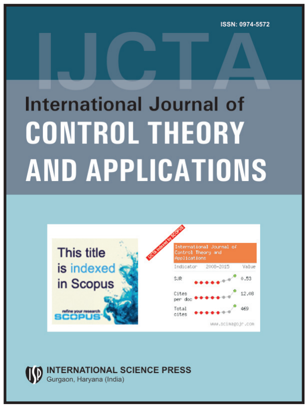

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# Development of Sliding Suction Cup based Wall Climbing Robotic System

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***Abstract:*** Climbing robots normally use suction cups for adhering to the surface. Most of the climbing robots using suction cup employs a remotely located huge suction generator to provide the required negative pressure to the suction cup. The negative suction pressure to the suction cups is delivered through long extendable tube which affects the dynamic balancing and stability of climbing robot. In the proposed work, the climbing robot using suction drag principle is realized with a suction cup integrated with a suction motor and hardware components using an embedded controller, pressure sensors and drive motors, which can move on smooth surfaces. This arrangement provides the required negative suction pressure for cup to adhere to the wall. It also enables to control the cup negative pressure by continuous monitoring. Catia software is used to design, simulation of the suction cup. This paper discusses about its basic mathematical analysis, the simulation of the model and the prototype wall climbing robot. The amount of suction force and corresponding negative suction pressure required by the suction cup system for holding the robot on vertical surface is computed theoretically and simulated using Matlab Simulink. It is observed through simulation that by varying the speed of the suction motor the negative pressure in the suction cup system can be controlled and the simulation result for the complete holding of the suction cup system considering the frictional forces is found to be –10.23 kPa. The simulation is also performed to find the sliding and drop off negative pressure levels by allowing a minimum suction leakage percentage. This is compared with the experimental suction cup system. The experimental results for the negative pressure in the suction cup system is found to be –6.63 kPa for holding the robot weighing 0.2Kg.The climbing robot can be realized by operating the suction cup system with a negative pressure lesser than –6.63 kPa by varying the speed of the suction motor. The drop off negative pressure value of the suction cup system is observed to be –1.82kPa.

***Keywords:*** Wall climbing robot, negative suction pressure, sliding suction system, Matlab Simulink.

## 1. INTRODUCTION

Wall climbing robot systems with adhesion mechanism are required to perform various operations such as inspection and maintenance of high-rise buildings, surveillance, inspection & cleaning of nuclear facilities etc. [1-5]. The automated systems available as on date have limited capabilities. Salient features of the robot to be designed are (1) On-board Suction Generator, (2) Light weight, (3) Automatic operation (4) The robot system shall have highest payload capacity and safe mobility. One of the most challenging tasks is to develop a proper adhesion mechanism to ensure that the robot system sticks to wall surfaces reliably without sacrificing mobility.

## 2. LITERATURE SURVEY

The various wall climbing robot systems with adhesion mechanism are available for wall climbing application. These mechanisms can be classified by the adhesion system and locomotion system. There are magnetic systems, negative pressure systems, air propeller, the gecko systems, sliding segments (crawling) [3-6], wheel driven robots, chain driven robots and legged machines. For climbing on smooth surfaces, the vacuum system driven by wheels seems to be the best solution Furthermore, the mechanical construction is relatively simple. Our mechanical concept of the climbing robot itself consists of a big vacuum chamber, which slides over the smooth surfaces. The traction mechanism is realized using drive-wheels. The authors Tae Won Seo. et. al., has developed an under actuated modular climbing robot with flat dry elastomer adhesives [7]. The main advantages are high speed, high payload, and dexterous motions but it has the disadvantages of vertical to ceiling translation movement and contamination caused due to use of elastomer. Guang zhao Cui et. al., proposed the design of a Climbing Robot based on Electrically Controllable Adhesion Technology, that has the advantages of Small size, climb various surfaces, consume low power but it has the disadvantages of very low Climbing speed, limited load capacity, and requires high voltage (1-5 kV). Zhiqiang Bi et. al., used Electromagnetic adhesion Technology which has advantages of Stability and High load capacity [8]. It cannot be used on non-ferromagnetic surfaces and at high temperatures as magnetization property varies. Jiajie Guo et. al., used Magnetic Wall climbing technology robot for testing large ferromagnetic structures[9]. The robot has sufficient speed and good load handling capacity but it is applicable only for ferromagnetic structures. Magnetic property variation will also occur at high temperatures. Hwang Kim et. al., used a tracked wheel mechanism of 12 sucking pads per wheel [10]. Xiao Qi Chen et. al., used Bernoulli’s principle to get non-contact adhesion [11]. It has advantages of high force/weight ratio (as high as 5), low cost, ubiquitous mobility under different surface conditions, and modularity but it is not capable to handle higher payload. Amir Degani et. al., used Single Actuator Technology, but the system is less stable and the load handling capacity is less[12].Jizhong Xiao et. al., used Vacuum based wheel drag system technology with good pay load capacity, Good stability but it requires more power since friction involved is more [13]. Carlo Menon et. al., used Bio inspired Gecko technology, where the robot can successfully climb up to 65 degree slopes at 2cm / sec. but the system cannot adapt to 3D circumstances and cannot avoid obstacles [14]. B.L. Luka et. al., used Vacuum suction based sliding frame walking mechanism technology which can step over small obstacles and good payload capacity but it is slow and doesn’t have 3D transition. Samuel G. Maggio developed remote-controlled devices that can travel on any vertical or inverted surface and that can be operated safely from the ground. Humans are not exposed to dangerous heights or to dangerous chemical or toxin environment. The International climbing machines made a device that can climb building structures and walls by using rolling seal and vacuum adhesion to surfaces.

