Stair Case Cleaning Robot: Design Considerations and a Case Study

Rajesh Kannan Megalingam,Abhijeet Prem,Aravind Hari Nair,Aditya Jayakrishnan Pillai,Bharath Sreekumaran Nair

***Abstract*—Using robots for cleaning surface, glass, rooms etc. are not new and are in the field of research for more than a decade. But when it comes to stair case cleaning, we see that the research area is only few years old. The main reason is the enormous difference is design mechanism when it comes to vertical climbing robots compared to the robots that move over surface. These robots function in 3-D space where as surface cleaning robots function in 2-D space which is comparatively easier to design and implement compared to the 3-D space robots. In this work, we present various design considerations for vertical climbing robots to be used in stair case cleaning. We also present a case study with the design of one such robot that functions in 3-D space, the implementation, the testing, and the performance. The test results are very encouraging for a possible good quality design outcome which can serve the intended purpose.**

***Index Terms*—Robots, cleaning, vertical climbing**

I. Introduction

Cleaning is one chore that is required every day in every facility including households, offices, public buildings etc. It is also a must chore in outdoor environments. Varieties of robots are being used for this purpose, though with limited characteristics. Cleaning robots can be broadly classified into two broad categories, indoor cleaning robots, and outdoor cleaning robots. Most of the commercial robots available for cleaning are for indoor environments. These include iRobot Roomba, Neato Botvac, V-Bot, Ecovas DEEBOT etc. They are available as floor cleaning robots, vacuum cleaners, sweeping robots, mopping robots etc. Though some of these claim to be outdoor cleaning, they refer 'outdoor' as pipe cleaning, window cleaning, gutter cleaning etc and in that sense outdoor cleaning robots are very few and limited.

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All the commercial products available and most of the ongoing research work present designs for cleaning robots which can move on an even surface which include only horizontal 2-D motion. Compared to vertical 3-D motion robotic design which requires vertical climbing up or down as the third dimension, the 2-D motion robots are easier to design. With the freedom to choose the size depending upon the stability of the 2-d motion robots, they are comparatively easier to implement. In this work, we are going to discuss about the design considerations of the stair case climbing robots which should conform with the design requirements of the 3-D motion robots. We are also going to present the design of the stair case climbing robot, the testing and evaluation of the design.The paper is organized as follows: Section II describes the problem under consideration which our research proposal addresses and the current research going on in this field is explained in Related Works Section III. This is followed by the in depth analysis of various design considerations for 3-D space climbing robots in Section IV. The system architecture and design approach are explained in Section V. The implementation of the system and the testing with the results are explained in section VI. The observation, the future works, and conclusion are presented in subsequent sections.

II. Problem Definition

All of us are closely associated with the facilities like houses, work environments, schools, malls, super markets etc., on daily basis. All these have stairs and any robot designed to automate the cleaning process must consider the 3-D nature of these facilities. Existing cleaning robots are 2-D in nature and cannot climb over stairs to clean them or reach other floors. While elaborate research is carried out in the 2-D space robots for more than a decade and still going on, 3-D space robots are relatively a younger research area. The 2-D space robots are limited in features that they can navigate over smooth surfaces only. For any cleaning robot to be complete in design must be able to climb the stairs, clean them, and reach other floors above or below to clean the entire building.

III. Related works

There are wide ranges of commercial robots employed in cleaning is available in the market as detailed in the introduction section. Researchers' contribution in the form of effort and hard work is an important factor for the commercial success of the robots used for cleaning. Earlier work point to multiple robots employed for cleaning robots in the form of algorithms. One such work is described by the authors in the paper [1] where in pattern based genetic algorithm is used for multiple cleaning robots. A localization algorithm used with sensors to estimate the condition of the robot by using Kalman filter is proposed in [2]. There are variety of cleaning robots -

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glass cleaning [3], hull-cleaning underwater [4], office cleaning [5], pipe cleaning [6], solar panel cleaning [7] are all proposed in several research works. Most of the research work toward this area point to more than a decade of research work particularly in surface cleaning robots which are 2-D in nature.

