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DESIGN AND DEVELOPMENT OF A CLIMBING ROBOT FOR SEVERAL APPLICATIONS

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Abstract

Lizards, which move vertically on about any surface, on closer examination one can find that they possess tiny thin hair and suction cups along their limbs. It is the basic observation, which leads to think about climbing robots. The climbing robot comprises of two limbs. Each limb has two suction cups. The suction cups are used to stick on to the surfaces. The two limbs are connected to two servomotors, one for each. The air removal from suction cups is done using vacuum pump, controlled by solenoid valves. A microcontroller is used to control the relays that in turn switch electricity to solenoid valves. Suction pipes are used to connect solenoid vales to suction cups. Up and down, right and left movements are controlled by the controller PWM signals, applied to the servomotors. Gears and joints are used to convert the rotational motion of the servos to linear motion of the robot limbs. An air reservoir is mounted on the climbing robot platform as well. The entire platform can find applications in wall cleaning for high rise buildings, wall painting application, may be used for glass cutting if load handling capability is increased, wired or wireless video surveillance, sensing applications like weather monitoring station etc.

Keywords: Robot, climber (glass/wall), suction cups, servomotors, solenoid valves, wireless control, wireless camera

I. Introduction

The last few years have witnessed a strong, renewed interest in climbing and walking robotic technologies. At the end of the decade, several different prototype robots were developed for different types of applications. The design of a climbing robot is based on the pneumatic principle. Lizards, which move vertically on about any surface, on closer examination one can find that they possess suction cups along their limbs. Suction cups produce a kind of vacuum between the surface on which it moves and its skin which allows it to stick on the surface.

II. Climbing robots in literature

Various robots have been designed for climbing applications, cleaning, surveillance and maintenance in the recent past. Currently there are some different kinds of kinematics for motion on smooth vertical surfaces: multiple legs, sliding frame, wheeled and chain track vehicle.

There are also four different principles of adhesion used by climbing robots: like vacuum suckers, negative pressure, propellers and grasping grippers. The robots with multiple- legs kinematics are too complex due to a lot of degrees of freedom. The kinds of robots which use vacuum suckers and grasping grippers for attachment to the buildings do not meet the requirements for miniaturization and low complexity. Generally the kind of robotics construction and control is very complicated, and does not offer the high efficiency and simple operation required by a wall cleaning robot.

The robots with the wheeled and chain-track vehicle are usually portable. The adhesion used by this kind of robot is always negative pressure of propellers, so robots can move continuously. One kind of robot has a pair of wheels actuated by electrical motors in its negative pressure chamber, so that it can move on the walls flexibly. But it can only deal with plane walls without any obstacles. A kind of pneumatic cleaning robot was developed for cleaning the embassy of Canada by a company in Japan, but it cannot walk sideways. Some modifications can be done to that such that it walks in all four directions.

III. Basic functions provided by climbing robot

The following might be the basic functions of any climbing robot. The paper is targeted to cover the basic requirements only. However, all of the functions can be implemented on the proposed climbing robot platform with a little bit of complexity.

1) Safe and reliable attachment to the surface
2) Movement spreading over all the working areas
3) The ability of crossing obstacles

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4) Enough intelligence for the discrimination of obstacle situations
5) Working autonomously with the corresponding effective treatment
6) Motion control function
7) Effective cleaning/ surveillance/ sensing/ painting /glass cutting etc.

The climbing robot should be sucked to the surface on which it is climbing safely and overcome its gravity. That is the first difference between a climbing robot and an ordinary walking robot on the ground. The robot should have a function to move in both the up-down direction as well as the right-left direction to get to every point on the glass. Once the task signals are sent by the user, the robot should keep itself attached to and move on the surface while accomplishing the tasks of may be cleaning, surveillance, sensing etc. To meet the requirements of all kinds of functions, precise motion control is needed. The precise position control of the movement will begin automatically as soon as the signals are received. Finally efficient application execution is the objective of climbing robot for the mentioned applications.