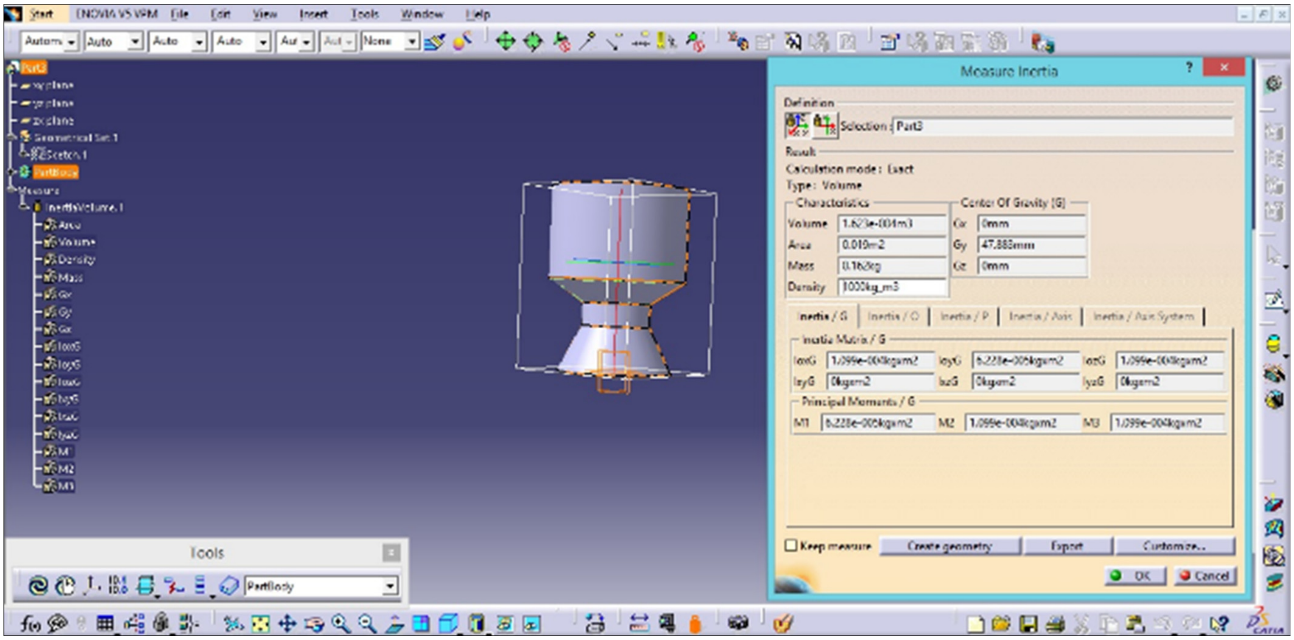
## 3. ROBOTIC SYSTEM

The Robotic Sliding Suction cup system (RoSS) is a climbing robot that uses sliding suction cup technique and capable to climb on vertical smooth surfaces. It also will overcome minimal (~1 mm) surface irregularities such as rivet heads, welds etc. The experimental model with a payload of 0.2 kg is developed. The developed robot travels at 0.6 meters/min. The outline of work is primarily focused on deriving the dynamical equations contributing for the mathematical system design of the suction cup system. The amount of suction force and corresponding negative suction pressure required by the suction cup for holding the robot on vertical surface is computed theoretically and compared with experimental suction cup system. The study of suction dynamics inside the suction cup is required for analyzing the proper suction variables to withstand in any situations and to adhere to the surface with the required holding force.

