Tampere University

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DESIGN OF AUTONOMOUS CLEANING ROBOT

Faculty of Engineering and Natural Science
Master of Science Thesis
December 2019

ABSTRACT

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Today, the research is concentrated on designing and developing robots to address the challenges of human life in their everyday activities. The cleaning robots are the class of service robots whose demands are increasing exponentially. Nevertheless, the application of cleaning robots is confined to smaller areas such as homes. Not much autonomous cleaning products are commercialized for big areas such as schools, hospitals, malls, etc.

In this thesis, the proof of concept is designed for the autonomous floor-cleaning robot and autonomous board-cleaning robot for schools. A thorough background study is conducted on domestic service robots to understand the technologies involved in these robots. The components of the vacuum cleaner are assembled on a commercial robotic platform. The principles of vacuum cleaning technology and airflow equations are employed for the component selection of the vacuum cleaner. As the autonomous board-cleaning robot acts against gravity, a magnetic adhesion is used to adhere the robot to the classroom board. This system uses a belt drive mechanism to manoeurve. The use of belt drive increases the area of magnetic attraction while the robot is in motion. A semi-systematic approach using patterned path planning techniques for the complete coverage of the working environment is discussed in this thesis.

The outcome of this thesis depicts a new and conceptual mechanical design of an autonomous floor-cleaning robot and an autonomous board-cleaning robot. This evidence creates a preliminary design for proof-of-concept for these robots. This proof of concept design is developed from the basic equations of vacuum cleaning technology, airflow and magnetic adhesion. A general overview is discussed for collaborating the two robots. This research provides an extensive initial step to illustrate the development of an autonomous cleaning robot and further validates with quantitative data discussed in the thesis.

Keywords: robotic vacuum cleaner, autonomous cleaning, autonomous board cleaner, autonomous vacuuming, path planning techniques

PREFACE

This master thesis has been carried out in the Faculty of Engineering and Natural Sciences at the Tampere University.

I would like to express my gratitude to Professor Kari T. Koskinen for vesting the opportunity of carrying out the thesis work at Mechatronics Research Group (MRG) and supervising my work. I would like to thank the project manager of the group Dr Jussi Aaltonen for his guidance and supervision. MRG has provided me with a great working atmosphere.

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Tampere, 17.12.2019

Lakshmi Bangalore Gangadharaswamy

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LIST OF SYMBOLS AND ABBREVIATIONS

BLDC	Brushless Direct Current	
CAD	Computer aided design	
DOF	Degrees of freedom	
Dpu	Dust pick up	
GPIO	General Purpose input/output	
IMU	Inertial Measurement Unit	
IR	Infrared	
LIDAR	Light Detection and Ranging	
Li-ion	Lithium ion	
MEMS	Microelectromechanical systems	
MCL	Monte Carlo localization	
RADAR	Radio detection and ranging	
ROS	Robot operating system	
RPS	Room positing system	
SLAM	Simultaneous localization and mapping	
SONAR	Sound Navigation and Ranging	
TOF	Time of flight	
A	area of the orifice	[m^2]
a	transmission probability of short structure	
A_{nozzle}	cross-section area of the nozzle	[m^2]
B	breath	[m]
C_{hose}	conductance in hose for a viscous laminar flow	[m^3/s]
$C_{orifice}$	conductance of orifice in viscous laminar flow	[m^3/s]
C_{dust_bag}	conductance in dust bag for a laminar flow	[m^3/s]
C_{nozzle}	conductance in nozzle for a viscous laminar flow	[m^3/s]
C	total conductance	[m^3/s]
d	inside diameter of the tube	[m]
F	Force	[N]
F_m	Magnetic adhesive force	[N]
$F_{f(i=1,2,3,4)}$	frictional force components	[N]
f_0	Static friction co-efficient	[N]
h	height	[m]
H	distance between the board surface and center of mass	[m]
I	Inertia	[kgm/ s^2]
l_{eff}	effective length of the line	[m]
l_{axial}	axial length of the hose with bends	[m]
l	total length of the hose	[m]
Kn	Knudsen number	
k_2	safety factor	
G	force due to gravity	[N]
L	length between the center of the rollers	[m]
m	mass	[kg]
M	mass of the brush	[kg]
M_A	moment about point A	[Nm]
$\bar{p}$	average pressure	[Pa]
p_1	exit pressure along the direction of flow	[Pa]
p_2	inlet pressure along the direction of flow	[Pa]

P	power	[W]
Q	airflow	[m^3/s]
$R_{(i=1,2,3,4)}$	reaction force	[N]
R	radius of the brush	[m]
r	radius of the wheel	[m]
S	pumping speed	[m^3/s]
S_{eff}	effective pumping speed	[m^3/s]
T_s	starting torque	[Nm]
T_o	operational torque	[Nm]
T	Torque	[Nm]
t	time taken	[s]
V	volume	[m^3]
v	speed of air	[m/s]
α	angular acceleration	[rad/s^2]
α_t	transmission ratio	
η	Efficiency	
θ	angle of the below/ bend	[deg]
δ	critical pressure number	
Δp	Pressure difference	[Pa]
λ	mean free path	[m]
ρ_{air}	density of airstream	[kg/m^3]
ω	angular velocity	[rad/s]
μ	Frictional co-efficient value	

1. INTRODUCTION

The integration of autonomous robots to human life is gaining rapid momentum. Cleaning has been one of the most important tasks in everyday human activity and it has always been a time-consuming process. It is not much of surprise that the demand for autonomous cleaning robots is increasingly been common in the modern digital world. The demand for household autonomous cleaning robots such as robotic vacuum cleaners, robotic lawn mowers is increasing exponentially. According to (Tobe 2017) the "International Federation of Robotics" has forecasted the annual growth of 33% through 2019 for these robots. The potential of this market as attracted various vacuum cleaner manufacturers to invest in this field. Products such as iRobot, Robo Vac, Botvac, Trilobite are some of the tested products in the market. These smart cleaners can clean homes without human assistance. However, the application of these smart devices has been limited just for domestic purposes.