When it comes to the cleaning robots that can climb the stairs and clean several floors in a building including the staircase, there is not much work to be referenced. In [8] the authors propose a crawler type home robot particularly the mechanical features of climbing robot. The design of the robot and experimental results shows that there is a long way to go to get good working robot. The research work in [9] lacks information about the implementation of the robot employed in cleaning. It highlights only about the hardware and software integration. In the papers [10] - [11] by the same authors describe about the mobile mechanism of a climbing robot for cleaning and locomotion on stairs. Again the results are not very convincing and much of the details is left to the readers to decide. In our work, we are developing a system carefully taking into consideration various design issues of a staircase cleaning robot which is suitable for all facilities - houses, schools, office buildings, public buildings etc.

IV. Design Consideration

A. Manual control, Semi-Autonomous and Fully Autonomous

The robot can be completely manual controlled one. In such case the user physically moves the robot close to the steps and controls it to climb up or down, turn left or right over the stairs and switch on or off when needed. Though the user will be able to avoid obstacles by controlling the robot, the robot has such will have weak intelligence level. It is also a tedious task for the user to control the robot throughout the stairs and the difficulty level is going to increase as number of floors to be cleaned increases. A semi-autonomous robotic design will be able to solve this problem to a certain extent but still the user involvement cannot be avoided and might become a difficult task similar to the manually controlled one if the number of floors in a building is large. A fully autonomous one will keep the user out of the scenario expect at the beginning or at the end. But it has to have powerful sensors and algorithms to make the process smooth and completely automated.

B. Mobility Mechanism

The mechanical structure of the 3-D stair case climbing robots can be broadly classified under three different categories: wheel based, leg based, and crawler type. Performance wise wheel based climbing robots are poor which are best suited for even surface navigation [8]. They are not suitable for climbing steps or gaps or tiny obstacles. The wheel size has to be proportionally large enough to climb over tiny obstacles or over steps. The design of leg based structure is complex and the control mechanism is difficult to realize. The cost of implementation is also high and they are power hungry [9]. There are also hybrid structures which use wheels and legs and are called 'wheg' systems [12]. They also have similar issues to that of wheeled and legged systems. The crawler based robotic design for climbing stairs or an uneven surface is considered to be most efficient as it is easy to build and control.

Most of the uneven terrain robot designs adopt this crawler based mechanism for vertical climbing. A variation of crawler based robot for climbing stairs is explained in [12] called perching robot. Many hopping based climbing structures have be proposed [12] which consists of mechanism to raise and lower the robots to climb stairs. These are again wheeled ones because they use only wheels for locomotion.

C. Stationary and Dynamic Obstacle Detection and Avoidance

In 2-D surface cleaning robot designs, obstacle detection and avoidance (for both stationary and dynamic) algorithm is an integral part. While in stairs we don't expect any stationary obstacle, dynamic obstacles cannot be avoided. People using the facility might me walking up or down the stairs while the robot is cleaning the stairs. The robot should be able to detect such obstacles and the intelligent algorithm should be able to avoid the obstacles for the smooth functioning of the robots.

D. Threshold Detection

The robot should be able to identify the stairs inside the building, start and the end of the stairs and edge of the stairs. Threshold algorithms should be used to identify the edges of the stairs to avoid falling while cleaning. There can be two types of fall - one in which the robot falls from one stair-step to another and the other in which the robot falls from a stair-step to the floor, from the sides. Sometimes the stairs might have completely covered handrails which can prevent the robot from falling on the sides.

In some scenarios the handrails might be one sided and the other side of the steps is the wall of the building without handrails. In yet another case the handrails might have gaps in between but the gaps might not be large enough for the robot to fall through them. In some other cases there might not be any handrails and the robot is prone to falling often. Considering all these scenarios the robot design must include good algorithms for threshold detection to avoid falling.