## A. Suction Cup System

The Suction cups are normally used in the climbing robots for adhering to the surface. The suction cups with the necessary negative pressure sticks to the surface firmly. The conventional suction cup system employs centralized operation provided by a common suction generator (suction motor). It may provide negative suction pressure to suction cup used for the movement of the climbing robot. The negative suction pressure to the suction cups is delivered through long extendable tube which affects the dynamic balancing and stability of climbing robot. The proposed suction cup system is developed to overcome the drawbacks of the existing systems. In the proposed model the suction cup is coupled with a suction motor by which the suction pressure for the cup is generated by its own. Figure 1 shows a picture of single cup mounted above with its suction generator, Figure 2 shows the simulated model by using Catia software for calculating the effective volume of air expelled by the suction generator.

**Figure 1: A single suction cup mounted above with a suction motor**



Selection : Part3

Calculation mode : Exact

Type : Volume

Volume 1.623e-004m3

Area 0.019m2

Mass 0.162kg

Density 1000kg_m3

Gx 0mm

Gy 47.883mm

Gz 0mm

IoxG 1.099e-004kgxm2
IoyG 6.228e-005kgxm2
IozG 1.099e-004kgxm2

IxyG 0kgxm2
IxzG 0kgxm2
IyzG 0kgxm2

M1 6.228e-005kgxm2
M2 1.099e-004kgxm2
M3 1.099e-004kgxm2

**Figure 2: Simulated model of the Suction cup system by using Catia software**

The climbing robot is realized with a single suction cup and a drive system. The robot moves using suction drag principle (active sliding technique). For mathematical analysis primarily single suction cup system is considered and the detailed dimensions of the various associated elements is given in Figure 3.

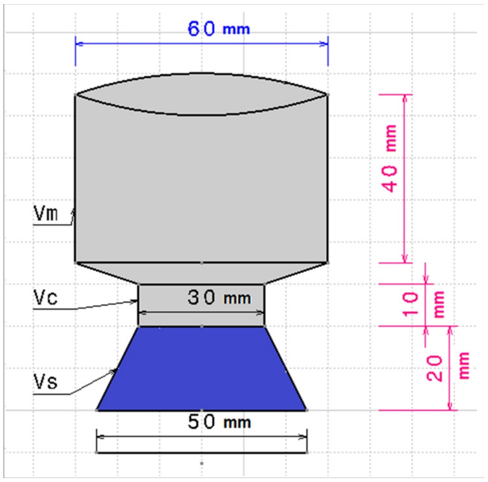


**Figure 3: Dimensions of the suction cup system**

The suction cup is selected with an outer diameter of 50 mm. The different functional states for a suction cup in correlation with speed of the suction motor is analyzed mathematically to calculate the effect of a working force of the suction cup required to rigidly hold to the surface. $V_m$, $V_c$, $V_s$ represents the volume of the corresponding segments of the suction cup respectively.

## B. Governing Equations for the RoSS Climbing Robot

Notational convention:

$N_c$ – Reaction forces exerted by the cup

$N_{w1}$, $N_{w2}$ – Reaction forces exerted by the drive wheels

$f_C$ – Frictional forces between the cup and the wall

$f_{w1}, f_{w2}$ – Frictional forces between the wheel and the wall

W – Weight of the robot

$L_1$ – Position of the wheels from the bottom edge

$L_2$ – Spacing between the wheels and the cup

$L_3$ – Position of the cup from the top edge

$h$ – Distance from the wall to the centre of gravity

$F_c$ – Suction force of the suction cup

µ – Static frictional coefficient

Figure 4. shows the force balance diagram for a single suction cup with drive wheel.Because of the symmetry in the drive system, $N_{w1} = N_{w2} = N_w$ [15].