IV. Materials and methods

Industrial applications, where a vacuum pressure is used include materials handling, lamping, sealing and vacuum forming. In terms of materials-handling applications, a pneumatic vacuum can be used to lift smoothly objects that have a flat surface and are not more than several hundred pounds in weight. Figure 2 shows a materials-handling application where a vacuum cup called a suction cup is used to establish the force capability to lift a flat sheet[5].

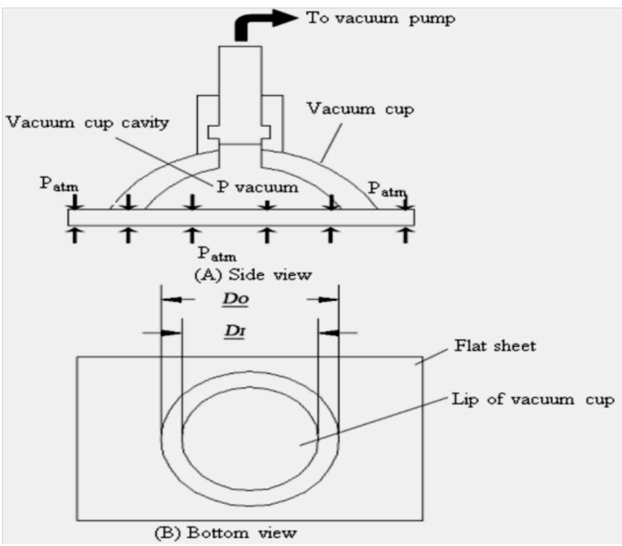

Fig. 1: Vacuum cup used to lift a flat sheet [5]

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.

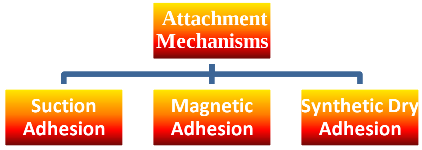

Fig. 2: Climbing Robot Attachment Methods in general

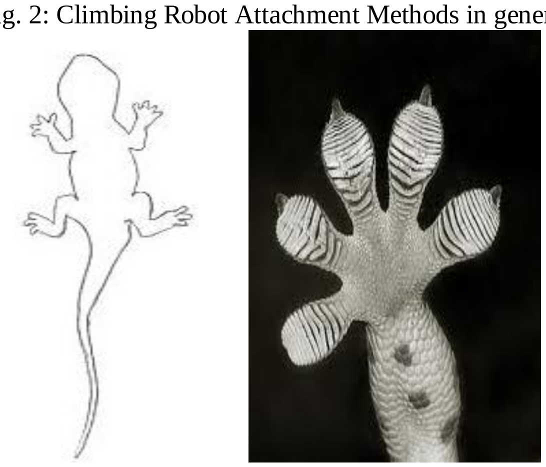

Fig. 3: Exemplary Lizard movement observation

A. Pneumatic vacuum systems

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 atmospheric pressure, the atmospheric pressure acting on the bottom of the flat sheet pushes the flat sheet up against the lip of the cup. This action results 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[5].

The magnitude of this force can be determined by algebraically summing the pressure forces on the top and bottom surfaces of the flat sheet as follows, as in:

$$F=P_{atm}* F = P *A_0 - P_{suction}*A_i \quad (1)$$

Where:

F = The upward force the suction cup exerts on the flat sheet

P_{atm} = The atmospheric pressure in absolute units,

A_0 = The area of the outer circle of the suction cup lip

$P_{suction}$ = Suction the suction pressure inside the cup cavity in absolute units

A_i = Area of the inner circle of suction cup lip

The atmospheric pressure on the top and bottom surfaces of the flat sheet cancels out away from the outer circle area of the cup lip. If all the air were removed from the cup cavity, we would have a perfect vacuum and thus the suction pressure would be equal to zero in absolute pressure units. The exact amount of suction pressure developed cannot be guaranteed and the resulting suction

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force must be at least as large as the weight of the object to be lifted.

