Re-Sizeable Autonomous Cleaning Robot

Submitted in partial fulfilment of the requirements for the degree of

Bachelor of Technology

in

Mechanical Engineering

By

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February 2022

Declaration

We hereby declare that the thesis entitled “Re-Sizeable Autonomous Cleaning Robot" submitted by Kahaan Patel (18BME0691), Sahil Chaudhary (18BME0668) and Mehul Chaurasia (18BME0640), for the award of the degree of Bachelor of Technology in Mechanical Engineering to VIT is a record of bonafide work carried out by me under the supervision of Dr. Chinmaya Sahu.

We further declare that the work reported in this thesis has not been submitted and will not be submitted, either in part or in full, for the award of any other degree or diploma in this institute or any other institute or university.

Place: Vellore

Date: 12th February 2022

Signature of the Candidates

Certificate

This is to certify that the thesis entitled "Re-Sizeable Autonomous Cleaning Robot" submitted by Kahaan Patel (18BME0691), Sahil Chaudhary (18BME0668) and Mehul Chaurasia (18BME0640), School of Mechanical Engineering, VIT University, for the award of the degree of Bachelor of Technology in Mechanical Engineering, is a record of bonafide work carried out by them under my supervision during the period, 15.01.2022 to 20.04.2022, as per the VIT code of academic and research ethics.

The contents of this report have not been submitted and will not be submitted either in part or in full, for the award of any other degree or diploma in this institute or any other institute or university. The thesis fulfils the requirements and regulations of the University and in my opinion meets the necessary standards for submission.

Place: Vellore

Chinmaya Sahu.

Date: 12th February 2022

Signature of the Guide

Internal Examiner

External Examiner

Head of the Department

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Abstract:

Cleaning robots have advanced significantly in recent years, owing to increased market presence and the demand for improved cleaning performance. However, due to geometric restrictions of the platforms in relation to the cleaning stage, as well as furniture and architecture, most robots have difficulty covering the whole cleaning area. The aim is to use the on-board sensors which will mainly be a combination of SLAM (Simultaneous Localization and Mapping) integrated using LIDAR and camera to detect obstacles and change the robot configuration accordingly and to navigate forward and backward and even sideways with the help of Mecanum wheels. The plan is to use a ball screw actuation mechanism to change the length of the robot according to what it maps about the local terrain using the sensors. For this purpose, a precise CAD model will be designed with the decided parameters so as to bring down the cost of making the cleaning robot to the bare minimum while also optimizing its cleaning efficiency at the same time.

Introduction:

Cleaning has always been an important and necessary aspect of human lives, and it has developed and changed over time. The need for completely automated floor cleaning robots has surged as a result of today's hectic lifestyle.

Automated floor cleaning robots are commonly employed in smart homes, residential, and office spaces to clean the floors.

According to a world market study, there is a strong demand for the application of these robots in domestic settings with fully automated functionalities and the least amount of human assistance, and while these robots still account for a small percentage of the global vacuum cleaner market, their recognition and implementation is growing at a rapid rate.

The robots are small and execute the cleaning operation without the need for human participation. These robots use motion planning algorithms to cover a large area while cleaning, such as spiral motion, backtracking spiral motion, boustrophedon motion (back and forth), and basic zig-zag motion patterns.

Even though fixed-configuration robots have sufficient path planning and motion skills, they may require more time and energy to complete the complicated task effectively than their changeable counterparts. As a result, building a re-sizeable robot that can increase the swept area in open spaces, and can reduce its size to reach inaccessible areas. This project focuses on the design and development of the same.

Literature Review:

Prassler et al. demonstrated almost how all commercial home cleaning robots are equipped with vacuum cleaners as their primary means of cleaning. Pool cleaning robots have also been developed. Some robots also have wet scrubbers to clean the floor (non-textile floor coverings), and some also clean carpets. Some industrial robots have sweepers along with vacuum cleaners. Duct cleaning robots with rotating brushes have also been developed. Sensors that are usually employed include Ultrasonic, LIDAR, IR, Cameras and Contact. Robots are navigated using dead-reckoning, manually using a joystick, or even using magnetic markers to guide the way. Safety features include front bumpers that absorb impact shock. Robot road sweepers have also been developed for cleaning large open spaces. [1]

Endres et al. developed robots for cleaning purposes in the supermarkets. There are some special features in these robots, they consist of a retractable wing which is inserted in the right part of the robot. The use of this retractable wing allows the robot to get close to the objects and precisely cleans the floor without colliding with the obstacles. Also, the size of this wing can be adjusted according to the requirement it can be extended or reduced as needed. The main features of this robot were: To identify the obstacles properly for cleaning the environment, executing the plan properly, no need to install any additional part to localize the robot, a systematic skill to move around the obstacles for least energy consumption. [2]