Apart from domestic homes, there is tremendous potential to implement autonomous cleaning robots to places such as schools, auditorium, shopping malls, etc. This thesis aims at creating a proof of concept of an autonomous cleaning robot for schools. In general, the most common cleaning tasks to be addressed in a school are floor cleaning and board cleaning. Hence, the main application of this autonomous cleaning robot is floor cleaning and board cleaning. Usually, the floor cleaning process is accomplished in two steps. First is the dry cleaning wherein the dust is cleared using a vacuum cleaner. It is then followed by wetting cleaning using a wet mop. This thesis focuses on developing a system for dry cleaning through vacuum cleaning. Here the robot must be able to move freely within its working environment while at the same time execute effective vacuum cleaning of the area. Generally, the school floor contains a combination of dust, bits of paper, gravel and small pebbles and the cleaning area is huge. Therefore, a robust vacuum cleaning system must be designed such that it has a good dust-pickup ability to suck the above-mentioned debris. Along with this, the system must have longer running cycles to clean the maximum area in one charging cycle. The selection of path planning algorithms and sensor array plays a vital role in providing complete coverage of the area and thereby effects the efficiency and safety of autonomous vacuum cleaning.

The advent of ferromagnetic boards in classrooms has eased the implementation of autonomous board cleaning robots through magnetic adhesion. Usually, the board cleaning robots are positioned on a vertically inclined plane wherein the robot can fall due to gravity while in motion. Hence it is important to design a light yet robust system that can efficiently maneuverer on the board without falling against gravity. The Conceptual design of an autonomous cleaning robot involves tasks such as the mechanical design of the system, component selection, modelling of the system and path- planning techniques. A single system built to carry out the tasks of floor cleaning and board cleaning simultaneously is much more advantageous than two separate systems. Furthermore, the proof of concept outlines the essential components and tasks involved in developing an autonomous cleaning vehicle.

1.1 Research methodology

This thesis focusses on designing a proof-of-concept for an autonomous cleaning robot. The autonomous cleaning robot can come in various designs and types based on the application area. The application area for this thesis work is school. Hence, the autonomous cleaning robot comprises of an autonomous floor-cleaning robot and an autonomous board-cleaning robot to cater to the needs of floor cleaning and board cleaning at school.

The methodologies followed in conducting this thesis are listed below

- **Defining objective –** The first step for the initiation of any project or research is defining its objective. The topic "design of an autonomous cleaning robot" involves a vast set of concepts, tools, theories, methods, and problems. It can be narrowed down only based on the project requirements. The idea of a robotic vacuum cleaner is good, but it is already existing at private homes. This motivated to design a proof of concept to a large area like schools. Nevertheless, the concept of automated board cleaner is still in the research stage. Hence, the idea of collaborative implementation of automated vacuum cleaner robot along with board cleaning robot was generated.
- **Background study –** The background study concentrated on reviewing and comparing the existing key technologies and recent developments related to the topic. A lot of books, journal articles, conference proceedings, product reports, and consumer reports were reviewed. The customer feedback on existing market products was extensively studied to understand the drawbacks of the cleaning robots.
- **Development of a proof of concept –** basic calculation for the autonomous floor-cleaning robot was done based on the equations of vacuum technology and airflow. The force diagrams and torque equations were used for the autonomous board-cleaning robot. SOLIDWORKS was used to create the CAD model and mechanical assembly.
- **Navigation techniques –** the techniques for mapping and path planning are discussed. Combination of planning algorithms were selected to achieve maximum cleaning efficiency. In addition to this, the collaboration of two autonomous robots is briefly discussed.

2. THEORETICAL BACKGROUND

2.1 Principle of Vacuum Cleaning Technology

A vacuum cleaner is a cleaning apparatus consisting of a motor with an impeller, nozzle, hose, tube, and a filter. It is used for a general-purpose cleaning of the floor, carpet, and other surfaces. The motor and fan together create a partial vacuum within the system to suck dirt and dust from the surface through the nozzle that passes through a tube and hose until it reaches the dust collection unit. The dust collection unit is either a disposable dust bag (filter) or a cyclonic separator. Finally, the filtered air is let back to the environment (Leffler, Sörmark 2013). Figure 1 represents the principal sketch of a canister vacuum cleaner.

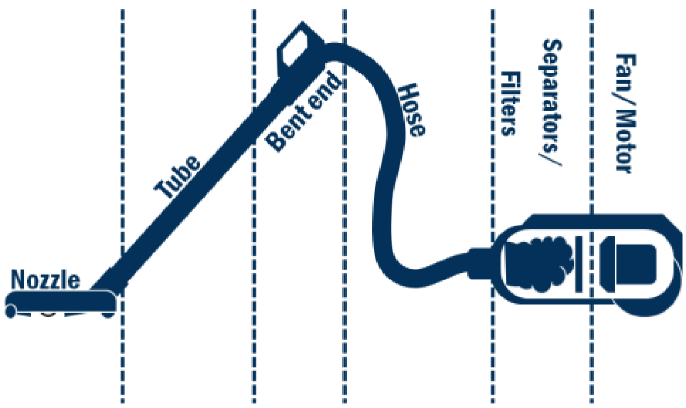

Figure 1. *Principal sketch of a canister vacuum cleaner (Leffler, Sörmark 2013)*

Today there are several types and brands of vacuum cleaners for various demands. The common ones being canister, stick and cordless, hand-held, and automatic vacuum cleaner. This can be seen depicted in Figure 2. Now the world is moving from hand moved vacuum cleaners to robotic vacuum cleaners.

Figure 2. *Different types of vacuum cleaners. Starting from left canister type, stick type, cordless type and robotic type vacuum cleaner (Larsson, Petersson 2009).*

2.2 Overview of Cleaning Robots

The modern robotics is a science of intelligent control and connection between perception and action. The action of the robot is fulfilled by locomotion for moving in and around the environment while the operation of objects present in the environment is through manipulation. Wheels, propellers, thrusters, crawlers and limbs form the basic locomotion components for a robot while the manipulation is achieved with end effectors, grippers, artificial arms, and hands. Sensors are used to obtain information about the state of the robot such as speed, position, range, vision, forces acting, etc. The micro-controller or robot computer is used to perform programming, planning and control (Siciliano, Khatib 2016).

Currently, the research is concentrated on designing and developing robots to address the challenges of human life in their everyday activities. The work is focused on developing a new generation of robots that can live together with humans by providing assistance and services to humans at their home, workspace, and public spaces.