Thus a factor of safety is applied with a value of between 2 and 4, depending on the application. When large, flat sheets are to be lifted, four to eight suction cups are used. In this way the sheet can be lifted uniformly. In addition, the load-lifting capacity is multiplied by the number of suction cups used. When a suction cup is placed on the top of a flat sheet and the vacuum pump is turned on, a certain amount of time must pass before the desired vacuum[5].

B. Wall-climbing robot design

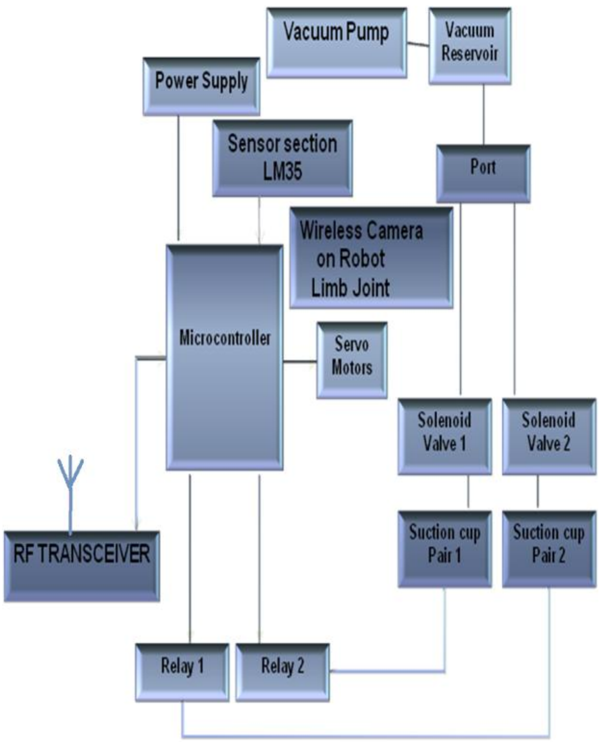

Fig.4 :Total Block diagram

The problem, how to hold on the wall is solved by many methods. There are many factors, which effect in holding, all forces, robot movement and mechanical design.

We keep on finding answers to the following questions during the design phase.

What are the design elements?
What is the principle employed in the design?
What is needed for the robot to stick on?
What makes the robot to climb?
What kind of mathematics involved?
What are the constraints of the design ?

Finally we come up with the following answers.

Design elements :
suction cups, vacuum pump, microcontroller
Principle employed :
vacuum pump principle,
Suction attachment, needed for robot to stick
Servo motors: To make the robot to climb
Mathematics involved : Volumetric
Constraints of the design : timing

- ***Capacity of suction pump (50 lpm) >> volume of suction***

  to be created
- ***Volume of suction to be created =***
  volume of vacuum reservoir +
  volume of suction cups (hemispherical) +
  volume of suction pipes(cylindrical)
- ***Vacuum reservoir volume***
  (rectangular l x b x h) > =
  volume of suction cups (hemispherical) +
  volume of suction pipes(cylindrical)
  Radius of suction cup r_1 = 2.5 cm
  Total length of suction pipes h_1 = 2 m
  Radius of suction cup r_2 = 0.5 cm
  Length, width and height of vacuum reservoir
  L = 6cm, w = 6cm, h_2 = 12 cm.
  Capacity of suction pump = 50lpm
- *Volume of suction cup = volume of hemisphere =* $2/3 * pi * r_1 3 = 0.26*10^{-6}\ m^3$
- *Volume of suction pipe = volume of cylinder = pi* $* r_2 2 * h = 157*10^{-6}\ m^3$
- *Vacuum reservoir volume = l x b x h =* $432*10^{-6}\ m^3$
- *Volume of suction to be created =*
  volume of vacuum reservoir +
  volume of suction cups +
  volume of suction pipes
  = $\mathbf{589.26*10^{-6}\ m^3}$
- *Capacity of suction pump = 50lpm*
  *= 50*10cm*10cm*10cm/60 s =* $\mathbf{833.33*10^{-6}\ m^3/s}$

Comparing the last two values, suction pump capacity is chosen comfortably more than the requirement as per the theoretical design.

