot

Pneumatically operated wall climbing bot mainly composed of two limbs:
i) Vertical limb with cylinder 1 , suction cups S1 & S2 mounted on it.
ii) Horizontal limb with cylinder 2 , suction cups S3 & S4 mounted on it.

Double acting cylinder 1 and cylinder 2 are used for motion along X-axis and Y-axis respectively. Both cylinders are actuated through solenoid operated spring return 5/2 direction control valves. When control unit sends electric pilot signal of 12 V to any DCV coil, spool position is shifted resulting into extension stroke of cylinder. Flow control valve is inserted in path to regulate the extension velocity of cylinder. Vacuum generator is a small device which creates vacuum pressure to outlet port when compressed air passes through its orifice. Suction cups S1, S2 are operated through vacuum generator VG1 and S3, S4 are operated through VG2. Both VG1 and VG2 are provided with compressed air supply through solenoid actuated spring return 3/2 direction control valves. Pneumatic hoses, T-connectors, inline connectors are used for all pneumatic connections.

2.3 Vertical Climbing Sequence

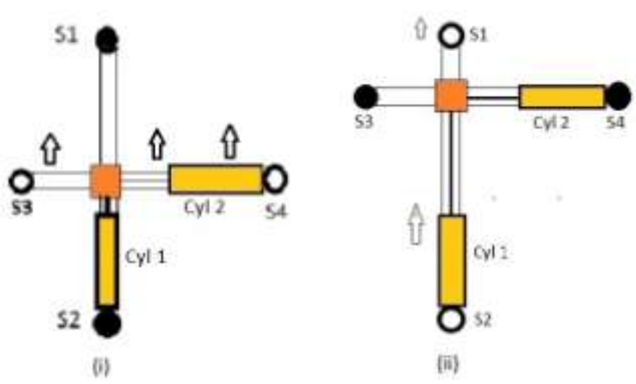


Fig.3 Vertical climbing sequence: (i) S1,S2 gripped; (ii) S3,S4 gripped.

At first, S1 & S2 are in gripped position and S3 & S4 are released (free to slide along the wall surface). Compressed air is supplied to piston side of cylinder 1 when corresponding DCV is triggered. During its extension stroke, horizontal limb slides over the vertical limb as shown in fig.3(i). After completion of extension stroke, S3 & S4 are brought into gripped position by using 3x2 DCV's of vacuum generator. When proper clamping of S3 & S4 is ensured, then S1 & S2 are detached which will result into the position shown in fig.3(ii). Now, spool position of DCV is shifted for the retraction stroke of cylinder 1. Since horizontal limb is fixed to wall at this moment, the sliding rod of vertical limb will slide through teflon drills due to opposite reaction force of compressed air. It will result into position (i) again and the cycle is repeated by clamping S1 & S2 first and then releasing S3 & S4.

Same procedure can be implemented for horizontal limb if robot needs to be moved in horizontal directions.

3. SAMPLE CALCULATION

If wall climbing bot needs to be designed for 5 kg carrying load, then procedure for selection of suction cup diameter is as follows:

3.1 Selection of Suction Cup Diameter

Theoretical holding force required to hold the robot against the wall is calculated first. Formula for theoretical holding force[8] is given by,

$F_H = (m/\mu) \times (g + a) \times S$

Where,

m = mass of robot including mass to be carried

μ = coefficient of friction

g = acceleration due to gravity

a = acceleration of robot

S = factor of safety

Surfaces	Coefficient of friction
Oily	0.1
Wet	0.2-0.3
Rough	0.6
Wood, metal, glass , stone	0.5

Table 2. Coefficient of friction between different surfaces and polyurethrene material of suction cup [14].

assuming a = 1 m/s^2 & g = 9.81 m/s^2,

S = 1.5 or 2 (for horizontal position of suction cup)

> 2 (for vertical position of suction cup)

$F_H = (5/0.5) \times (9.81+1) \times 4$

$= 432.4$ N

- Calculated breakaway force (F_A)

If several suction grippers are used simultaneously in a vacuum application, the result of the theoretical holding force F_H calculation must be divided by the number of suction grippers. In our case, we are using two suction cup on each limb of robot which will be sharing the load of robot at the moment, Therefore,

$F_A = F_H / n = 432.4/2 = 216.2$ N

Following table gives the allowable breakaway force at different suction cup diameters of material polyurethrene at -0.5 bar vacuum pressure,

Cup diameter	8	10	15	20	30
Breakaway force (N)	2.3	3.9	8.5	16.3	40.8
Cup diameter	40	50	60	80	100
Breakaway force (N)	69.6	105.8	166.1	309.7	503.6