Kushal et al. have worked on a cleaning robot ATMEGA 2560 which worked with two modes: automatic and manual. The hardware used were Arduino Mega 2560, Ultrasonic Sensor, DC Generated Motor, Vacuum Motor, L298n Dual H-Bridge Motor Driver, VL53LOX Laser TOF Sensor and Servo Motor. Since the robot has two modes, one of them is manual mode which is selected when the robot switch is high and allows the users to reach places which are not automatically detected by the robot. And for the autonomous mode there is an algorithm which is followed by the robot with path planning. There is also a water sprayer attached so that the robot can also be used for the moping purposes as for the convenience of the user. [3]

Sewan Kim et al. demonstrated the Roboking system integration in an autonomous cleaning robot. The purpose of this robot was the protection of the indoor cleaning environment while the robot is working. There are many different sensors and the functions which are integrated in this system. The robot uses a digital signal processor from Texas Instruments (320LF 2406A). It works on 40MHz frequency with 24 sensors performing the operations together gathering different signals from internal subsystems. Also, there are 14 ultrasonic sensors which are installed in the robot, where nine of them were used in the lower part to find the obstacles. And the others were used on the upper part so that the robot does not collide with the tall obstacles. For the Roboking mechanism, there are cliff detecting sensors which determine the upliftment of the robot and prevent the robot from falling down. [4]

Liu et al. developed a system that did not rely on mapping and global self-localization. It consists of three layers. The lowest layer contains the sensors and hardware, which include ultrasonic (13 pairs, 7 for the front and the rest for the sides), IR, encoders, DC motors, vacuum etc. The second layer is responsible for the behaviour of the robot, which include point turning, line following, wall following, side shifting, and obstacle rounding. The third layer is responsible for carrying out tasks, like environment learning, cleaning and homing. [5]

Mahmud Hasan et al. demonstrated the use of bumper contact sensors and cliff IR sensors. The path planning algorithms include Random walk, spiral, ‘S’-shaped path and wall follow. These four algorithms are cycled between until the entire area is covered. The motor specification is 2Amp/6VDC, 5500 rpm with 70:1 gearbox for the driving wheels. The side brush controlling motor specification is 0.5Amp/6VDC with a 30:1 gearbox. The vacuum motor is 5Amp/6VDC with 8000rpm (Cyclonic type dry vacuum is used). The battery used is 6V/4.5Ah lead-acid. The robot can operate for an hour. The battery takes 5-6 hours to charge. [6]

Joon et al. developed a combination of Lidar and camera. A manipulator arm containing the vacuum was attached to the mobile robot. The collector box has a volume of 378 cubic cm (10 cm × 6 cm × 6.3 cm). [7]

Shakhawat Hossen et al. discussed how LIDAR and GPS have been used for mapping and localization. IR proximity sensors and ultrasonic sensors were used for object detection. [8]

Gerstmayr-Hillen et al. discussed how an omnidirectional camera was used to generate panoramic images of the environment in order to map it, and hence guide and navigate the robot to cover a rectangular segment of the robot’s workspace. The omnidirectional camera is used to simultaneously localize the robot and also map the environment. Hence, the camera carries out local visual homing and provides the data to generate a dense topological map. The robot is guided along parallel paths by controlling its distance from the previous lane. The distance is estimated using images from the camera and the robot’s odometry. Only the robot’s distance from the previous lane and its orientation are calculated. [9]

Karur et al. discussed various path planning algorithms. Dijkstra and A* algorithms are used for static environments, whereas D*RRT (Rapidly-Exploring Random Trees), Genetic, Ant Colony and Firefly algorithms are used for Dynamic environments. [10]

Dakulovic et al. demonstrated complete coverage of D* algorithm for path planning, using a combination of D* and PT algorithms. [11]

Lamini et al. demonstrated how GA (Genetic Algorithm) with improved crossover operators and fitness functions were employed to find optimal solutions. [12]

Amine Yakoubi et al. demonstrated that GA was used for path planning. Each gene represents the robot position and the chromosomes represent the mini-path. [13]

Liu et al. developed an algorithm for complete coverage path planning, which combines random path planning and local complete coverage path planning. Random path planning is very flexible for unstructured environments, but is inefficient. On the other hand, local complete coverage path planning generates a comb-like path to cover a relatively small area with high efficiency, but fails to do so in a larger area in an unstructured and dynamic environment. The proposed technique combined the benefits of both. 11 pairs of ultrasonic sensors were used, 7 for the front and the rest for the sides. [14]

Hofner et al. demonstrated path planning of a rectangular non-holonomic robot. Two changing maneuvers were used to navigate the robot – U-Turn and Side-Shift. Based on the parameters of the robot and the environment, the path planning algorithm will choose the most appropriate path planning template such that the entire floor area is covered efficiently. Localization was done using ultrasonic sensors and dead-reckoning. Subgoals were determined in the vicinity of various pre-planned landmarks. Vehicle guidance was done by finding the specified start location and compensation of path errors. [15]