C. Working principle

As shown in the block diagram, a microcontroller controls all the required actions. A wireless hand set is used to control the direction of the robot in all four directions. The corresponding LED

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flashes to indicate the direction. The signals are sent and received using an RF tranceiver. An LCD display is

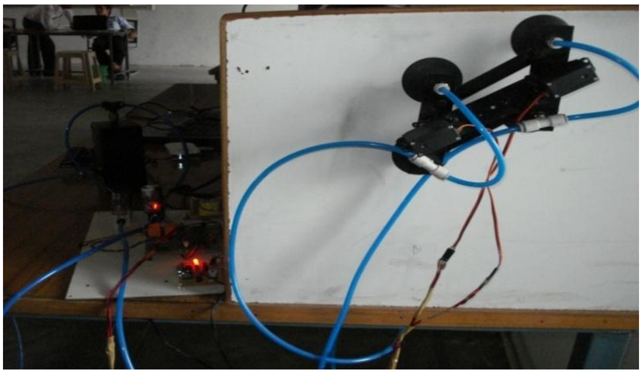

Fig. 5: The climbing robot platform prototype

facilitated to display the sensed values sent by the microcontroller of the climbing robot. When the direction control signals are received by the microcontroller, it acts according to the program written in the memory.

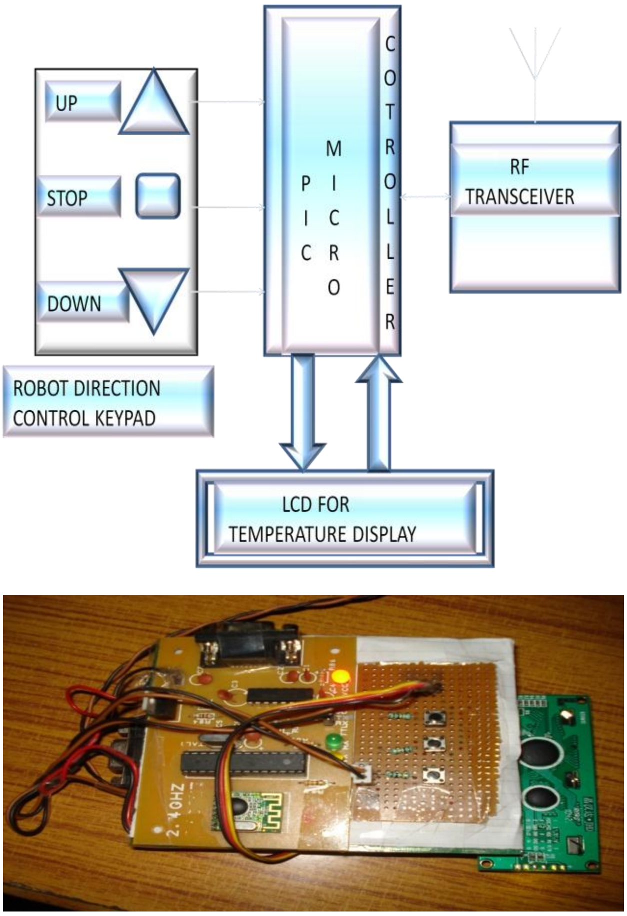

Fig. 6: Direction controller Handset Block diagram and implemented hardware

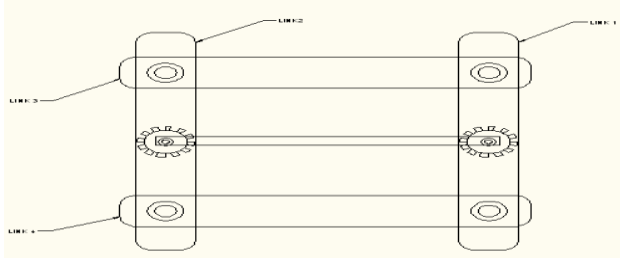

Fig. 7: CAD model of Climbing Robot Platform

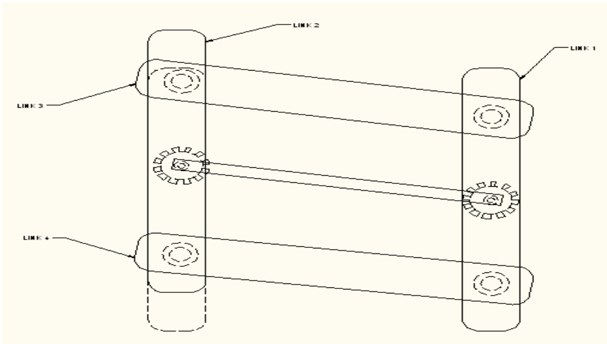

Fig. 8: Robot left limb displaced for upward movement

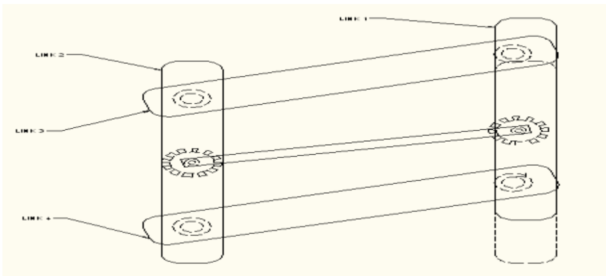

Fig. 9: Robot right limb displaced for upward movement

When we power up all the electronic circuits initially, a piece of code will be executed in the microcontroller to make the robot limbs stick t the walls by removing air in the suction cups. In order to do that, air compressor/ vacuum pump must be turned on. So the relay 3 in the diagram will be activated to power up the air compressor. Now it's the turn of the solenoid valves to open and let the air to be sucked by the compressor. Therefore relays 1 and 2 must be activated to provide electricity to the solenoid valves. Now the four suction cups are stuck to the surface, usually a wall.