Considering the Force balance,

X axis:

$$N_c + N_{w1} + N_{w2} = F_c + 2F_w \tag{1}$$

Y axis:

$$f_c + f_{w1} + f_{w2} = W = mg \tag{2}$$

Moment around the Point A:

Case 1: if Suction cup is in holding condition

$$Wh = (L_1 + L_2)\,(F_c - N_c) - L_1(N_{w1} + N_{w2}) \tag{3}$$

Case 2: if Suction cup is in moving condition

$$\left.\begin{aligned} f_C &\le \mu N_c \\ f_{w1} &\le \mu N_{w1} \\ f_{w2} &\le \mu N_{w2} \end{aligned}\right\} \tag{4}$$

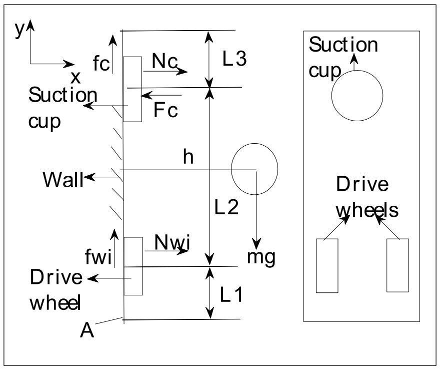


**Figure 4: Force balance diagram**

Case 3: if Suction cup is in falling condition i.e., zero reaction forces applied to the suction cups can be obtained from (1), (2) and (4) as

$$f_c + f_{w1} + f_{w2} \le \mu(N_c + N_{w1} + N_{w2}) \tag{5}$$

$$W \le \mu(F_c + 2F_w) \tag{6}$$

As the system is about to fall the reaction force at the cup tends to zero i.e., $N_c = 0$ and so also is $F_w$ i.e., $F_w = 0$.

Hence (1) and (3) will simplify to (7) and (8) respectively

$$(N_{w1} + N_{w2}) = F_c$$

$$\Rightarrow \quad 2N_w = F_c \tag{7}$$

$$Wh = (L_1 + L_2)F_c - L_1(N_{w1} + N_{w2})$$

$$\Rightarrow \quad Wh = (L_1 + L_2)F_c - 2L_1N_w \tag{8}$$

Using (7) and (8),

$$Wh = (L_1 + L_2)F_c - L_1F_c \quad \Rightarrow \quad F_c = \frac{Wh}{L_2} \tag{9}$$

This shows that when the mass (= W/g) of these system increases the holding force required also increases, as can be anticipated.

Theoretical Force calculation:

Mass, $m = 0.2$Kg

Length between cup and wheel, $L_2 = 120$mm

Height, $h = 110$mm

Gravity, 9.81m/s$^2$

$$\mu = 0.3$$

Safety factor, S = 2

Substituting the above values in (6), (9) and assuming the system is stationary, $F_w = 0$

$F_c = 6.5$N (considering the frictional force)

$F_c = 13$N (considering the frictional force and safety factors)

Substituting the above values in (9)

$F_c = 1.79$N (frictional force is not considered).

$F_c = 3.58$N (considering the safety factor, S without considering the frictional force).

By considering suction cup diameter as 50mm and area of the suction cup to be $A = 1.96 \times 10^{-3}$ m$^2$. The Active sliding suction cup can be achieved with this value of $F_c = 1.79$N (with No. frictional force) and $F_c = 6.5$N (considering the frictional force) and the corresponding suction pressure of −0.91 kPa and −3.316 kPa respectively.

By considering the safety factor, S = 2, the minimum suction pressure required will be −1.82 kPa and −6.63 kPa respectively to tightly hold the robot on the surface/ wall without sliding.

## C. Drive System

The drive system consists of single wheel units, driven by 7 kgf torque square gear motor, steerable presently with one degree of freedom. The drive unit is positioned centrally for a balanced operation and imparts a speed of 0.6 meters /min. Figure 5 shows the extended view of the drive motor with drive wheel accommodated with highly flexible rubber overlay for providing required friction for movement and reduce the slip.

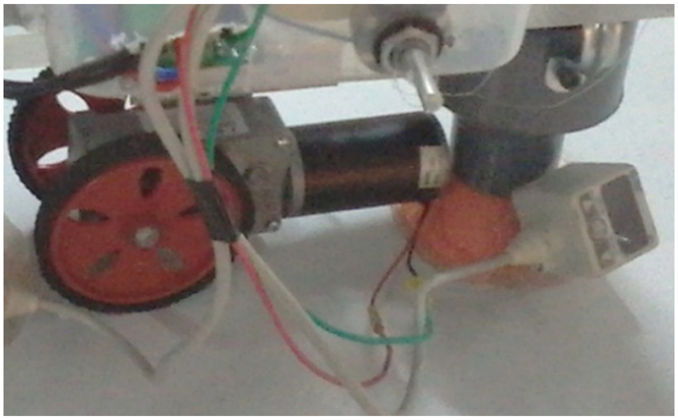


**Figure 5: Drive system**

## 4. EMBEDDED CONTROL SYSTEM

The closed-loop control of the negative pressure sliding suction cup system is implemented using Atmega microcontroller 328. The pressure sensor, drive motor, suction motor and High Definition Camera is connected through this microcontroller. A dedicated control algorithm is programmed to maintain the required negative pressure inside the suction cup to adhere with the wall and also functions to maintain the mobility of the climbing robot.