Ramalingam et al. developed an algorithm for detecting and classifying debris as solid and liquid spillage using CNN and SVM was developed. This helped the robot to avoid hard to clean debris, as robots are mostly unable to clean such debris and hence end up spreading them on the floor rather than cleaning it, thus also reducing their efficiency. [16]

Schmidt et al. developed an algorithm that has been developed to memorize uncleaned areas that couldn't be cleaned in the first sweep because of a temporary obstacle, and then come back to clean it after the remaining area has been cleaned. [17]

Parween et al. developed a self-reconfigurable robot called hTrihex has. It enables the robot to cover spaces that are generally missed or inaccessible by the usual circular shaped cleaning robots (like corners). This robot can configure itself into three different configurations based on the requirements, namely – Straight, Chevron and Closed. The sensors used onboard are encoders, LIDAR and IMU, along with a PID controller for implementing a closed-loop system. A differential drive has been implemented to steer the robot and hence control the heading. [18]

Parween et al. developed another similar self-reconfigurable robot is the hTetrakis. It consists of four equilateral triangles, and can change between three configurations namely – "I", "A", and "U" shapes. These configurations enable the robot to access convex and narrow corners that are generally inaccessible by the common circular shaped cleaning robots. [19]

Forlizzi et al. demonstrated that mecanum wheels have their omnidirectional property that allow them to have excellent manoeuvrability and ability to move in a congested space. Congested spaces usually mean environments with static or dynamic obstacles or narrow areas respectively. Due to the Mecanum wheel's high manoeuvrability, it is ideal for outdoor applications like transportation purposes in warehouses, mining activities and even for military activities and indoor applications like autonomous robot cleaning that is the objective of this Capstone project. [20]

Laurena et al. developed and demonstrated control mechanism for actuating ball screw linear actuator. A ball screw linear actuator converts rotatory motion to linear motion. It has low friction and can withstand thrust loads. The programming and control system for the linear actuator was developed. [21]

Bhowmik et al. developed an algorithm for navigation of a cleaning robot by modifying the Dijkstra algorithm. A provision for backtracking and hill climbing were incorporated. This improved the performance of the Dijkstra algorithm. [22]

Gaps in the Literature:

After the exhaustive literature review it has been concluded that,

1. All the commercially available cleaning robots are fixed in size and configuration.
2. A handful of self-reconfigurable robots have been developed. The aim of these robots is to cover hard-to-reach places, that conventional fixed configuration robots cannot.
3. Hence, the aim is to develop a re-sizeable robot that can increase its length to cover more area in a single sweep, and can also reduce its size to reach inaccessible areas.

Problem Definition:

Cleaning robots are available in a variety of sizes and can clean a specific area in a single sweep. However, in open places with little impediment, such as broad halls and living rooms, cleaning can be done quickly by sweeping a larger area in a single sweep. To address this issue, a re- sizeable cleaning robot is being developed that can extend its length, allowing it to cover a larger area in a single sweep, and can also reduce its size to reach inaccessible areas.

Objectives:

1. To design a system that can change the length of the robot depending on the need and area that is currently being cleaned.
2. To integrate an actuation mechanism for changing the length.
3. To integrate SLAM using LIDAR.
4. To integrate object detection using camera and/or ultrasonic sensors.

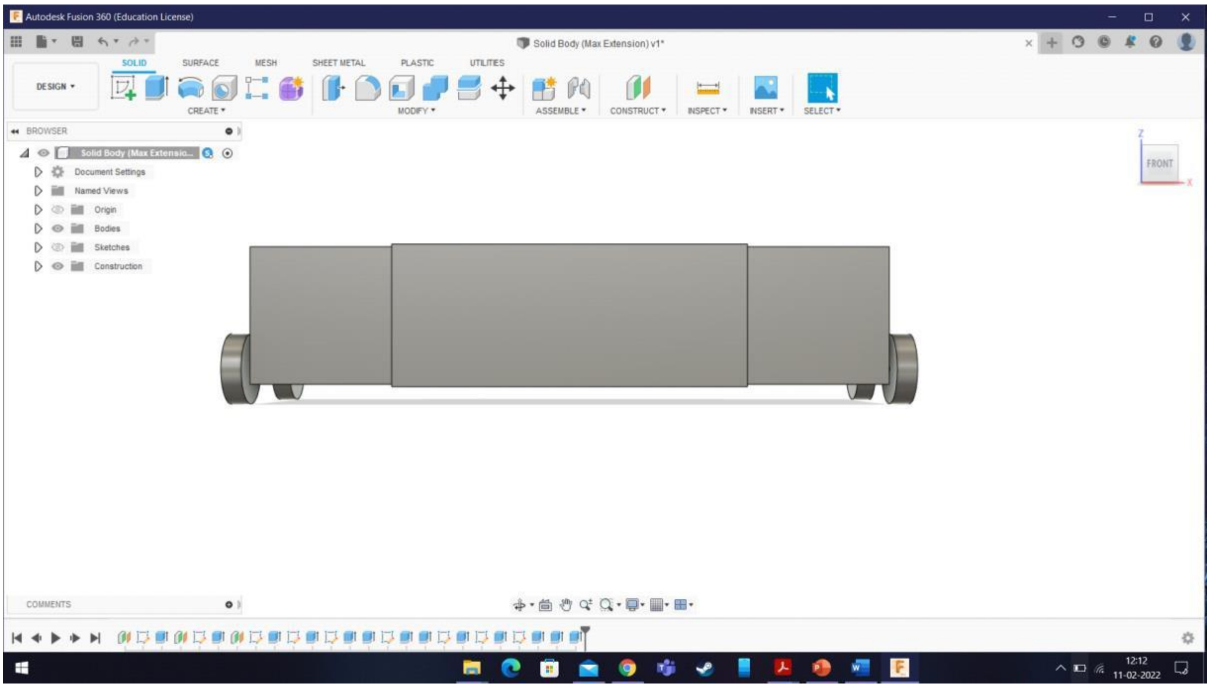
Methodology:

The theoretical design of the robot, as well as the basic components needed, have been finalised after extensive study and detecting gaps in the literature review, as well as recognising scope for improvement. The following steps will be to create a CAD model, programme the robot's many functions like the ability to change its length according to the environment, and do simulations like controlling the opening and closing of the vacuum suction hole and the ability of the robot to manoeuvre with the help of Mecanum wheels. The on-board sensors will include LIDAR and camera to detect obstacles and change the robot configuration accordingly.

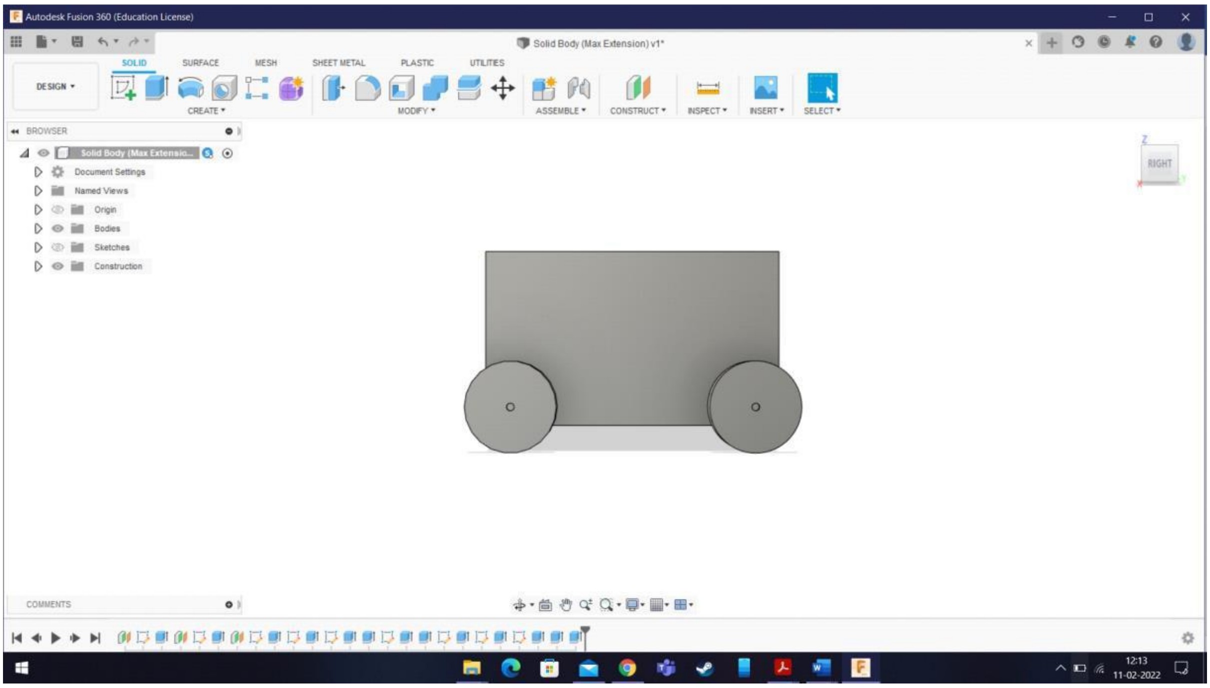
Work Carried Out So Far:

1. Literature review has been completed.
2. Problem statement defined.
3. The primary components required to make the robot have been finalised.
4. The conceptual design of the robot, including the mechanism to change its size, has been developed.