In order to make movements, the controller receives the direction controlling signals from the user's handset. Controller, now executes the piece of code to free one limb i.e one pair of suction cups by letting air into the suction cups, from the air reservoir. For this controller needs to turn off the air compressor by de activating the relay3. Now one limb is free to move up and down. Now

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controller provides the specified movement with the help of servos.

After achieving the required movement , now again the free limb i.e the pair of suction cups need to stick on. For this, air compressor must be turned on by activating the relay3. In the similar fashion the other limb of the climbing robot can also be controlled to move up and downn by the microcontroler. The joints which are connecting the limbs with the servos plays a vital role.

D. Suction Cups

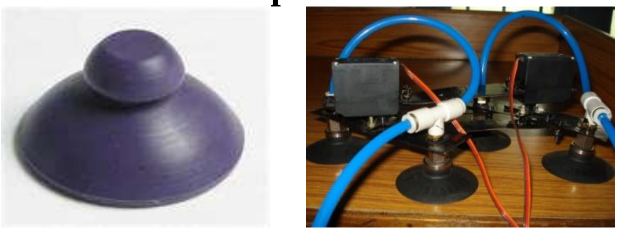


Fig. 10: A rubber suction cup without and with suction pipes respectively

A suction cup, also sometimes known as a sucker is an object that uses negative fluid pressure of air or water to adhere to nonporous surfaces. They exist both as artificially created devices, and as anatomical traits of some animals such as octopuses and squid. The working face of the suction cup has a curved surface. When the centre of the suction cup is pressed against a flat, non-porous surface, the volume of the space between the suction cup and the flat surface is reduced, which causes the fluid between the cup and the surface to be expelled past the rim of the circular cup. When the user ceases to apply physical pressure to the centre of the outside of the cup, the elastic substance of which the cup is made, tends to resume its original, curved shape.