E. Dimension of the Stair Steps.

In case of autonomous design the dimension of the stair steps are very important. Where the floors of any facility is expected to be with even surface, the same expectation fails when it comes to stair cases. There is no standard applied while constructing the staircases. Hence the height, the width, and the depth of the staircase steps vary widely.

The stair case might also have several turns and landing space between two floors. The autonomous stair case cleaning robot must take in to consideration all the above features of the dimension of the staircase steps. The dimension of the robot design must also be based on the staircase step dimensions.

F. Weight

Heavy robot designs won't be able to climb over the staircase steps elegantly.

The weight of the robot is a crucial factor to determine the success of the climbing aspect. If it's too heavy it might keep treading down very fast or it might find difficult to climb up. The weight depends on height and the depth of the stair case steps. The center of the mass of the robot must not fall outside the staircase step that it is climbing for the robot to climb without any difficulty.

V. SYSTEM ARCHITECTURE

A. System Design

The proposed system architecture consists of the crawler robot chassis, the cleaning brush, motor control, microcontroller board and control board. The current phase design is entirely manually controlled robot. The control is based on switches. The user can control the robot to climb up, down, left, right and stop with these switches. The wired control mechanism is used for this setup. The brush is attached to the front of the robot which is servo motor controlled, which can be controlled to move up and down by the user with the switches and the microcontroller board (MCB). The wheels of the robot are attached with the belt to tread easily over the surface and climb up or down the stairs. The MCB takes input from the switches and drives the motor controller which in turn drives the rear motor to make the robot move in front, reverse, right or left directions. While cleaning the brush is at the surface level so that the dust and garbage can be pushed to the direction in which the robot moves. While climbing up or down, the brush is adjusted to the raised to the level to balance the robot so that the robot can easily climb up or doesn't fall down while climbing down.

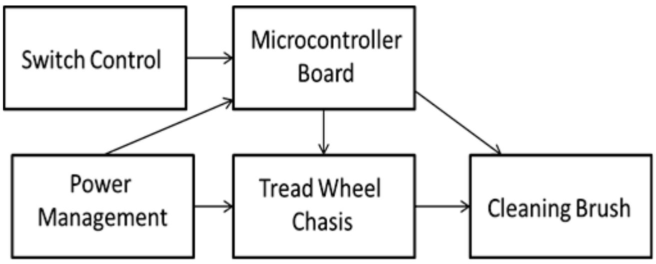

Fig. 2. General system architecture of the design

B. The Brush Used for Cleaning

The brush used for cleaning the staircase steps is in itself acts as balancer of the robot while climbing up and down. The various position of the robot and the brush are shown in Fig. 2 (a) to Fig. 2(d). Fig. 2(a) shows the chassis position and the brush position on the surface of the floor, at the bottom of the stairs. The brush bristles will be touching the surface. The position of the chassis and the brush while climbing the stairs is shown in Fig. 2(b). In this case the tread belt of the robot is touching the edge of the step and the brush is touching the surface of the staircase step about to be climbed. The brush acts as a support for the robot to climb. In Fig. 2(c) the brush is held upward and back to balance the weight while the robot is trying to complete the climbing. Fig. 2(d) shows the position of the robot after climbing the staircase step.

The Fig. 3(a) to 3(d) show various positions of the chassis and the brush of the robot while climbing down the staircase step. While climbing up, the center of the mass of the robot must now fall outside the staircase step for the robot not to fall while climbing. The center of the mass of the chassis and the center of the mass of the brush might be at different positions but the overall center of the mass of the robot must always fall inside the staircase step the robot is climbing. The climbing, the cleaning of the step, the direction of the movement of the robot, positioning the brush while climbing and positioning the brush while cleaning are all are all controlled by the user. In either case, i.e. while the robot is climbing up or down, the brush can move to a maximum of 135^{o} position back and to the reference position to balance the weight of the robot so that it will not fall down. The reference position is the position of the brush when it is touching the ground i.e when the tip of the bristles of the brush is touching the ground.