Automated cleaning robots, as the name indicates it is used for autonomous cleaning of the house, work or public spaces. They find their applications in-floor cleaning, pool cleaning, lawn mowing, and window cleaning. They are characterized by the capability to perform their function autonomously over a substantial time in the presence of obstacles. These are categorized under service robots or domestic robots. In (Prassler, Ritter et al. 2000) there is a taxonomy of cleaning robots presented which includes research prototypes, commercial products as well as industrial prototypes. This taxonomy is based on the function of the robot namely robotic vacuum cleaners, sweepers, carpet cleaners and scrubbers, duct cleaning robots and robotic road sweepers. In this project, the emphasis is laid on the floor cleaning and board cleaning robots and schools being its working environment. However, the literature on autonomous board cleaning robot was very limited. Hence, a study on wall climbing and window cleaning robots was done to draw ideas for developing methodologies for the design of an autonomous board cleaning robot.

2.2.1 Floor cleaning robots

The principle of robotic vacuum cleaner is to vacuum and collect dust by navigating in a known or unknown environment without colliding into any obstacles. Figure 3 and 4 show some of the first developed products such as Cye (CBSNews com 1999), first personal robot, Dyson's DC06 (Smith 2015), with 70 sensors and 54 batteries and Koala by Swiss Institute of Technology to study the possible shape of cleaning robot, sensor placement, etc. None of it was a commercial success. The failure to commercialize the product lies within its cost; these were priced much higher than the traditional vacuum cleaners.

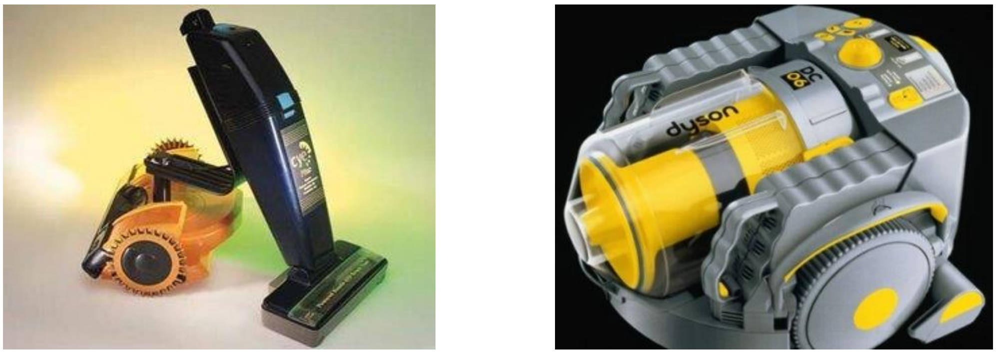

Figure 3. *Right - Cye personal robot vacuum cleaner (Robotnews 2007). Left - Dyson's DC06, autonomous robotic vacuum cleaner, made up of three CPU's, over 70 sensors and 54 batteries (Hanlon 2004).*

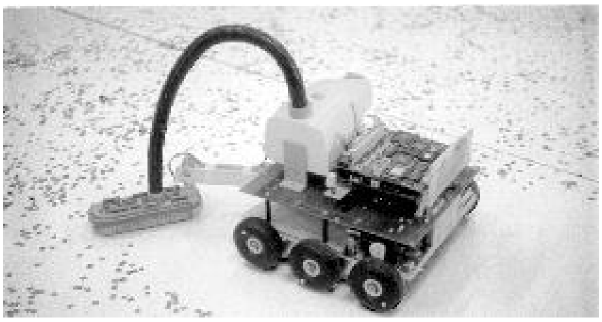

Figure 4. *Koala cleaning robot built by Laboratory of Microcomputing, Swiss Institute of technology to study the possible shapes of vacuum cleaner and its sensor placement (Ulrich, Mondada et al. 1997).*

After reviewing various developed robotic vacuum cleaners, the important requirements for a robotic vacuum cleaner to fulfill its task are listed below

Cleaning system – the basic components of a cleaning unit includes side brushes to clean along walls and contours, rotating brushes to collect dust and finally the vacuum unit/suction pump to pick up dust. The Dyson DC06 (Hanlon 2004) in addition to the motor and brushes uses cyclone technology for dust collection making it a bag-less robotic vacuum cleaner. The dust particles are extracted using the centrifugal force when it passes through a cone-shaped cylinder. The iRobot's Roomba vacuum cleaner has a side brush on the right side to clean along the walls and a centrally placed rotating brushing to collect dust. It empties the collected dust to a bag at the docking station. This bag is disposed of later (Maruri, Martinez-Esnaola et al.). Unlike the normal dry-cleaning robotic cleaners, Zucchetti's Orazio has an additional option of wet cleaning. It uses a cleaning cloth moistened with detergent solutions (Siciliano, Khatib 2008).

Sensor array – perception is the key to the robot's obstacle free motion. The safety of the robot and surroundings objects are of utmost importance. To achieve a collision-free safe motion the selection of sensors is crucial. The primary purpose of the sensor in these cleaners is mapping and detection of obstacles. The most commonly used sensors are the Infrared sensor (IR), LIDAR (light detection and ranging), RADAR (Radio detection and ranging), Proximity sensor. All these sensors use light to tell how far the obstacle is. While SONAR (Sound Navigation and Ranging) uses sound waves, the ultra-sonic sensor uses ultrasonic waves and Tactile or the bumper sensor is a simple push-button switch to detect obstacles.

The Trilobite 2.0 uses SONAR for navigation and obstacle detection, and IR for cliff and staircase detection, the Robocleaner RC3000 and eVac Robotic Vacuum uses a tactile sensor for obstacle detection, CleanMate sensors use bumper and photo-sensors for stair and obstacle detection. (Siciliano, Khatib 2008). Roomba uses IR cliff sensors to prevent falling down the stairs. It comes with a piezoelectric sensor to detect dirt. The bits of dirt can generate smaller electrical impulses when they strike the sensor thereby slowing the robot at higher dirt concentrations (Woodford 2018).

Navigation strategy – localization to know the robot's position and path planning for complete area coverage is the key for efficient cleaning of the surrounding. According to (Siciliano, Khatib 2016) there are three kinds of approach for area coverage.

- **Systematic approach –** it requires accurate and absolute positioning and motion planners.
- **Semi-systematic approach –** also called as the semi-intuitive method, it achieves minimal coverage. This is achieved by combining random motion with coded motion patterns such as meander-shaped, spiral, following the wall or contours or following other objects for complete coverage.
- **Random motion –** also known as bang and bounce method. It can be achieved by using just a bumper sensor. The robot moves in random straight motion until it hits an obstacle, once it hits, it bounces back, turns around, and moves in another random direction until it encounters the next obstacle. Thereby cleaning in a random direction. This is time-consuming and suitable for private homes.