E. Servo Motors

A Servo is a small device that has an output shaft.

Fig.11: A Vigor Vs 2 and its parts

This shaft can be positioned to specific angular positions by sending the servo a coded signal. As long as the coded signal exists on the input line, the servo will maintain the angular position of the shaft. As the coded signal changes, the angular position of the shaft changes. In practice, servos are used in radio controlled airplanes to position control surfaces like the elevators and rudders. They are also used in radio controlled cars, puppets, and of course, robots.

Servos are extremely useful in robotics. The motors are small, as you can see by the picture above, have built in control circuitry, and are extremely powerful for their size. A standard servo such as the Futaba S-148 has 42 oz/inches of torque, which is pretty strong for its size. It also draws power proportional to the mechanical load. A lightly loaded servo, therefore, doesn't consume much energy. The guts of a servo motor are shown in the picture below. You can see the control circuitry, the motor, a set of gears, and the case. You can also see the 3 wires that connect to the outside world. One is for power (+5volts), ground, and the white wire is the control wire.

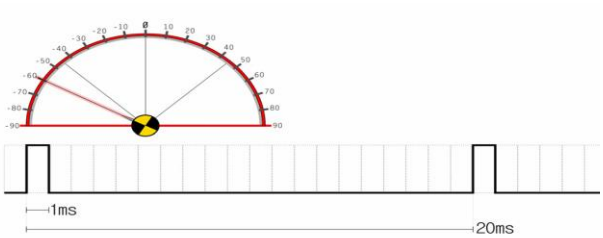


Fig. 12: Servo mechanism illustration with timing aspects

Delay programming for Servo mechanism for the robot arm movements:

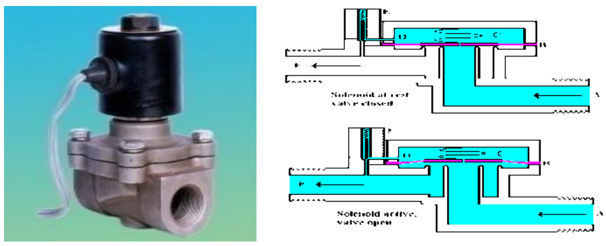
for (i = 98 ; i > 0 ; i - -)

Equivalent assembly code generated by the compiler

Movlw	98	1 CYCLE = 1 uS (fosc = 4 MHz)
Movf	R0	1 CYCLE
Decfsz	R0,1	1 (2) CYCLE

Total time = 1 + 1 + (98*2) +1 = 199 uS

F. Solenoid Valves



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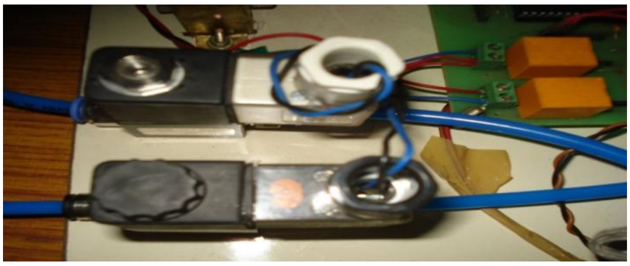

Fig.13: solenoid valve and its operation
A- Input side B- Diaphragm C- Pressure chamber
D- Pressure relief conduit E- Solenoid F- Output side

A solenoid valve is an electromechanical valve for use with liquid or gas. The valve is controlled by an electric current through a solenoid coil. Solenoid valves may have two or more ports: in the case of a two-port valve the flow is switched on or off; in the case of a three-port valve, the outflow is switched between the two outlet ports. Multiple solenoid valves can be placed together on a manifold. Solenoids offer fast and safe switching, high reliability, long service life, good medium compatibility of the materials used, low control power and compact design.

