Modelling and simulation of semi-automatic glass window cleaning machine

A Abhijith Kumar¹, R K Akhil, A A Ajnas, E V Abdul Vasihi and J Jithu
Department of Mechanical Engineering, NSS College of Engineering, Palakkad, Kerala, India
¹E-mail: abhijith98001@gmail.com

Abstract. The proposed design of the glass cleaning robot has two columns, each of whose ends are connected to four vacuum suction cups. Vacuum ducts connect the suction cups to the vacuum pump. Solenoid valves are used for controlling the suction in the suction cups so that the effective movement of the legs can be achieved. The vacuum supply to the two suction cups at the end of one column is cut off for moving the robot. Now, the pneumatic piston is used to move that column while keeping the other column fixed. This helps in the vertical motion of the robot. Similarly, another set of columns connected to a pneumatic piston is fixed perpendicular to the vertical column, which enables the robot to move in a horizontal direction. A cleaning unit is attached to the robot for the desired cleaning purpose. It consists of a microfiber brush, which continually cleans the surface as the robot moves with the help of a DC motor. A CAD model was designed and a static stress analysis while the robot is fixed on the surface was done using Autodesk® Fusion™ 360. The movement of the robot on vertical as well as on inclined surface is simulated. The results of the analysis show that the robot can successfully hold on to the wall with four suction cups and is able to climb vertical surfaces with more ease than inclined surfaces.

1. Introduction
With the development of infrastructure, buildings are taller than before and most of these buildings use glass for aesthetic purposes. One of the main problems while using glass is that it requires cleaning regularly. Statistics show that 30 people per year are facing critical injuries during window cleaning in the UK. This shows that the window cleaning job is one of the most dangerous jobs. There are so many risks associated with health and safety aspects for the window cleaners such as falling from a ladder, through fragile roofs, external sill, etc. Accidents can also happen due to accessibility issues associated with the cleaning equipment. The window cleaning process takes many stages over time and can be classified as manual stage, manual stage with the aid of machine and machine only stage.

The body of the robot should be kept close to the vertical surface, reducing the power needed to hold the weight of the robot. The weight of this kind of robot should not be more than 5kg. The centre of gravity of the robot must be kept as close as to the vertical surface as could be allowed, as the power needed to hold the entire weight of the robot will be diminished. The cleaning operations can be made safe by designing a cleaning robot that is smaller in size and whose weight is less [1]. The review of wall-climbing robots using different adhesion techniques has been presented by Aishwarya S. Shinde et al., [2]. The wall-climbing robots can achieve the capability to stick with a surface by different methods like suction cups, magnetic or gripping to the surface, etc. Suction cups can easily stick to any surface by creating a vacuum pressure which helps the cups to stick with the surface. Ritesh G Mahajan et al. [3] developed a wall cleaning robot using suction cups. The structure of the
robot is developed such that one frame sticks the robot to the surface or wall and the other frame is used for the movement of the robot. An Arduino controller is used to control the complete action of the robot. Santosh S. Gudi et al. [4] studied the feasibility of the suction cup mechanism for wall-climbing robots by calculating the adhesion force and payload. The results show that the robots have improved adhesion force which provides more gripping capability. The improved gripping capability ensures more payloads, which is reflected in the payload calculations. Nazim Mir-Nasiri et al. [5] developed a robot that climbs on the window glass surface which employs four suction cups. Cleaning of the wall is done with the help of a rotational wiper which wipes the surface. This robot is characterized by its lightweight and mini size. Many researchers have carried out studies by varying the shape as well as mechanical configurations of the robot. A robot was developed by Vinod Kumar M V et al., [6] by designing a triangular shaped frame which consists of a motor-powered automatic cleaner. A threaded shaft was used to move the cleaner in the vertical direction. The adhesion to the wall surface was achieved by the suction cup method. Another work emphasizes the development of periodical inspection of operational robot systems, proposed to use at the exterior of buildings that are built from modular glass panels [7]. A robot named 'Smart WindoroV1.0' was developed by Young-Ho Choi et al. [8] which uses magnet pairs instead of suction cups. The adhesion to the surface of the window is achieved with the help of four permanent magnet pairs which are incorporated between the inner and outer units. Navigation of the robot was done by the inner unit and cleaning of the window was done by the outer unit.