The systematic approach seems more accurate but most of the available robotic cleaners have adopted a semi-systematic or random motion approach. This is because the systematic approach requires many expensive sensors, accurate positioning techniques for absolute positioning which increases the cost. The Electrolux's Trilobite 2.0, the Sharper Image's eVac use the semi-systematic coverage while the famous iRobot's Roomba uses just the random motion. When cost is the priority, random motion is quite effective and suitable for private homes where time is not a criterion. Random motion is not suitable for large spaces and professional cleaning applications.

Localization – it is important to know where the robot is to execute its task. Some of the techniques that can be employed for indoor localization are

- **Landmark-based position estimation** – it uses artificial or natural landmarks such as objects or contour to locate its position. A detailed approach to this technique can be found in (Willems 2017).
- **Active beacons** – position estimation using active beacon systems of SONAR, IR or radio. These systems contain an RFID (radio frequency identification) receiver that receives the signal from an ultra-sonic transmitter beacon that can be placed on paths to track position (Kim, Lee et al. 2006).
- **Dead reckoning localization** – uses odometry to know the position for short distances. However, it is not accurate for long distances, must have an estimate of the initial pose (books.org 2015).
- **Probabilistic localization** – it includes techniques such as Monte Carlo localization and Markov localization. It employs sensory data and robots uncertainty beliefs in knowing where it is (Thrun, Burgard et al. 2008).
- **Simultaneous localization and mapping (SLAM)** – the robot creates the map of the environment and locates its position simultaneously (Kudan 2016, Siciliano, Khatib 2008)

User interface/ human-robot interaction – though the autonomous robot can execute its task autonomously it still needs human assistance at some levels such as switching on and off, emergency stop, recovery from error, etc. Another noticeable factor here is the end-user. A non-technical person must also be able to operate the device. Hence, the user interface panel must be designed taking into considerations the limits of the operator. It should not force the user to acquire extra skills. The most simple user interface panel will have an on/off switch, reset button, emergency stop button, in some dry and wet vacuum cleaners there are buttons to select different cleaning mode (Siciliano, Khatib 2016, TheVacuumDoctor 2018). Now the development for user interfaces as gone ahead in developing the interface panel through the phone. The Roomba robot can be controlled through the phone using its app (McHugh 2015).

Safety – safety and precaution are important to keep the robot, humans and surrounding objects safe. All the vacuum robots are programmed to prevent falling down the stairs or cliff. Emergency stop button helps to retrieve the robot from a dangerous situation. The Roomba motors shut off once lifted from the floor to prevent injuries (Siciliano, Khatib 2008).

Power supply – In the autonomous motion the distance covered is dependent on the power supply, the robot must move in and around through different workspaces. Unlike non-robotic vacuum cleaners, it cannot be operated using power cords. So, batteries are used to power these autonomous robots. The constraint of weight and size limits the capacity of batteries. This is not an issue in domestic cleaning as their operation time frame is 30-60 min. However, the robots in large workspaces must require a longer working cycle. Some professional cleaning applications use 24V lead-acid batteries, but they are heavy. Therefore, the choice is tricky and there is a compromise of weight or time. Some of them now come with the feature of automatic charging; when the power hits low levels, they automatically dock themselves to the charging stations (Siciliano, Khatib 2016, Siciliano, Khatib 2008).

Table 1 and 2 lists the technical specifications such as sensors used, coverage methods followed in some of the existing domestic cleaning robots.

Table 1. *Specifications of Domestic cleaning robots (Siciliano, Khatib 2016), (Siciliano, Khatib 2008), (iRobot), (Voltra), (Mall.SK).*

Manufacturer	iRobot	Kärcher	Electrolux	Friendly Robotics
Model	Roomba	RC3000	Trilobite 2.0	Friendly Vac
				
Sensors	IR range sensors, IR cliff sensors (4)	IR cliff sensor (4), contact sensor (360^0)	180^0 ultrasound sensors, IR cliff sensor with a Magnetic stripe detector, contact sensor in the front side	Sonar sensor, touch sensor, cliff sensor
Coverage Method	Bang and bounce combined with a random motion, spiral motion and also contour following	Bang and bounce with random motion, see saw motion for spot cleaning	Random motion and wall-following with obstacle detection	Has contour follow, motion patterns (parallel and spiral) and bang and bounce
Cleaning Technology	Counter rotating side brush (2) with suction pump	Rotating brush with suction pump	Rotating brush with suction pump	Rotating Brush
Automatic recharging	Yes	Yes	Yes	No
Run time (min)	60 – 90	20 – 60	60	60

Table 2. *Specifications of Domestic Cleaning Robots (Siciliano, Khatib 2016, Siciliano, Khatib 2008, Cooper 2012, RobotReviews 2012, TestsAndReview 2016, Liszewski 2017).*

Manufacturer	Evolution Robotics/ iRobot	LG	Samsung	Neato Robotics
Model	Mint 4200	Hom-Bot 3.0	Navibot SR 8895 Silencio	Neato XV-21
				
Sensors	Cliff sensors, bumper, gyroscope, Northstar indoor GPS	Camera for ceiling and floor, sonar and IR for collision avoidance, cliff sensors, gyroscope	Range sensors camera, collision sensor, cliff sensors, gyroscope	1-D laser range finder, cliff sensor, gyroscope, accelerometer
Coverage and Navigation Method	Systematic coverage, SLAM with north star, map building	Systematic coverage, SLAM	Systematic coverage, SLAM based with visionary mapping system (using ceiling pictures)	Systematic coverage, SLAM based with RPS (using laser range finder)
Cleaning Technology	Dry or wet microfiber cloths	Two side brushes with brush roller	Two side brushes with brush roller	Bristled Brush
Automatic recharging	No	Yes	Yes	Yes
Run time (min)	180	75	90	90

Comparing all the mentioned (from Table 1 and 2) cleaning robots, it is evident that they all use similar technology with minor changes. The vacuuming unit majorly consists of the brush (side or rotating depending on the robot) and fan along with the suction pump. The important point in all these class of robots is the use of a few inexpensive sensors such as tactile, dirt or cliff sensors to make the product more economical. Pre-programmed motion patterns such as bang and bounce, spiral, see-saw or parallel motion together with random motion seem to be effective considering the limited number of sensors. The success of any automated cleaning robot reflects the integration of state of art automated services.