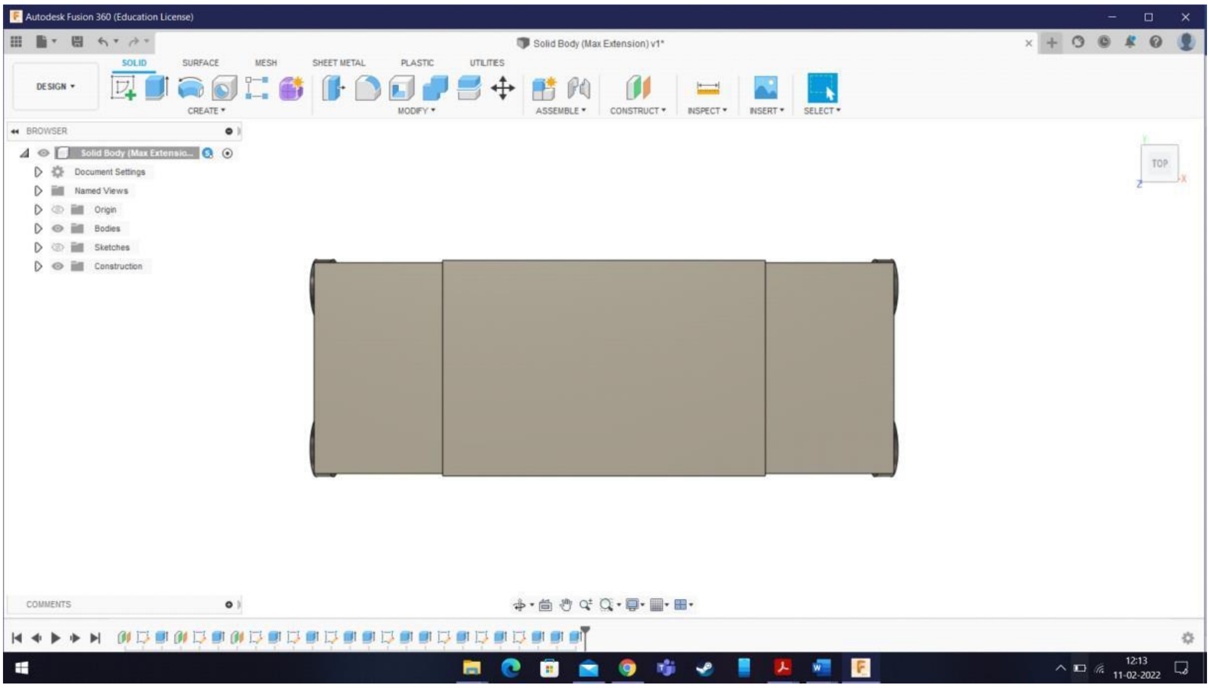
<u>Design Prototype:</u>



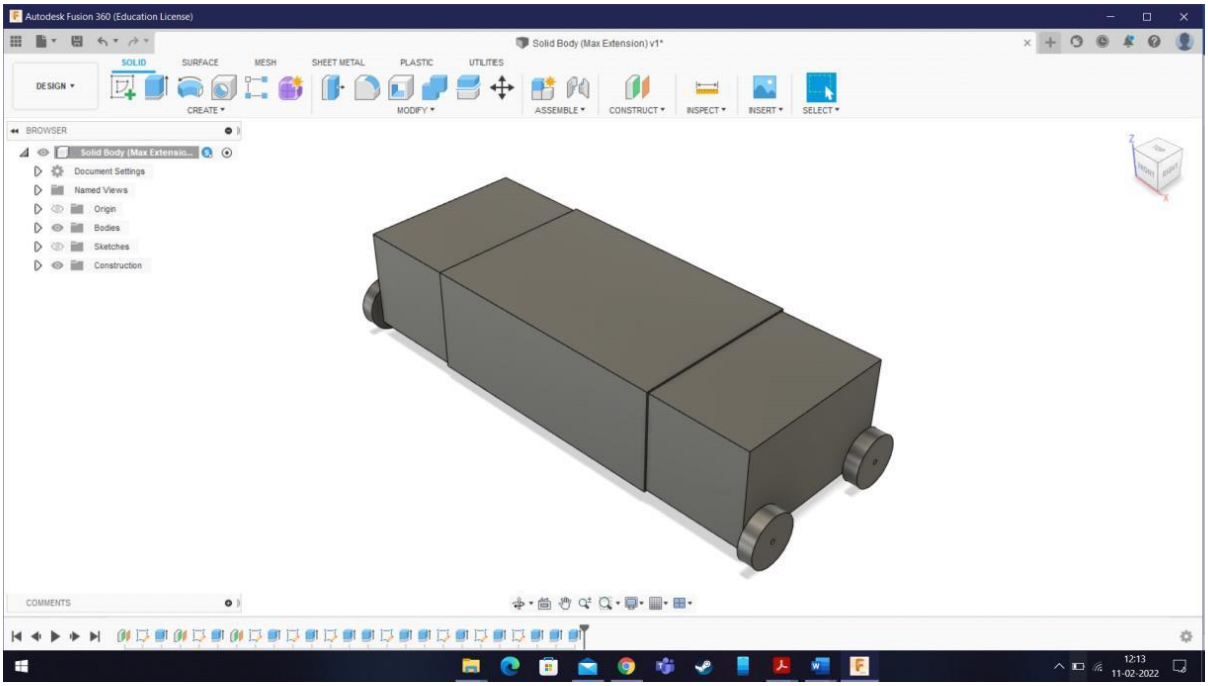
FRONT VIEW



SIDE VIEW



TOP VIEW

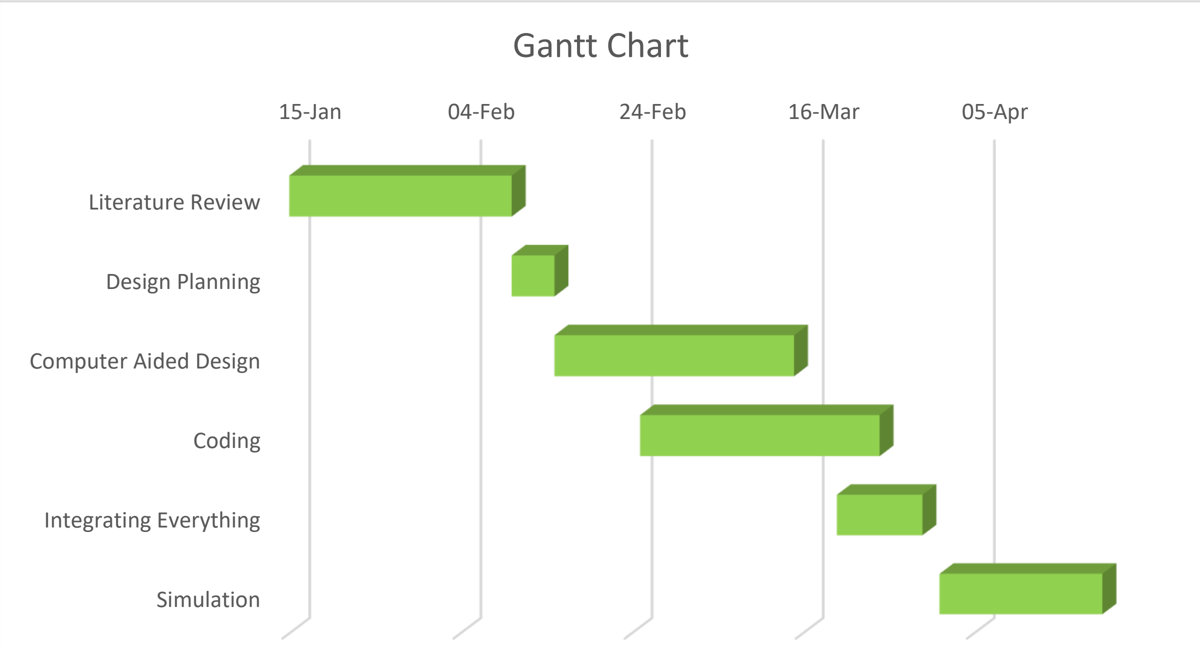


ISOMETRIC VIEW

Work to be Done:

1. A CAD model for the robot- After deciding upon the dimensions, the objective is to model it in Autodesk Fusion 360 so as to achieve the goal of making a re-sizeable autonomous robot that can change its dimensions according to the terrain.
2. Integrating SLAM using LIDAR and object detection using camera- Simultaneous Localization and Mapping will be used by the cleaning robot to create a map of the terrain and the concept of Light Detection and Ranging is used which collects information about variable distances between the robot and an obstruction using light in the form of a pulsed laser.
3. Developing the control system to actuate the Ball Screw Linear Actuator used to change the size (length) of the robot.
4. Integrating Mecanum wheels control in the robot.
5. Designing size changing vacuum slit for the robot- The size of the vacuum opening needs to change proportionally along with the length of the robot.
6. Integrating Dijkstra algorithm for path planning.

Gantt Chart:



	Simulation	Integrating Everything	Coding	Computer Aided Design	Design Planning	Literature Review
Start Date	01-Apr	20-Mar	25-Feb	15-Feb	10-Feb	15-Jan
Days to Complete	20	10	28	28	5	26

Milestones in the Project Phase:

1. Chassis design
2. CAD design for actuation mechanism

3. Path Planning Algorithm
4. Object Detection Algorithm
5. Developing the control system to actuate the Ball Screw Linear Actuator used to change the size of the robot

References:

[1] E. Prassler, A. Ritter, C. Schaeffer and P. Fiorini, “A Short History of Cleaning Robots,” *Autonomous Robots,* vol. 9, pp. 211-226, December 2000.