After analyzing many studies about the wall-climbing robots, it is clear that the mass that can be carried by the suction cups should be sufficiently higher than the total mass of the robot, owing to the movement and stability factors. The total weight of the robot is not to exceed 5 kg. A microcontroller is used for cost-effective and efficient control of the solenoid valves and vacuum pumps. It was also noted that the body should be kept as close as possible to the vertical surface, reducing the power needed to hold the weight of the robot. Various methods for suction or holding the robot on the glass surface were reviewed from different papers and finally, the use of suction cups for creating a vacuum or suction pressure was considered viable for this project. The suction pressure required for the suction cups can be calculated considering the weight of the robot [4]. Switching the vacuum generator off when the desired vacuum is reached. Also, the movement of the robot was based on controlling this suction pressure [9]. After analyzing different methods of locomotion for the robot, the usage of pneumatic cylinders for the movement of the robot was selected.

2. Methodology
A CAD model of the robot was made using Autodesk® Fusion 360TM. The designed model is shown in Figure 1. One of the main design conditions used is the suction pressure required to hold the robot on the glass surface. Suction pressure created by each suction cup was calculated and thus the mass that can be carried by the suction cups was also calculated [4]. It is given by,

\[ d = 1.12 \times \frac{m \times S}{P_u \times n \times \mu} \]  (1)

where, \( d \) = diameter of suction cup = 5 cm, \( m \) = mass of the robot = 2 kg, \( S \) = safety factor = 4 for vertical and 2 for horizontal, \( P_u \) = suction pressure created by the suction cup, \( n \) = number of suction cups = 8, \( \mu \) = coefficient of friction = 0.5 for glass. The weight of the whole robot was not to exceed 2 kg. The diameter of the suction cups was assumed to be 5 cm. Considering the above conditions and substituting the values, the force required is calculated as \( P_u = 0.1003 \text{ kg/cm}^2 = 9.836 \text{ kPa} \).

Therefore, the mass carried by eight suction cups = \( 8 \times \text{Area of suction cup} \times P_u = 15.7550 \text{ kg} \). Thus, the maximum payload that can be carried by the eight suction cups is 15.75 kg. But while moving, only four suction cups are in contact with the surface at a time. The maximum load supported by four suction cups would be 7.8775 kg.
The simulation of the designed model was carried out using Autodesk Fusion 360. Fusion 360 uses NASTRAN (NASA STRuctural ANalysis) as a solver to run its calculations. Static stress analysis was done on the vertical and horizontal columns when they are climbing a vertical and an inclined surface. When the robot moves along the surface, one of the columns is fixed and the other one moves, i.e. when four suction cups on one column are fixed on the surface, the column containing the other four moves. The analysis was done on the column fixed on the surface to find out whether the fixed column can withstand the weight of the robot while it travels on a vertical and an inclined surface. The stress distribution, displacement, and reaction forces on the column were obtained and compared after the analysis. The main components under consideration and the materials assumed for them during the analysis are shown in Table 1.

| Component                                      | Material            |
|------------------------------------------------|---------------------|
| Suction cups                                   | PVC, Flexible       |
| Block holding the suction cups and the pneumatic cylinder | Nylon 6/6          |
| Centre block connecting the vertical and horizontal columns | Nylon 6/6          |
| Two rods connecting the pneumatic cylinder to the opposite suction block | Aluminum 5454, Cold-formed |

Figure 1. Different views of the CAD model of the robot
The cleaning unit was suppressed since it did not have any significant effect. The column was meshed using a parabolic element order, as parabolic elements yield better results compared to the linear elements. Even though the parabolic elements require more computational resources than the linear elements, they can represent curved boundaries more accurately and produce better approximation results [10]. The average element size is 6% of the model-based size. Fixed type constraints were applied to the four suction cups in consideration. Contact sets were applied to all the parts to avoid the exclusion of components from the simulation. A pressure of 0.009638 MPa was applied on the four suction cups and a force of 19.6 N was applied uniformly under all the lowermost surfaces in the downward direction as shown in Figure 2. The surface on which the downward force is applied is indicated by the blue arrow marks in Figure 2.