2.2.2 Window cleaning robots

According to (Siciliano, Khatib 2008) back in the 2000's the concept of automated window cleaning robot was still a conception. However, today we were able to witness some commercial products in the market such as Ecovas Winbot, Alfawise (Ezvid Wiki) and Hobot (TopTen Reviews). The reason for it is the increase in window glasses outside the buildings compared to private homes with fewer window glass panes. High-rise buildings along with huge glass windows are now part of current modern architecture design. Manual reaching onto the outer glass for cleaning is dangerous and of low output. The demand for automated cleaning robots to be part of building maintenance is going to be a reality soon (Akinfiev, Armada et al. 2009).

The development of automated window cleaning robot is much more complex and challenging than the automated floor-cleaning robot for several reasons, which will be discussed in this section. The main hurdle to the design is gravity. Designing cost-effective locomotive mechanisms against gravity on vertical fragile glass planes are quite challenging. Crossing over windowpane outside the buildings can get tricky. Nevertheless, this has not stopped the research and development of window cleaning robots (Siciliano, Khatib 2008, Miyake, Ishihara 2003).

From (Miyake, Ishihara et al. 2006b), the main requirements for developing a window-cleaning robot are it must be light, small and compact, easy portability, can run continuous cleaning motions, execute automatic crossover between frames and most important not to forget the corners.

The three main units for designing a window-cleaning robot are adhesion unit, locomotion unit, and the cleaning unit.

- **Adhesion unit** – there are different adhesion techniques for a robot to hold itself against the glass surface such as magnetic attraction, vacuum system, counterweight to balance the robot and use of sticky material (Miyake, Ishihara et al. 2006a). The vacuum system seems to be a promising adhesion method for a glass surface compared to the magnetic attraction, which requires the usage of ferromagnetic substances, counterweight that demands ropes and wires to balance or the sticky material that gets the glass dirty. The vacuum method uses suction cups and vacuum-motor, to make use of the negative pressure to seal the robot against the glass surface (Muscato, Longo et al. 2003). All the existing commercial products currently use a safety tether to hold the robot against falling (when it loses adhesion).
- **Locomotion unit** – for the free movement of the robot. It can be linear motion or rotatory or a combination of both. The different mechanisms employed are crawlers, drive wheels, caterpillar drives equipped with suction cups (Yoshida, Shugen Ma Dec 2010), legs or limbs (Kawasaki, Kikuchi 2014) and parallel links. The

most used locomotion units for private home window cleaning robot are the suction cups, Figure 5.

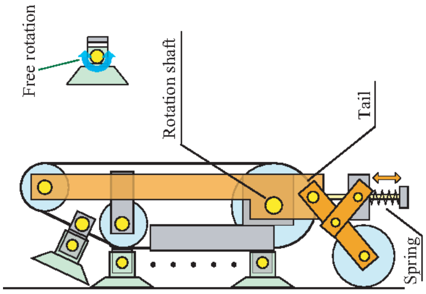

Figure 5. *Locomotion with suction cups (Yoshida, Shugen Ma Dec 2010).*

- **Cleaning** – glass cleaning involves dry cleaning followed by wet cleaning (using cleaning fluids) or vice versa with effective cleaning pattern. Therefore, it can include a rotating brush (KITE Robotics), microfiber cloth or a cleaning pad with a manually sprayed cleaning liquid (Stevenson 2014). The cleaning pattern for Winbot 730 is the back and forth method. At first, the window dimensions are measured. It then follows the back and forth method to move the robot from top to bottom. After it finishes cleaning the perimeter, it returns to the start position (O'connell 2013).

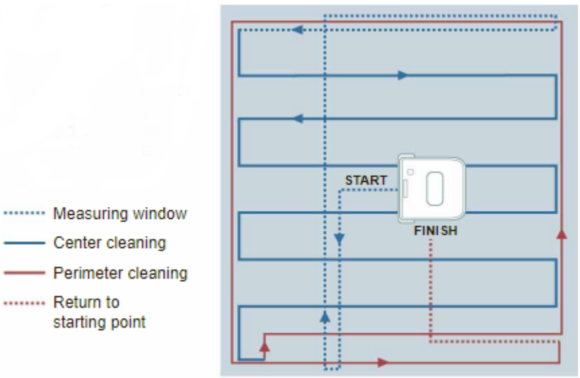

Figure 6. *Cleaning pattern of Winbot 730 from top to bottom, back and forth method (O'connell 2013).*

The current existing commercial window cleaning robots have similar functions and operating procedure. They have a motor-powered suction system for adhering to the glass surface. Some of them are battery operated, the Hobot-168 while others such as the Winbot w730 is not battery operated. In terms of safety, they have all high strength safety tether or rope to hold the robot when it loses suction. The operator fixes the safety tether manually every time the robot must clean. The Hobot-168 comes with anti-dropping algorithm too. They notify the operator once the cleaning cycle is complete (TopTen Reviews).

The automated window cleaning robots are gaining name slowly. However, the review after usage has not been very positive. The common complaints have been the high price, slipping quite often, leaves white trails on the glass and the critical one being breakage of glass. A lot of negative pressure of the suction cups can crack the glass.

2.2.3 Automated Board cleaning robot

The idea of an automated robot cleaning the boards in classrooms seems brilliant, but it is still in its infancy. There are few pieces of research at some universities but nothing yet as a commercial product. Most of the developed prototype employs a pulley or belt system as seen in Figure 7. The unit comprises of side rods or railings coupled with the duster to belt. The belt is driven by the motor, which in turn moves the duster along the area of the board (Simolowo, Ngana 2014). Another proposed design by (Zhang, Lathrop 2012) uses a wheeled chassis with magnetic adhesion to adhere to the board. There has not been much development or reference to an autonomous board cleaning robot.