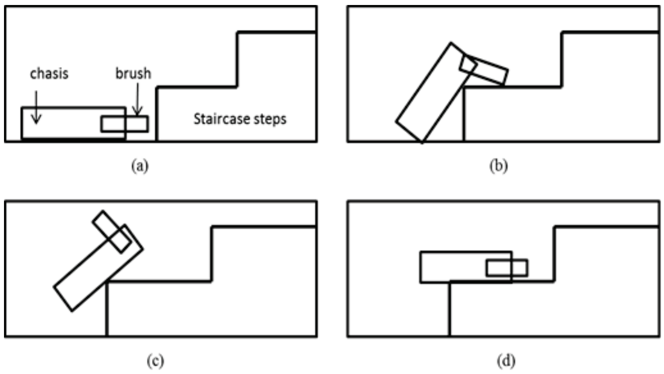

Fig. 2. Various positions of the robot while climbing up

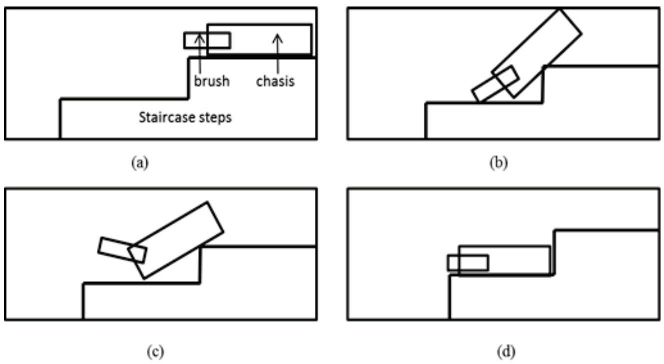

Fig. 3. Various positions of the robot while climbing down

VI. DESIGN IMPLEMENTATION

The entire setup was implemented on a chassis of height 8.5 cm, width 25 cm and depth of 22 cm, as shown in Fig 4. The robot moves with the help of tread belt over the wheels. The rear wheels are controlled by DC motors which in turn controlled by MCB through motor drivers. The entire setup is controlled by a switch box with five switches, two of them to control the climbing of the robot, either up(front) or down (rear), two of them to control the direction of the robot, either left or right and one switch is used to the brush to raise it either up or down. The raising of the brush up/down is crucial for climbing up or down as show in Fig. 2 and Fig. 3.

Fig. 4(a) to Fig. 4(h) shows the robot in various positions while testing. Fig 4(a) shows the robot experimental setup with the wheels attached to tread belt and the brush attached in front. Fig. 4(b) to 4(h) show the robot in action. When the robot is about to climb the brush is held high as shown in Fig. 4(b). Fig. 4(c) shows the position of the robot when it is about to climb up.The brush is held low over the step, to give support for the robot to climb up. Fig. 4(d) shows the robot climbing up and Fig. 4(e) shows the position of the robot after climbing up the staircase step. The robot cleaning the staircase step is shown in Fig. 4(f). Fig. 4(g) and Fig. 4(h) shows the position of the robot while climbing down the stairs. A three step staircase of height 6.5 cm, width 87 cm and depth 51 cm is created for this purpose. Fig. 5 shows the three step stair case for testing our 3-D space robot design.