![Figure 2. Forces applied on the suction cups](image)

For the simulations on inclined surfaces, the inclination was assumed to be 20° from the vertical. The surfaces on which the robot was simulated are shown in Figure 3.

![Figure 3. Vertical and Inclined surface on which the robot was simulated](image)

3. Results and Discussion
A model of the robot was designed using CAD software and simulation was done using the model on vertical and inclined surfaces. The joints were considered as bonded joints and fixed constraints were applied to the suction cups. A static stress analysis was performed on the model and its stress distribution, displacement, and reaction forces were obtained. The calculations were done with 36096 tetrahedral elements for the vertical column and 36046 tetrahedral elements for the horizontal column. Finer meshes further may lead to more accurate results, but a compromise was done due to processing power limitations. However, mesh controls were added to areas of specific interest to compensate for
this limitation. The different configurations in which the robot was simulated and the values obtained for different parameters are given below.

3.1. Vertical column on vertical surface
The vertical column is fixed when the robot moves horizontally along the surface. After applying the constraints and loads, the model was solved and the result is as shown in Figure 4. On analyzing the result, the maximum displacement is obtained as 0.1187 mm and the stress distribution is most concentrated on the top suction block with a maximum of 15.28 MPa, which is within the safe limits. The maximum stress occurs at a point in one of the Aluminum 5454 Cold-formed rods connecting the pneumatic cylinder to the opposite suction block. The ultimate strength of Aluminum 5454 alloy ranges from 240 – 300 MPa. It is also notable from Figure 4 that, the maximum stress occurs only at an area so small that it is almost negligible, and most portion of the body experience stress values close to the minimum value. The maximum reaction force was obtained as 1.988 N.

![Figure 4. Simulation results of vertical column on a vertical surface: (a) Actual displacement (b) Adjusted displacement (c) Stress distribution (d) Reaction force](image)

3.2. Horizontal column on vertical surface
The horizontal column is fixed when the robot moves vertically along the surface. Here, the stress concentration was maximum on the Aluminum rod near the centre block at 1.448 MPa. This is within the safe limits but this can be reduced even more by decreasing the length of the Aluminum rods. The maximum reaction force was 0.9129 N and the maximum displacement was 0.1286 mm. The results obtained in this scenario are shown in Figure 5.
Figure 5. Simulation results of horizontal column on a vertical surface: (a) Actual displacement (b) Adjusted displacement (c) Stress distribution (d) Reaction force
3.3. Vertical column on inclined surface

The robot moves horizontally along the surface in this case and the inclination was assumed to be 20° from the vertical axis. Upon solving this model, the results are generated as shown in Figure 6. It shows that the maximum displacement obtained was 0.1226 mm and the maximum stress obtained was 14.69 MPa. The reaction force on the suction cups was found to be at a maximum of 1.406 N.

![Figure 6](image)

Figure 6. Simulation results of vertical column on an inclined surface: (a) Actual displacement (b) Adjusted displacement (c) Stress distribution (d) Reaction force

3.4. Horizontal column on inclined surface

The angle of inclination was assumed to be 20° from the vertical and the robot moves in the vertical direction. Figure 7 shows the result obtained in this case. The displacement illustrates that the most deflection occurs on the Aluminum rod near the centre-piece. The maximum stress is 2.737 MPa and the maximum reaction force on the suction cup is 2.702 N.