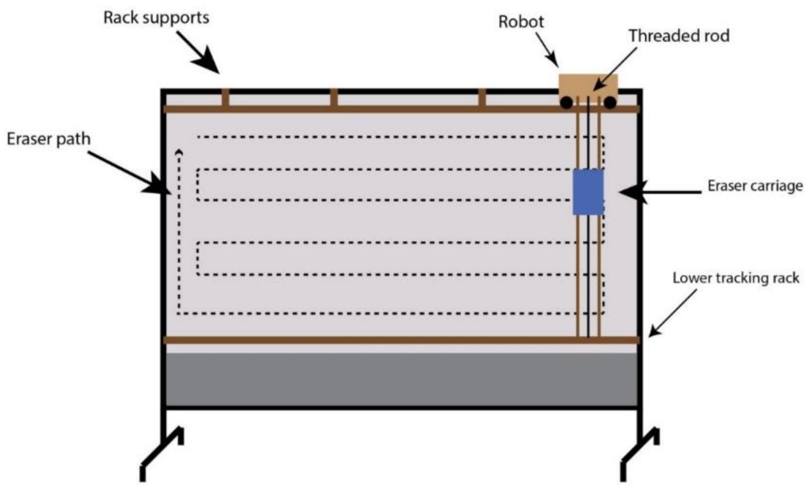

Figure 7. *One of proposed board cleaning robot design (Zinsmeyer 2014).*

2.2.4 Climbing robots

Climbing robots are characterized by their ability to adhere and move on vertical surfaces (wall), ceilings, rooftops, ducts, and pipes. The wall-climbing robot, window-cleaning robot, duct inspection robot are all examples of climbing robots. They can be used to replace humans in hazardous conditions, perform inspection tasks where human access is difficult and ensure safety in the working environment. Any climbing robot must adhere itself to the surface against gravity and move around. Hence, the adhesion and locomotion mechanisms are an important criterion while designing these climbing robots. They define the capability of any climbing robot. According to (Chu, Jung et al. 2010) the possible locomotion and adhesion mechanisms are

- Locomotion types – legged, wheel-driven, tracked, translation, cable-driven and the combined type.
- Adhesion types – suction, magnetic, gripping, clamping, rail-guided and biomimetic

The selection of the adhesion and locomotive mechanisms depends on the application of the robot. Applications such as inspection and maintenance on ferromagnetic surfaces employ magnetic adhesion. It can be permanent magnets, electromagnets or earth magnets coupled with legs, wheels, and tracked or sliding frame mechanism. Well, the most preferred adhesion technique is through suction or negative pressure adhesion, Figure 8A. The major disadvantage of suction cups is a loss of negative pressure and dust. Furthermore, the gripping, or clamping mechanism can be termed under mechanical adhesion, Figure 8B. They make use of claws or spines (legged systems) to adhere and climb or make use of Gecko principle (Autumn, Gravish 2008) to adhere. The gecko principle is inspired by lizards, this uses microscopic fibrillate to stick to the surface (Menon, Murphy et al. 2004). Besides these, there are studies on employing electro-adhesion, sticky tapes or thermal glue (Schmidt 2013). Simple, compact and lightweight is the key to design an effective climbing robot.

A

B

Figure 8. *A – ALICIA3 climibing robot for wall inspection, negative pressure adhesion (Longo, Muscato 2006).Fig. B - Climbing robots with claws, CLIBO (Sintov, Avramovich et al. 2011).*

3. CONCEPTUAL DESIGN OF AN AUTONOMOUS FLOOR CLEANING ROBOT

3.1 Overview of the autonomous floor cleaning robot

As the name, autonomous floor-cleaning robot suggests its primary aim is autonomous floor cleaning by navigating in a known or unknown environment without colliding into any obstacles. Generally, the process of cleaning can comprise of both dry cleaning (through a vacuum suction) and wet cleaning (using liquid solution or dampened cloth). However, in this project, the cleaning process mainly focuses on the dry cleaning of the floor. The dry cleaning is achieved through the vacuuming process.

As explained in section 2.1, the fan-powered by a motor creates a negative pressure or pressure lower than the surrounding atmosphere simply known as the vacuum. Vacuum (pressure difference) causes airflow. The air picks up dust and dirt through the nozzle from the surface and flows along with the hose to the dust collection unit. The dirt and dust are separated from airstream after passing through a filter or to a disposable dust bag. The filtered clean air is let out to the surrounding. As the system is autonomous, it cannot be powered using a cable cord. Hence, lithium-ion batteries are used as a power supply for the system. The main components of an autonomous vacuum cleaner are listed below

- Chassis/platform – to reach every spot and it houses all the components of the autonomous cleaning system.
- Electric motor and fan unit – to create vacuum or suction
- Nozzle – to remove dust from the surface
- Hose – to connect the nozzle with the main vacuum system
- Dust collection unit/ dust bag – to accumulate the dirt
- Filter – to entrap dust from the airstream before the exhaust

3.1.1 Robotic Platform

As per (books.org 2015), the platform is a framework on which the builder/ developer can house several components and subsystems for the robot to function. Some of the basic requirements of the platform in this thesis work are

- Must be light but strong enough for the application.
- Easy to add components and subsystems.
- Easy access to removal of parts.
- Well balanced within its maximum weight capacity. Must not trip over.
- Must have a practical size for easy maneuver.

- Efficient sensor array. Must detect and function in the presence and absence of light, transparent obstacles and avoid cliffs.
- Reliable power supply for long working cycles of the robot.

It was decided to choose Pulurobot M as the robotic application platform for the above-mentioned reasons. It is designed and manufactured by (Pulurobotics Oy Ltd). The specifications of the selected platform are listed in Table 3. Figure 9 shows the appearance of the Pulu-M robot platform.

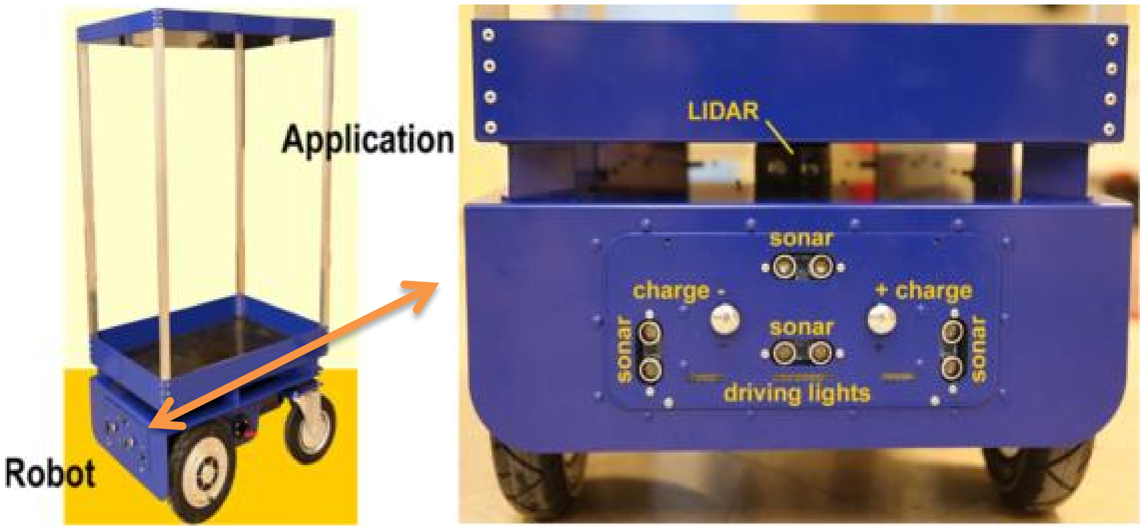

Figure 9. *Pulurobot M, robotic application platform. The right image shows the full robot platform wherein the chassis supports the application. The left image is the enlarged picture of the sensor array on the front end of the robot. (Pulurobotics Oy Ltd).*