G. Air Reservoir/Vacuum Reservoir

Fig.14: Air/ Vacuum reservoir

Air/ Vacuum reservoir is used to store the air that got removed from the suction cups

H. Air Compressor/Vacuum Pump

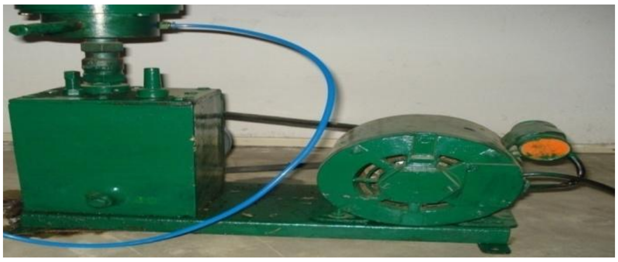

Fig.15: Vacuum pump

Air Compressor/Vacuum Pump is used to create a very low pressure end to suck the air inside the suction cups with the help of reservoir. It operates on 230 volt AC supply.

I. Relays

A relay is an electrically operated Switch. Many relays use an electromagnet to operate a switching mechanism. Relays find applications where it is necessary to control a circuit by a low-power signal, or where several circuits must be controlled by one signal. In the project we are using 12V relays.

J. Microcontroller

Table 1. PIC16F877A Features

Device	Program Memory		Data SRam (Bytes)	EEPROM (Bytes)	I/O	10-bit A/D (ch)	CCP (PWM)	MSSP		USART	Timers 8/16-bit	Comparators
	Bytes	# single word instructions						SPI	Master I2C			
PIC 16F877A	14.3K	8192	368	256	33	8	2	Yes	Yes	Yes	2 / 1	2

The microcontroller use is PIC 16F877A from Microchip corporation which has the following features.

A/D conversion is a required feature as we interface the microcontroller with sensors. SPI protocol is also a required feature as we interface the microcontroller with a transceiver to transmit the sensors data after processing. In the project we require to operate the relays, thus I/O pins will be useful. Some programming must be done to provide some delay routine and to do various conversion routines on the sensor data.

Finally, two RF Transceivers will be required to communicate the sensor outputs and the direction control inputs to/from the robot to/from the hand held remote control.

One standard Wireless Camera, laser gun, PC or Television are required for surveillance monitoring purposes. Temperature Sensor LM35, Humidity Sensor, Ultrasonic Distance Sensor are required to interface with the microcontroller to measure temperature, water content in the atmosphere and height from a reference point at which the robot is currently present respectively. Proper care is also required regarding power supply requirements.

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The following are the softwares used in the whole project.

a. **MICROCHIP MPLAB IDE**
b. **HI-TECH C COMPILERS**
c. **EXPRESSPCB (for PCB design)**

MPLAB IDE is a free, integrated toolset for the development of embedded applications employing Microchip's PIC® & dsPIC® mcus

HI-TECH C Compiler, compilation technology, for Microchip Technology's 8-, 16-, and 32-bit PIC® and dsPIC® microcontrollers

K. Video Surveillance feature

Parameter/Attribute	Feature/value
Body size	45cm x 45cm x 10cm (excluding cables)
Body mass	1 Kg
Motor	Product name: Vigor vs 2 Servo Size: 4cm Nominal voltage: 5 V Maximum current: 1mA No load speed: 800 rpm
Suction cups	Disc type, 0.08m diameter
Leg stroke	0.20 m
Vertical speed	0.10 m/s
Payload	4 kg
Relays	12 v, 2 No.s
solenoid valves	24 v, 2 No.s
Controls	semi-autonomous RF Transceivers range: 100 m. PWM for servo motors
Adhesion mechanism	Suction type: non destructive suction
Vacuum pump	50 lpm, 230v ac, 2880 rpm, HP 0.25

Fig. 16: Wireless camera and its accessories

Last but not the least, the wireless camera is placed on the robot body, along with a battery for power supply. The remaining accessories support the proper display for video surveillance in a display unit, say a laptop in our case, as shown in the results photograph.