![Figure 7](image)
The results are tabulated in Table 2. From the table, we can see that as the robot travels on an inclined surface, the values of stress and reaction force increases in all cases. The values of displacement increase in the case of the vertical column and decrease for the horizontal column. Even though there is a variation of results when the robot moves from a vertical to an inclined surface, all the values are within the safe limits. This shows that the robot can stick to the vertical or inclined surface without falling.
Table 2. Simulation results

| Scenario                   | Stress (MPa) | Displacement (mm) | Reaction force (N) |
|----------------------------|--------------|-------------------|-------------------|
| Vertical column on vertical surface | 1.793E-6 15.28 0 0.1187 0 1.988 |                    |                   |
| Horizontal column on vertical surface | 3.878E-7 1.448 0 0.1285 0 0.9129 |                    |                   |
| Vertical column on inclined surface | 1.915E-6 14.69 0 0.1226 0 1.406 |                    |                   |
| Horizontal column on inclined surface | 6.873E-7 2.737 0 0.076 0 2.702 |                    |                   |

4. Conclusions

The main objective of this paper was to design and simulate a semi-automatic robot that can be used to clean glasses or windows of buildings. The CAD model was successfully designed using Fusion 360. After reviewing many journals, the type of adhesion method, mode of locomotion, and form of cleaning unit to be fixed on the robot was decided. The calculations for finding out the desired suction pressure and the diameter of the suction cups to be used were performed and the data from these calculations were used to carry out the simulations.

The designed model was simulated in two working environments, vertical and inclined surface. The horizontal and vertical columns were simulated separately on both the surfaces and the results were derived from it. The simulation results obtained are satisfactory and validates that the robot can traverse across a vertical or inclined surface without tumbling.

The semi-automatic robot proposed here can be used to climb vertical glass surfaces for cleaning them. This has eliminated the need for traditional manual cleaning methods, which are hazardous for human at times. The compact size and low weight of the robot enable it to freely move along the surface of the glass surface when compared to the bulky and heavy, suspended type cleaning machines. But, the freedom of the robot is limited due to the constraint placed by the vacuum pump since it cannot be mounted on the robot and has to be connected externally. Hence further research could be conducted on getting the vacuum pump onboard without compromising the size and weight of the robot.

Acknowledgments

We would like to extend our profound gratitude and deep regards to our project guide for his exemplary guidance, monitoring, and constant encouragement. We would also like to thank our friends, faculties of the college, and parents for their valuable feedback and support.

References

[1] Jemish A Mistry, Harinkumar N Prajapati and Umang V Topiwala 2015 Conceptual working of glass cleaning robot Int. J. Adv. Res. Eng. Sci.& Technol.2 Issue 2
[2] Aishwarya S Shinde, Sayali S Kalebag, Sonam T Mali and Shrenik S Sarade 2017 Review of glass wall cleaning robot using wireless technology Int. J. Res. Appl. Sci. & Eng. Technol.5 Issue 9 pp 1433-36
[3] Ritesh G Mahajan and Prof S M Patil 2013 Development of wall climbing robot for cleaning application Int. J. Emerging Technol. and Adv. Eng. 3 Issue 5 pp 658-62
[4] Santosh S Gudi and K Bhat 2016 Design and development of pneumatic suction based wall climbing robot for multiple applications Int. Res. J. Eng. and Technol.3 Issue 7 pp 745-48
[5] Nazim Mir-Nasiri, Hudiyaja Siswoyo J and Md Hazrat Ali 2018 Portable autonomous window cleaning robot Int. Conf. on Rob. and Smart Manufacturingvol 133 (Chennai: Procedia
[6] Vinod kumar M V, Prem kumar naik, Prasad B G and Syed Razeequilla 2014 Design and Fabrication of automated glass curtain cleaning machine *Int. J. Sci. & Tech. Res.* 3 Issue 9.

[7] Dănuţ Pavel TOCUŢ 2013 Design of cleaning robot system to external glass walls of buildings *Fascicle of Management and Technological Eng.* Issue 1 pp423-26

[8] Young-Ho Choi, Jae-Youl Lee, Jong-Deuk Lee and Ka-Eun Lee 2012 Smart windoro v1.0: smart window cleaning robot *9th Int. Conf. on Ubiquitous Robots and Ambient Intelligence* (Daejeon: IEEE) pp 116-19

[9] Anubhav Jagtap 2013 Skyscraper’s glass cleaning automated robot *Int. J. Scientific & Eng. Res.* 4 Issue 7 pp 806-10

[10] J E Akin 2010 *Finite Element Analysis Concepts: Via SolidWorks* (World Scientific)