Table 3. *Specification table for PULU-Robot M*

Chassis	• Riveted aluminum chassis • Size – 650mm by 470mm with a height of 230mm and about 304mm from ground • Supports 90kg during vehicle motion • Speed – 0 to 7 km/hr
Motors	• Two motors • 300W 24V brushless DC (BLDC) wheel hub motor
Suspension	• The rear wheels are freely rotating • The four wheels are always on the ground
Battery	• Constructed from 18650 Li-ion cells • The default capacity is 240Wh • 1KWh of a battery can be housed by the platform

Charger	• The wall unit can connect to 110V/220V • 100W built-in charger • The robot can find and mount to its charger automatically
Sensor Array	• LIDAR for long distance navigating and mapping • Four 3D Time of Flight (TOF) cameras to see in direct sunlight or at night and to sense obstacles lower or higher than the 2D LIDAR plane. • SONAR for detecting transparent obstacles such as glass doors, etc.
Electronics	• All electronics are in the same place on Robot Board for easy maintenance • It comes with two Raspberry Pi's on the Robot Board and a possibility to stack up to five of them • Socket for Raspberry Pi 2/3
Controller board	• STM32 microcontroller for sensor management & low-level navigation • MEMS gyroscope, accelerometer, compass • Powerful lithium ion charger (100W) • Strong 5V power supply for computers, tablets, etc. (10A) • 2 x BLDC motor controllers, 700W peak each • On-board Raspberry Pi for running mapping (SLAM) & route-finding algorithms • Internet connection through WiFi and/or 3G/4G

3.2 Components selection for vacuum cleaning

Generally, the input power of different vacuum cleaners is compared to rate the performance. However, the dust-pick-up (dpu) factor decides the percentage of dust a vacuum cleaner can pick up from the different surfaces during cleaning. The parameters that influence the design and selection of the vacuum cleaner components are

- Dust pickup factor
- Dust storage capacity
- Cleaning surface
- Size
- Weight
- Storage

Initially, the designing of a vacuum cleaner system and its components selection was based on assumptions. This was achieved through the practical understanding and assumptions made by comparing the existing domestic vacuum cleaner products in the market. Usually, the selected components are subjected to practical tests to rate their performance. Later the system is refined based on the suction performance, dust removal performance, weight and size by applying theories of vacuum technology.

3.2.1 Motor and fan

The present vacuum cleaner motors are characterized by their small size and high rotational speeds. They can produce a relatively high vacuum along with quick discharge. The motor inputs the electrical energy and converts it into mechanical energy in the form of airflow and suction. The fan also known as impeller creates the suction by the effects of the centrifugal force acting on it. The rotary motion of the fan rotates the air and moves it outward from the hub to create a partial vacuum. The motor and fan are assembled into a single unit. The selection of motor and fan unit is very important because they are the biggest influencer on the size and performance of the vacuum cleaner (Facts about Vacs b, Facts about Vacs a).

The combination of airflow and suction or vacuum measured in watts is known as suction power. The suction and airflow curves or air performance graphs is an important tool for motor selection. It shows the efficiency of the motor in converting the input power to suction power. The quoted suction power and efficiency for any motor will be at its peak suction power also known as load point. However, in reality, both suction power and efficiency varies from zero to maximum. This can be seen in Figure 10. The load point value is considered for the design calculations (AEA Energy & Environment, Consumer Research Associates 2009).

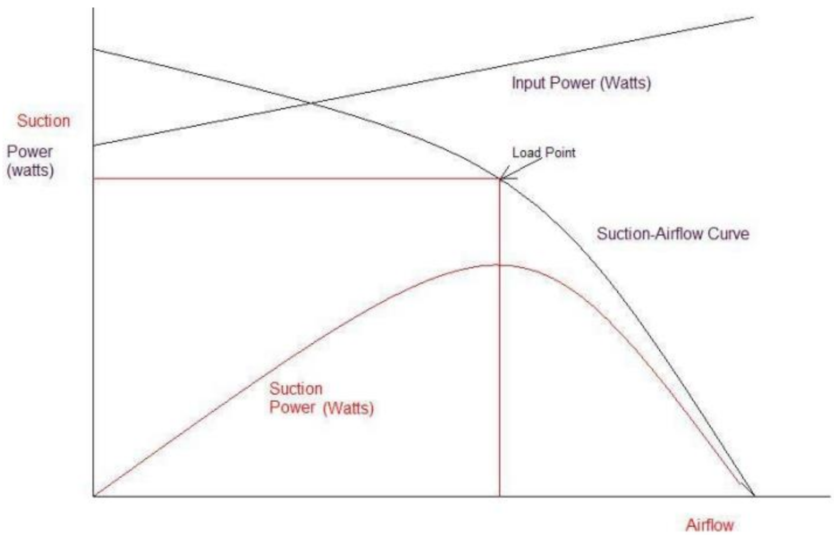

Figure 10. *Suction and airflow curves showing the effect of input power and suction power (AEA Energy & Environment, Consumer Research Associates 2009).*

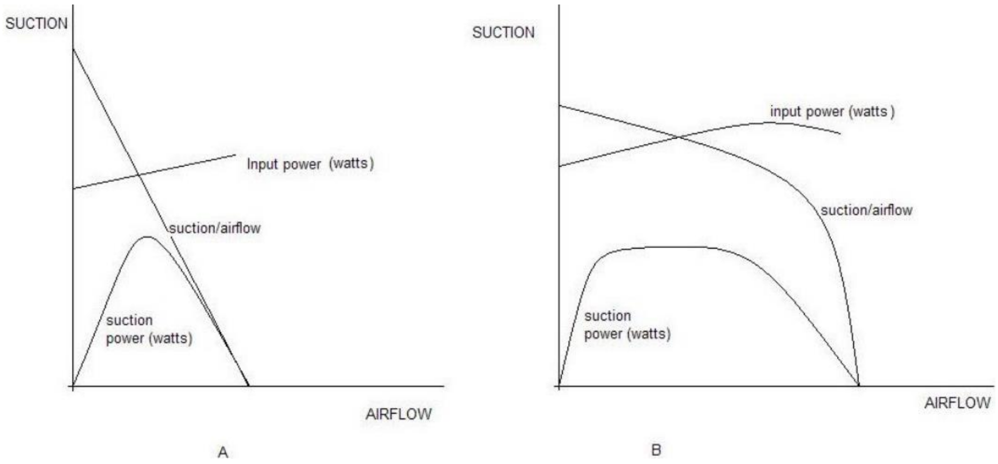

Figure 11. *Represents the characteristics of motor and fan of two vacuum cleaners A and B. Even though A has higher suction power, B is considered to have better cleaning performance as its load point is over long range (AEA Energy & Environment, Consumer Research Associates 2009).*