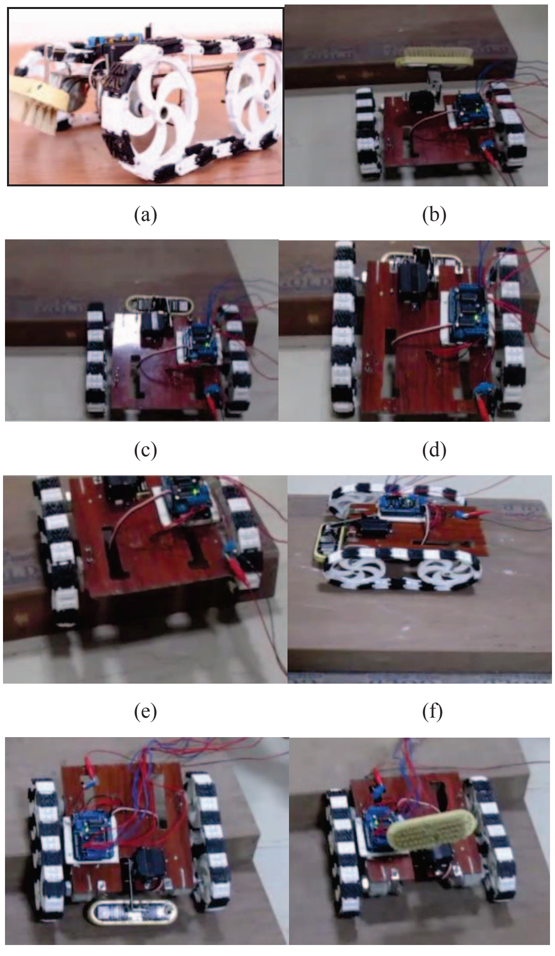

Fig. 4. Experimental Setup

The paths of the movement of the robot over the three steps are shown in the 3-D plot in Fig. 6 and Fig. 7. Fig. 6 shows the paths of the robot treading over the staircase steps while climbing up. Similar paths while the robot climbing down is shown in Fig. 7. The x-axis represents the width of the step, the y-axis, the height and the z-axis the depth of the staircase step. It is clear from the graphs that the robot is not taking a straight line path and it depends on the control of the robot by the user.


Fig. 5. Three step stair case setup for testing

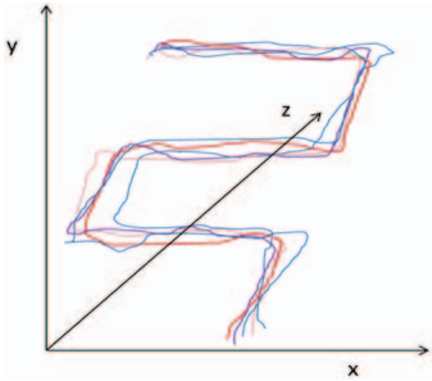

Fig. 6. Paths of the robot while climbing up

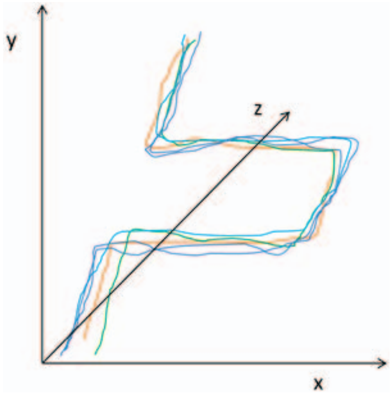

Fig. 7. Paths of the robot while climbing down

VI. Observation

The case study presented with the design of the staircase climbing robot tries to address the design considerations for the 3-D space climbing robots. As this is a work-in-progress, the robot is a manually controlled one, using switches. In addition it is a crawler based mechanism with the obstacle and threshold detection yet to be implemented. The dimension of the staircase steps and the weight of the robot is considered in such a way that the robot is able to climb the staircase steps. The brush is used to balance the robot weight while climbing up or down. As the robot is manually controlled, the path treaded by the robot while climbing up or down and left or right is not a straight line one as shown in the path graphs given in Fig. 7 and Fig. 8.

VII. Future Works

The presented work here is a work-in-progress where in the design considerations of the 3-D vertical climbing staircase cleaning robot are to be fully considered for further work. This includes the design changes for autonomous climbing and cleaning, threshold detection, weight consideration, modeling etc. need to be done. Vigorous and continuous testing of the robot has to be carried out for validation. Intelligent algorithms must be implemented for meeting the design considerations.

VIII. Conclusion

In this on-going research work, we have presented the need for indulging robots to clean facilities including houses, offices, schools and public buildings. The design considerations for such cleaning robots are explained in detail particularly the robots need to clean both the even surfaces / floor and staircase step as they are expected to climb several floors in a facility. One such robot which is implemented and tested by us is detailed in this paper. The testing environment and the evaluation of the robot points to a promising end result of this ongoing research.

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