The feedback from the pressure sensors is used to maintain the negative pressure by varying the speed of the suction motor through specified motor drivers. The control scheme is explained in Figure 6. The pressure sensor data and the inspection HD Camera data is also transmitted wirelessly to the remote computer for data logging and analysis. The complete embedded system is shown in Figure 7.

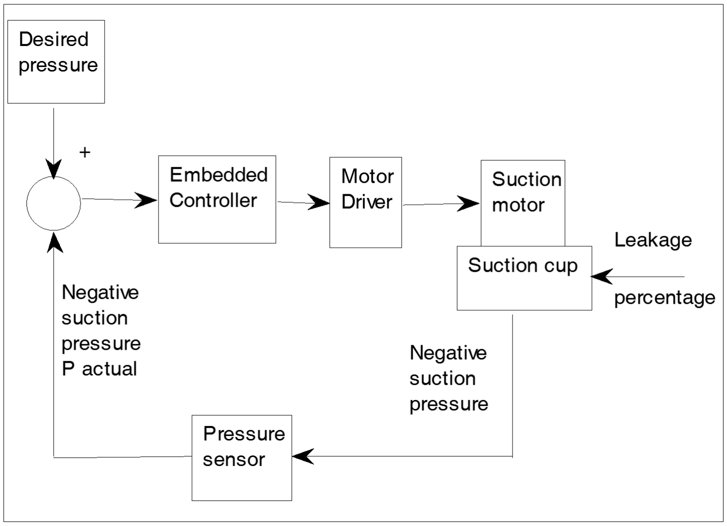


**Figure 6: Negative suction pressure controller – basic control loop**

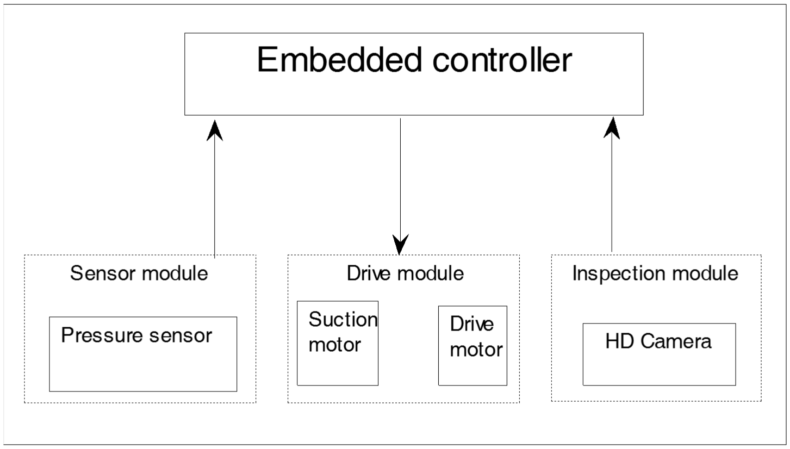


**Figure 7: Block diagram of RoSS – Robotic System using Sliding suction cup**

## 5. ROSS SUCTION PRESSURE CONTROL

### A. Matlab Simulation

The Simulink design using the PID controller is shown in Figure 8. Several blocks are used to design the overall Simulink model including the DC motor with driver block, suction pump and scope to monitor the suction pressure.

The input speed coming through the rotation of the DC motor is connected to the suction cup to generate the required suction pressure which is viewed through the scope.

The RoSS suction pressure control is achieved through controlling the Speed of the DC Motor with Proportional-Integral-Derivative (PID) controller. The PID controller is a closed loop feedback mechanism controller, which eventually controls the speed of the DC motor. The PID controller continuously calculates the error value as difference between the actual pressure and the desired pressure. The controller attempts to minimize the error and finally controls the DC motor speed.