[2] H. Endres, W. Feiten and G. Lawitzky, “Field Test of a Navigation System: Autonomous Cleaning in Supermarkets,” *IEEE International Conference on Robotics and Automation* , 06 August 2002.

[3] N. Kushal, H. Chaudhuri and H. Nikithesh, “Autonomous Floor Cleaning Bot,” *International Research Journal of Engineering and Technology (IRJET),* vol. 5, no. 6, June 2018.

[4] S. Kim, “Autonomous Cleaning Robot: Roboking System Integration and Overview,” *IEEE International Conference on Robotics and Automation,* 07 June 2004.

[5] Y. Liu, S. Zhu, B. Jin, S. Feng and H. Gong, “Sensory Navigation of Autonomous Cleaning Robots,” *Fifth World Congress on Intelligent Control and Automation,* 18 October 2004.

[6] K. Hasan, A. Nahid and K. Reza, “Path Planning Algorithm Development for Autonomous Vacuum Cleaner Robots,” *2014 International Conference on Informatics, Electronics & Vision (ICIEV),* May 2014.

[7] A. Joon and W. Kowalczyk, “Design of Autonomous Mobile Robot for Cleaning in the Environment with Obstacles,” *Applied Science 2021,* vol. 11, no. 17, p. 8076, 31 August 2021.

[8] S. Hossen, R. Shaharear, F. Islam, S. Islam, N. Hossain and S. Datta, “Designing and Optimization of An Autonomous Vacuum Floor Cleaning Robot,” in *2019 IEEE International Conference on Robotics, Automation, Artificial-intelligence and Internet-of-Things (RAAICON),* November 2019.

[9] L. Gerstmayr-Hillen, F. Röben and M. Krzykawski, “Dense Topological Maps and Partial Pose Estimation for Visual Control of An Autonomous Cleaning Robot,” *Robotics and Autonomous Systems,* vol. 61, no. 5, May 2013.

[10] K. Karur, N. Sharma, C. Dharmatti and J. Siegel, “A Survey of Path Planning Algorithms for Mobile Robots,” *Electrified Intelligent Transportation Systems,* vol. 3, no. 3, pp. 448-468, 04 August 2021.

[11] M. Dakulović, S. Horvatić and I. Petrović, "Complete Coverage D* Algorithm for Path Planning of a Floor-Cleaning Mobile Robot," *IFAC Proceedings Volumes,* vol. 44, no. 1, pp. 5950-5955, January 2011.

[12] C. Lamini, S. Benhlima and A. Elbekri, "Genetic Algorithm Based Approach for Autonomous Mobile Robot Path Planning," *Procedia Computer Science,* vol. 127, pp. 180-189, 2018.

[13] M. Yakoubi and M. Laskri, "The Path Planning of Cleaner Robot for Coverage Region Using Genetic Algorithms," *Journal of Innovation in Digital Ecosystems,* vol. 3, no. 1, pp. 37-43, June 2016.

[14] Y. Liu, X. Lin and S. Zhu, "Combined Coverage Path Planning for Autonomous Cleaning Robots in Unstructured Environments," *2008 7th World Congress on Intelligent Control and Automation,* 08 August 2008.

[15] C. Hofner and G. Schmidt, "Path Planning and Guidance Techniques for An Autonomous Mobile Cleaning Robot," *Robotics and Autonomous Systems,* vol. 14, no. 2-3, pp. 199-212, May 1995.

[16] B. Ramalingam, A. Lakshmanan, M. Ilyas, A. Le and M. Elara, "Cascaded Machine-Learning Technique for Debris Classification in Floor-Cleaning Robot Application," *Applied Science 2018,* vol. 8, no. 12, p. 2649, 17 December 2018.

[17] G. Schmidt and C. Hofner, "An Advanced Planning and Navigation Approach for Autonomous Cleaning Robot Operations," *International Conference on Intelligent Robots and Systems,* 06 August 2002.

[18] R. Parween, M. Heredia, M. Rayguru and R. Abdulkader, "Autonomous Self-Reconfigurable Floor Cleaning Robot," *IEEE,* pp. 114433-114442, 01 June 2020.

[19] R. Parween, V. Prabakaran, M. Elara and A. Vengadesh, "Application of Tiling Theory for Path Planning Strategy in a Polyiamond Inspired Reconfigurable Robot," *IEEE,* pp. 6947-6957, 18 December 2018.

[20] J. Forlizzi and C. DiSalvo, "Service Robots in The Domestic Environment: A Study of The Roomba Vacuum in The Home," *HRI 06': Proceedings of the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction,* pp. 258-265, 02 March 2006.

[21] P. Eng, B. Laurean and D. Telea, "Management and Motion Control of Ball Screw Actuators Applied in the Robotic Structures," *Control Systems Engineering,* June 2012.