Table 3. Suction cup diameters and corresponding breakaway force[14]

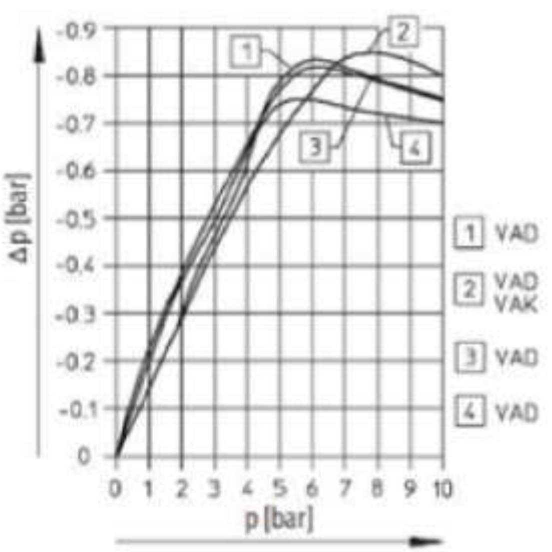
Calculated breakaway force must be less than allowable breakaway force. Hence, suction cups of 80 mm diameter are selected since 216.2 < 309.7 N.

3.2 Selection of Vacuum Generator

Required specifications of vacuum generator can be determined by using following graphs.
For designing parameters: Operating pressure : 3 bar and Vacuum pressure :- 0.5 bar, Vacuum generator with VAD 1/8 pneumatic connection is selected.

Pneumatic connections	M5	G1/8	G1/4	G3/8
Nominal size of laval nozzle	0.5	0.8	1.0	1.5

Table 4. Size of laval nozzle for different Pneumatic connections[14]



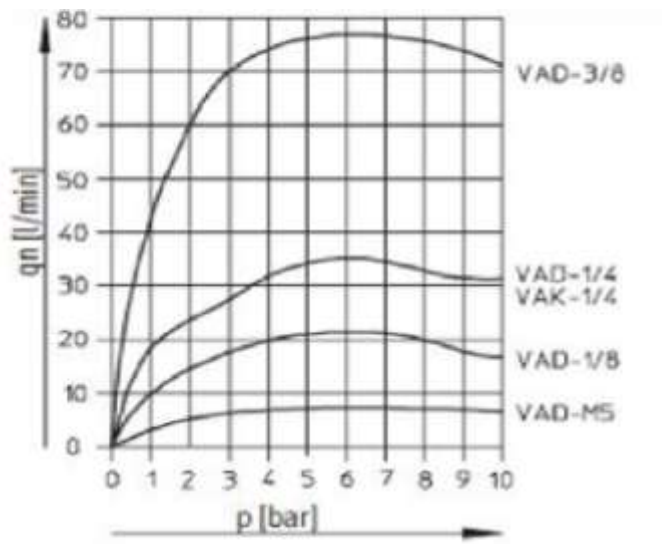


Fig.4 Vacuum Δp as a function of operating pressure p[14] and Suction capacity qn as a function of operating pressure p [14]

Suction capacity :
2 suction cups are operated at a time.
Suction cup volume = 25 cm^3
Evacuation air volume= 2 x 25 = 50 cm^3
Taking evacuation time as 0.25 sec (from Schmalz Catalogue), we have
=50 cm^3 in 0.25 sec
=200 cm^3 in 1 sec
=200x60x10^(-6) m^3 in 1 minute
i.e. 0.012 m^3/min
i.e. **12 lit/min**

Above graph can be used to cross check suction capacity of selected VAD 1/8 vacuum generator.

4. WIRELESS CIRCUIT

Since triggering of solenoid operated DCVs is the key for movement of limbs of bot as well as for vacuum generation in suction cup (Ref. fig.(2)), wireless circuit can be used as control unit in order to make robot's operation semi-autonomous. Wireless circuit consists of Arduino, Bluetooth module, Relay circuit, power supply and mobile application. All of the above components are connected to each other by using male and female connectors. Arduino having 82 female pins which are divided in five parts namely PWD (pulse width modulation), Communication, Digital, Analog IN, power. Bluetooth module consists of four pins: TX, RX, GND, 5V. TX and RX are used for transmitting and receiving the signal respectively. Relay having five terminals.