The controller provides the desired speed to regulate the air flow and thereby achieving the suction pressure.

$$V_{sm}(t) = K_{sc} \,.\, \Delta P_{sc}(t) + K_{sc} \,.\, \frac{\Delta t}{T_{sc}} \,.\, \sum_{T=1}^{t} \frac{\Delta P_{sc}(T) - \Delta P_{sc}(T-1)}{2} + K_{sc} \,.\, \frac{T_{sc}}{\Delta t}\,(P_{sc}^{act}(t) - P_{sc}^{act}(t-1))$$

The above equation gives the PID controller functions using the portions of proportional, integral and derivative constants where

$V_{sm}(t)$ is the speed of the suction motor.

$K_{sc} \cdot \Delta P_{sc}(t)$ is the function of proportional constant ($K_p$) of suction cup pressure.

$K_{sc} \,.\, \frac{\Delta t}{T_{sc}} \,.\, \sum_{T=1}^{t} \frac{\Delta P_{sc}(t) - \Delta P_{sc}(T-1)}{2}$ is the function of Integral constant ($K_i$) of suction cup pressure.

The tuning of PID controller is performed through the simulation results observed in Simulink model. The simulation parameters for PID controller is set to the constants as follows:

$$K_p = 1,\ K_i = 0 \text{ and } K_d = 0$$

The desired pressure simulated in the controller design of Simulink model is shown in Figure 9, where 1 indicates the port to be simulated through the Simulink model of control design.

The results of the model are shown in Figure 10(a) and 10(b) closed loop with PID and closed loop with minimum leakage percentage. The model is simulated for single sliding suction cup.