[22] S. Bhowmick, R. Adhikari and S. Dutta, "Practical Applications for Mobile Robots based on Mecanum Wheels - A Systematic Survey," *IJIREEICE,* vol. 6, no. 12, pp. 20-24, December 2018.

[23] M. Zhao, H. Lu, S. Yang, Y. Guo and F. Guo, "A Fast Robot Path Planning Algorithm Based on Bidirectional Associative Learning," *Computers & Industrial Engineering,* vol. 155, p. 107173.

[24] A. Lakshmanan, R. Mohan, B. Ramalingam, A. Le, P. Veerajagadeshwar, K. Tiwari and M. Ilyas, “Complete Coverage Path Planning Using Reinforcement Learning for Tetromino Based Cleaning and Maintenance Robot,” *Automation in Construction,* vol. 122, p. 103078, April 2020.

[25] Z. Yan, S. Schreiberhuber, G. Halmetschlager, T. Duckett, M. Vincze and N. Bellotto, “Robot Perception of Static and Dynamic Objects with An Autonomous Floor Scrubber,” *Intelligent Service Robotics,* pp. 403-417, 08 June 2020.

[26] H. Wang, Y. Yu and Q. Yuan, “Application Of Dijkstra Algorithm in Robot Path-Planning,” *IEEE,* 18 August 2011.

[27] L. Yang, J. Qi, D. Song, J. Xiao, J. Han and Y. Xia, “Survey of Robot 3D Path Planning Algorithms,” *Journal of Control Science and Engineering,* vol. 2016, no. Article ID 7426913, 04 July 2016.

[28] M. Elara, N. Rojas and A. Chua, “Design Principles for Robot Inclusive Spaces: A Case Study with Roomba,” *IEEE,* 29 September 2014.

[29] J. Jones, “Robots At the Tipping Point: The Road to iRobot Roomba,” *IEEE,* pp. 76-78, 2006 February 2006.

[30] Gross and Jennifer, “Interviewing Roomba: A Posthuman Study of Humans and Robot Vacuum Cleaners,” *Explorations in Media Ecology,* vol. 19, no. 3, pp. 285-297, 01 September 2020.

[31] B. Tribelhorn and Z. Dodds, “Evaluating The Roomba: A Low-Cost, Ubiquitous Platform for Robotics Research and Education,” *IEEE,* 21 May 2007.

[32] Bergman and Joel, “Robot Vaccum Cleaner,” *School of Industrial Engineering and Management (ITM),* p. 70, 2019.

[33] T. Asafa, T. Afonja, E. Olaniyan and H. Alade, “Development of a Vacuum Cleaner Robot,” *Alexandria Engineering Journal,* vol. 57, no. 4, pp. 2911-2920.

[34] Z. Zhang and Z. Zhao, “A Multiple Mobile Robots Path Planning Algorithm Based on A-Star and Dijkstra Algorithm,” *International Journal of Smart Home,* vol. 8, no. 3, pp. 75-86, May 2014.

[35] N. Buniyamin, W. Ngah, N. Sariff and Z. Mohamad, “A Simple Local Path Planning Algorithm for Autonomous Mobile Robots,” *Control Systems Engineering,* January 2011.

[36] M. Elara, N. Rojas and A. Chua, “Design Principles for Robot Inclusive Spaces: A Case Study with Roomba,” *2014 IEEE International Conference on Robotics and Automation (ICRA),* 29 September 2014.

[37] P. Adithya, R. Tejas, S. Varun and B. Prashanth, "Design and Development of Automatic Cleaning and Mopping Robot," *IOP Conference Series: Materials Science and Engineering,* vol. 577, no. 012126, 16 August 2018.

[38] M. Ilyas, S. Yuyao, R. Mohan, M. Devarassu and M. Kalimuthu, "Design of sTetro: A Modular, Reconfigurable, and Autonomous Staircase Cleaning Robot," *Journal of Sensors,* vol. 2018, no. Article ID 8190802, 24 July 2018.

[39] T. Ichimura and S.-i. Nakajima, "Development of an autonomous beach cleaning robot "Hirottaro"," *2016 IEEE International Conference on Mechatronics and Automation,* 05 September 2016.

[40] V. N. Shah, Sathvik and A. Vaghela, "Floor Cleaning Robot (Autonomus/Manual)," *International Journal of Engineering Research & Technology (IJERT),* no. 2016.

[41] V. Silva, J. Roche and A. Kondoz, "Robust Fusion of LiDAR and Wide-Angle Camera Data for Autonomous Mobile Robots," *Sensors 2018, Depth Sensors and 3D Vision,* vol. 18, no. 8, p. 2730, 20 August 2018.

[42] C. E. O. Lima and S. Sano, "Design and Analysis of a New Type of Mecanum Wheel," in *Proceedings of 175th IASTEM International Conference – Tokyo, Japan,* April 2019.