V. Results

The force analysis is guarantee that the robot can hold and move on the wall. On analysis, force acting with the wall that the wall should have only slope from 0° (parallel with the ground) to 60° (slant line). All forces are acting on the slope of the wall can show in free-body diagram. Figure.10 shows free-body diagram that consists of all forces, vacuum force, reaction force, robot weight and friction force. The vacuum force is exerted by pressure difference between atmosphere pressure and inside vacuum cup pressure. The robot weight is force, which depends on the robot Mass (M) and acceleration of gravity (9.81 m sec-2), which has downward direction. Friction force is due to the irregularities of the surfaces in contact.

At equilibrium condition, we express all forces in equilibrium by sum all forces that equal zero. We thus obtain the following two equilibrium equations from equation 2 and 3, which express, respectively, that the sum of the X-Component and the sum of the Y-Component of given forces must be zero:

$$\Sigma Fy = 0; \quad (2)$$

Recation force –vacuumforce- robotweigth= 0 (3)

$$\Sigma Fx = 0; \quad (4)$$

Robotweight - friction force = 0 (5)

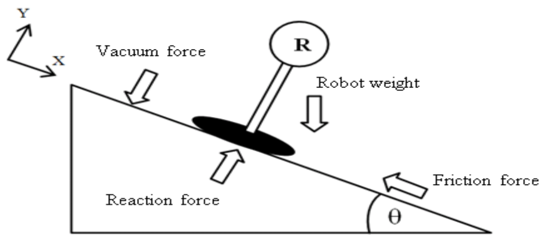

Fig.17:All forces acting on the sloped wall[5]

Table 2: Physical parameters and attributes for the climber robot

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Fig. 18. Total experimental setup at a glance

The climbing robot is operated to climb a glass wall. It was tested for surveillance and sensing applications by having a wireless camera mounted on the climbing robotic platform. During the test, the results were satisfactory.

VI. Applications

With little or no modification, the climbing robot can be used for the following applications and also its advantages are mentioned.

1. It can be a replacement for GONDOLA system for high rise building cleaning
2. Has the potential to serve as a base on which to mount data acquisition devices, surveillance equipment, or object-manipulation tools
3. Wireless/wired video surveillance possible
4. public safety & military applications (surveillance, search & rescue)
5. Consumer applications(window cleaning and painting)
6. Inspections (building, aircraft & bridges, Pipes) etc.
7. Wall/glass cleaning and water sprinklers can be mounted
8. On board vacuum cylinders are not used, which increases payload capacity

VII. Future Enhancement

On close observation, the climbing robot can be further enhanced in many ways. They can be listed as follows.

1. Payload can be increased by increasing the pumping capacity
2. Robot weight can be reduced.
3. Elevation angle of the robot on walls can be enhanced.
4. Leg stroke can be improvised.
5. Robot movement Speed on walls can be increased.
6. Obstacle detection can be added.

VIII. Conclusion

As expected, the results of the project came out to be satisfactory and the important observations are summarized as follows. The robot is facing difficulty in climbing the normal surfaces where air leakage is a problem. The robot is facing difficulty in climbing more than 90^0 slant angle on walls. Robot is capable of carrying loads of weight around 4 kg. Compared to normal walls, it is working fine on glass walls and wooden walls. Wireless camera placed on the robot body is transmitting good quality video output up to 10 m. Direction control headset is working fine and properly transmitting the navigation (Up, Down) signals and also receiving the sensor data effectively. Similarly the robot is receiving the direction control signals and changing the directions as expected up to a distance of 100 ft. he suction mechanism is working satisfactorily. The temperature sensor placed on the robot body is also functioning properly.

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