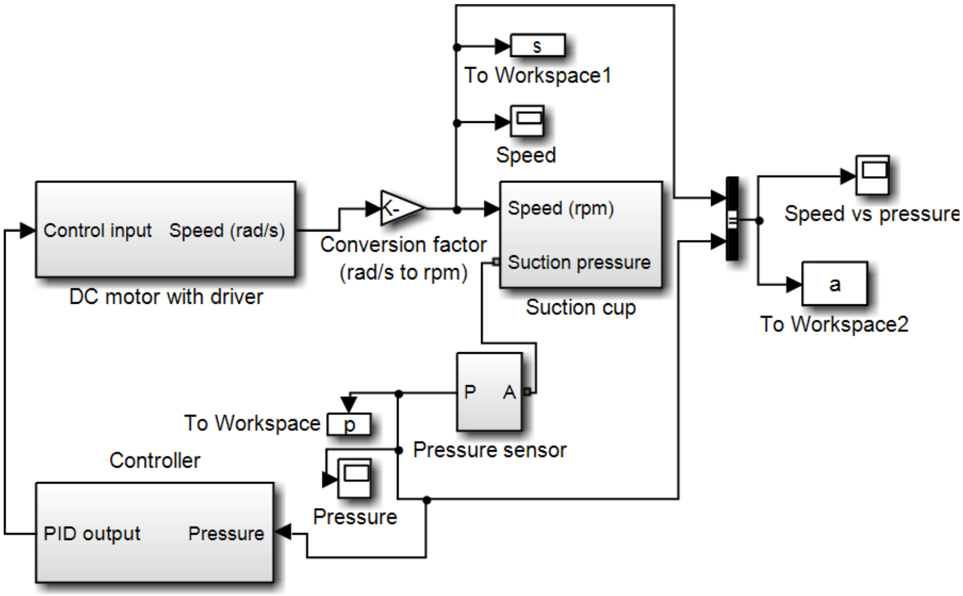


**Figure 8: Simulink model of DC motor with driver and controller**

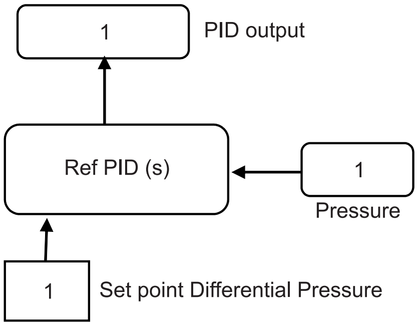


Figure 9: PID controller with desired pressure

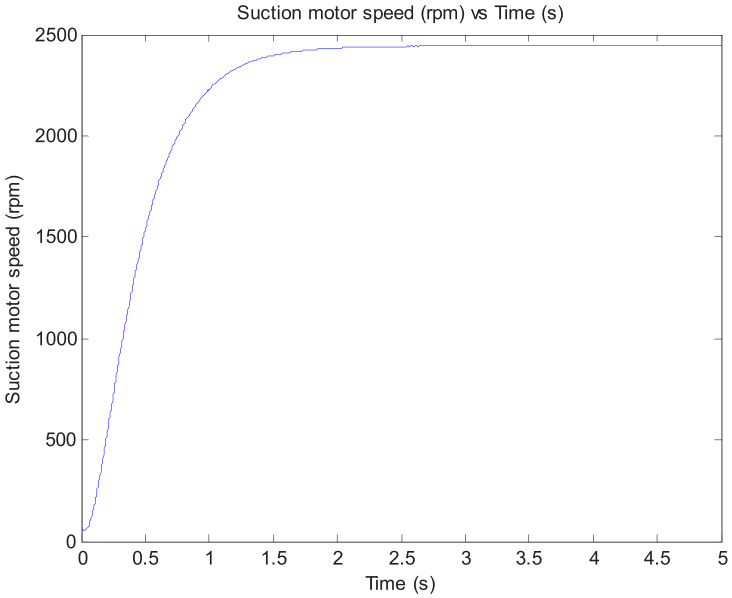


Figure 10: (a) Graph of suction motor Speed vs Time (with PID controller)

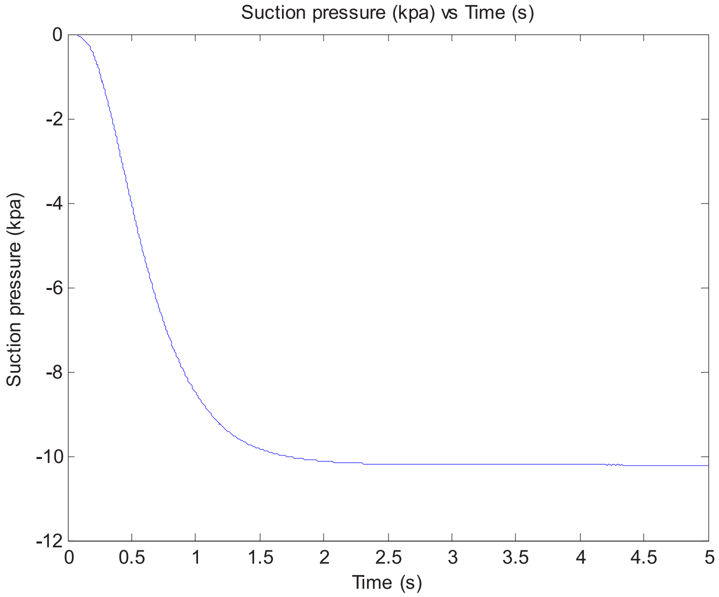


Figure 10: (b) Graph of suction Pressure vs Time (with PID controller)

Figure 11.shows the Simulink model observed with the PID controller giving minimum percentage and leakage caused due to the gap. Figure 12 shows the result of the simulink model when observed with PID controller and different leakage percentage.