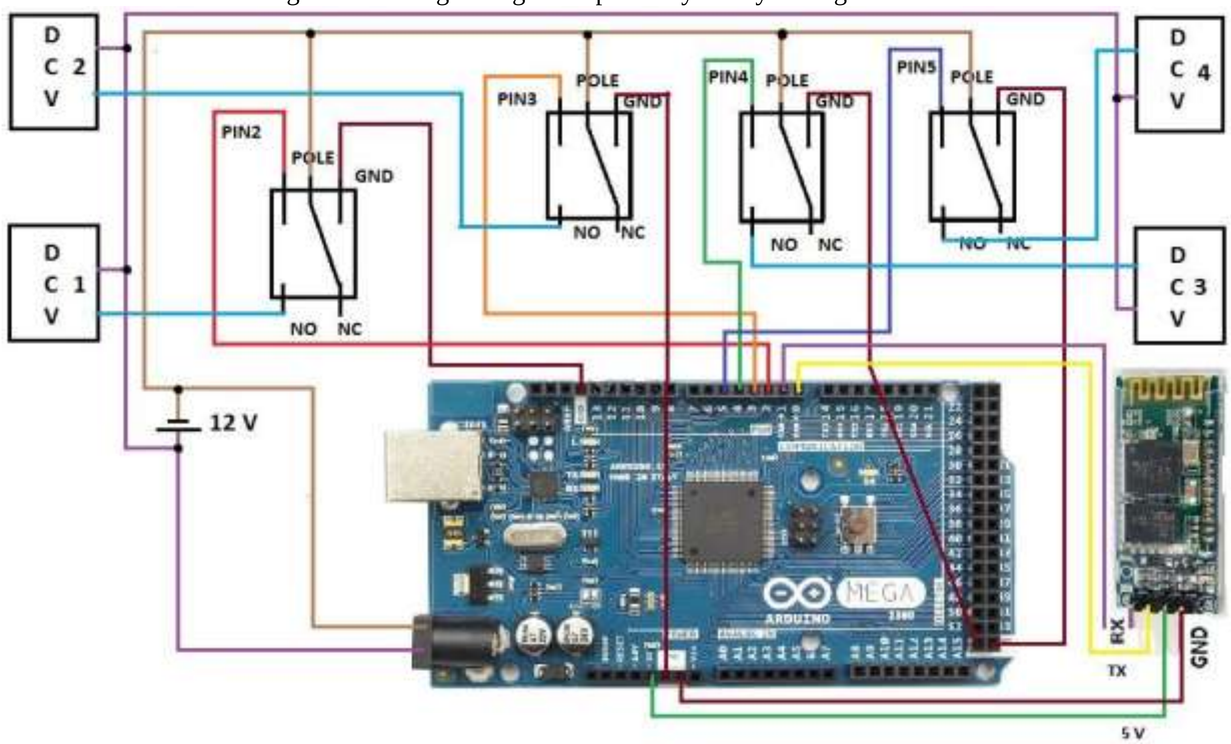


Fig. 6 Wireless circuit connection (Control unit)

In above fig. the PWD pins 2,3,4,5 are connected to the relay 1,2,3,4 respectively which are at normally close condition. Poles are connected to the negative terminal of the battery and the normally open terminal is connected to the respective DCVs 1,2,3,4 while remaining fifth terminals are GND. For bluetooth module the RX terminal is connected to the TX pin of the arduino and the TX terminal is connected to the RX pin of the arduino as, transmitted signal from bluetooth module must be received by arduino and vice versa. The power supply for bluetooth module of 5V is supplied through arduino. And the fourth pin of bluetooth module is GND. A 12V power supply is used for DCVs and arduino.

When user gives respective pin signal from mobile app to the bluetooth module, it transmit that signal to the RX of the arduino which turn on the respective pin and passes the signal through that pin to the respective relay. The signal switches the relay to its normally open condition and current flows towards the respective DCV. The current shifts the position of spool in DCV and changes the direction of air flow.

5. CONCLUSION

As expected, the results of the project came out to be satisfactory and the important observations are summarized as follows. The robot can move upward, downward, left, right along the wall. It is facing difficulty when suction cup overlaps the interruption where air leakage is a problem. Designed robot is capable of carrying loads of weight around 5 kg and its capacity can be expanded upto 100 kg if appropriate large diameter of suction cup is selected and high pressure compressed air is available. Compared to normal walls, it is working fine on glass walls and wooden walls. Bluetooth module placed on DCV panel on the robot have working range up to 10 m which can be extended using Wi-Fi module or GSM module. Response of this wall climbing model observed is 6 m/min which is sufficient for skyscraper glass cleaning and for ultrasonic flaw detection tests of nuclear reactor walls..

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