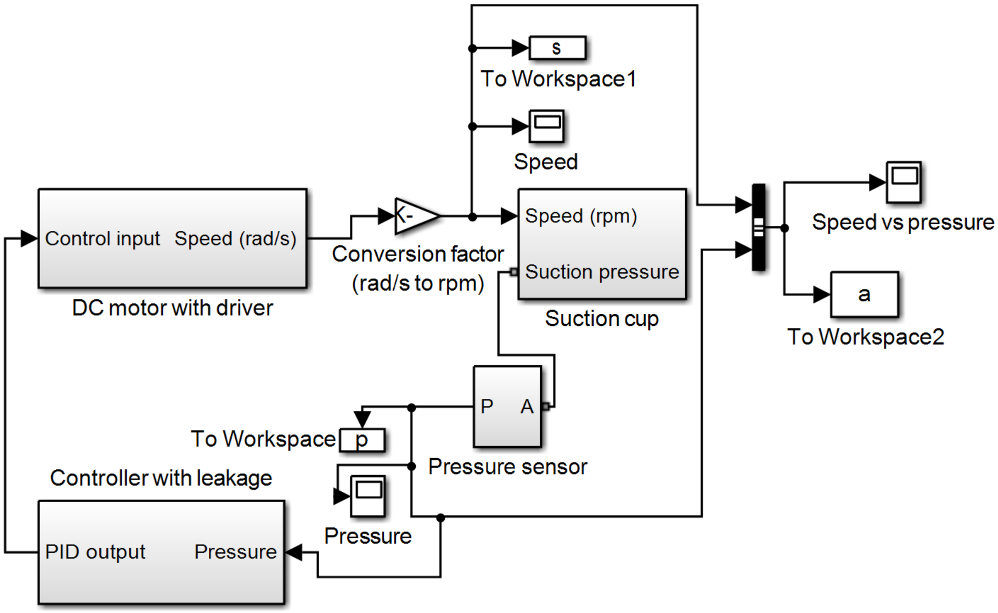


**Figure 11: Simulink model with minimum leakage**

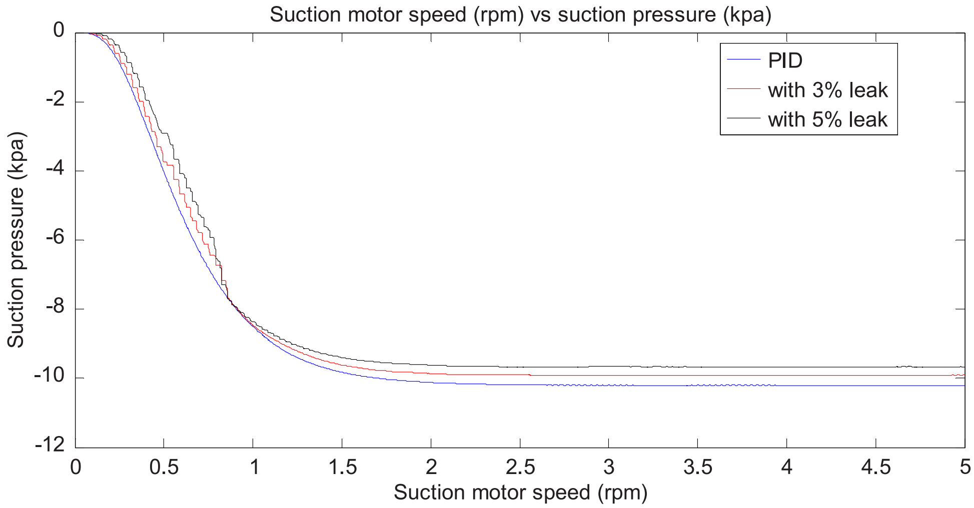


**Figure 12: Comparison graph plot for Suction pressure vs Time with leakage of 3% and 5%**

## 6. EXPERIMENTAL RESULTS

RoSS is tested in real time smooth surface environment with single suction cup. Suction cup has its own suction motor to provide necessary adhesion force. Figure 13 shows the experimental RoSS prototype of climbing robot. This investigation is carried out to find the adherence characteristics of the suction cup to the smooth surface and helps to find the holding capacity of the robot. The main objective of the proposed robot is to develop a climbing robot, which can adhere to the smooth wall surface and also able to move without falling at any instance.

**Figure 13: Prototype of RoSS – climbing robot**

This simulation result is compared with the experimental data. The simulation is carried out in two ways: (a) Closed loop with PID controller and (b) Closed loop with PID controller and minimum leakage. The experimental data is shown in Table 1, represents the trend of increase in negative pressure with respect to speed (which is anticipated).

**Table 1**
**Experimental data – Speed vs Negative Pressure**

| *Speed (RPM)* | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|
| *Negative Pressure (kPa)* | 0.95 | 1.12 | 1.39 | 1.64 | 1.82 | 2.02 |

The real time model delivers the pressure of –3.316 kPa and –6.63 kPa for active sliding and holding the robot, whereas the Simulink design achieves the pressure of approximately –10.25 kPa with controller for the design of 0.2 kg of mass. The Simulink design concludes that the maximum of 5% of leakage is allowed to stick on the wall firmly. It is also observed in simulation that by setting the controller and desired pressure to be 10, the maximum pressure achieved by neglecting the leakage is around –11 kPa.

## 7. CONCLUSION

In this paper, the design of RoSS climbing robot which is capable of moving vertically on a smooth surface wall is attempted. The preliminary results examined conclude that a sliding suction cup technique can be used for climbing the smooth vertical wall structures. It is also observed that higher complexity is to be addressed to reduce the slip of the motor over the smooth surface. The implemented control algorithm is able to provide a maximum speed of 0.6 metre/min. The time delay introduced by the controller to realize the target speed of the suction motor has to be reduced for improving the performance of the robot for safe mobility. The future work will be to tune the control algorithm for efficient operation and also to reduce the height of the system to increase the adhesion force and allow calculated suction leakage enabling the climbing robot to climb faster. The contact area of the wheels of the drive motor also will be studied for reducing the slip to improve the climbing speed.

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