An optimization of suction and airflow specifies optimal suction power. Proper tuning of these values results in the suction airflow curve to be bowed outwards (Figure 11 B). This results in moving the peak suction power closer to maximum airflow. The objective is not just about achieving higher suction power; it must have a considerable value over a long-range. The comparison between higher suction power and long-range of suction power is explained in Figure 11.

The motor selection will be made based on the airflow value as this is accounted based on the power of the vacuum cleaner. This is followed by viewing the air performance charts to see the range of it. According to (Roberts 2015) the common operating range of the airflow in a vacuum cleaner is around 1.4 to 2.8 m^3/min (0.023 to 0.047 m^3/s)

The selected motor is a "Wet & Dry Vacuum Cleaner Motor – 24V500W". It is a brushless 24V DC motor weighing 1.91 kg. It is important to find the flowrate and vacuum pressure values the selected motor can generate for the designed system. The system consists of nozzle, hose and dust bag. At first, the conductance value of the motor for different orifice loadings are found. Then the value that corresponds to the total conductance of the system is noted and its corresponding flowrate and vacuum pressure are considered to be the total systems flowrate and vacuum pressure.

According to (Vacuum 2007) there are three types of flow in any vacuum systems depending on the nature of the gas. The Knudsen's number (Kn) is used in determining the nature of the gas. The Knudsen's number (Kn) is determined by the ratio of the mean free path to the diameter of the piping element.

$$Kn = \frac{\lambda}{d} \qquad (1)$$

Where, λ – mean free path, m

d – diameter of the piping element, m

As per (O'Hanlon 2005), Mean free path (λ) is the possible straight-line distance that different molecules can travel before a collision. For room temperature, it is given by the following equation

$$\lambda = \frac{6.7 \times 10^{-4}}{\bar{p}} \quad (2)$$

Where, $\bar{p}$ – average pressure, Pa. Given by

$$\bar{p} = \frac{p1 + p2}{2} \quad (3)$$

Where, p_1 – downstream pressure, Pa

p_2 – upstream pressure, Pa

The three categories of flow are

- **Continuous flow** – this occurs in the viscous or rough vacuum region. Here the flow can be termed as either laminar viscous flow or turbulent flow. Usually, the continuous flow is considered to be laminar viscous unless a vortex motion appears in the system. In any vacuum system, the flow is considered to laminar viscous when the Knudsen number is less than 0.01, i.e. $Kn<0.01$.
- **Molecular flow** – this occurs in ultrahigh vacuum ranges. In this region, the mean free path is much higher when compared to the piping size. Hence, the molecules can travel freely without mutual collision. In this flow, the Knudsen number is greater than 1, i.e. $Kn>1$
- **Knudsen flow** – the region between continuous flow and molecular flow is known as the Knudsen flow, medium vacuum range. The Knudsen number is less than 1 but greater than 0.01. i.e. $0.01<Kn>1$.

The flow of gas in any piping element is dependent on the pressure drop across the pipe and its geometry which is defined by conductance. There are different formulas for conductance calculation depending on the type of flow and type of piping element (orifice, round pipes, rectangular, slit, etc.).

At first, the ‘Kn’ for different orifice loadings in this case was calculated and it was found to be less than 0.01. This says that the flow through the orifice is laminar viscous. The conductance value of the motor for different orifice loadings are calculated and tabulated in Table 4.

The equation for calculating conductance through an orifice (Vacuum 2007) depends on the ratio of downstream pressure (P_2) to upstream pressure (P_1) i.e.

$$\delta = \frac{P_2}{P_1} \quad (4)$$

Where, p_1 – downstream pressure, Pa

p_2 – upstream pressure, Pa

When δ value is equal to 0.528 it is critical pressure situation if it is less than 0.5298 the flow is choked. However, he obtained δ value for all the orifice loading was greater than 0.528 (Table 4).

The equation to calculate conductance through an orifice is given by

$$C_{orifice} = 766.\delta^{0.712}\sqrt{1-\delta^{0.288}}\frac{A}{1-\delta} \quad (5)$$

Where, $C_{orifice}$ – conductance through an orifice in laminar flow, m^3/s

A – area of the orifice, m^2

The calculated conductance values for different orifice loading along with the specifications of pressure and airflow of the selected motor are listed in Table 4.

Table 4. *Conductance values for different orifice loading of the selected motor*

Orifice diameter (mm)	**Air Flow – Q (m^3/s)**	**Vacuum pressure Δp(kPa)**	**δ**	**$C_{orifice}$ (m^3/s)**
0	0	11.23	0.89	0
6.5	0.00033	9.53	0.91	0.043
10	0.0079	9.06	0.91	0.1
13	0.015	8.3	0.92	0.18
16	0.021	7.34	0.92	0.28
20	0.026	6.03	0.94	0.51
23	0.032	4.37	0.96	0.84
30	0.037	2.69	0.97	1.65
40	0.038	1.62	0.98	3.61
50	0.039	1.33	0.99	8.03

3.2.2 Hose and tubing

This module consists of two types of a hollow tube. One is the rigid tube right after the nozzle; it has no bends hence minimal pressure losses. 30 mm diameter hose was considered for the design as it is the most widely used dimension and other attachments can be easily found. Before, finding the conductance value through the hose it is important to find out if the flow is laminar or molecular. At first, the mean free path is found using Equation 2 followed by the Knudsen number. For the purpose of calculations, the average pressure in the hose is assumed to be similar to the average pressure generated by the motor at an orifice loading of 30 mm (as the chosen hose diameter is 30 mm). The obtained mean free path value is $6.72.10^{-8}$ m while the Knudsen number is $2.24.10^{-6}$ which is less than 0.01. Hence the flow is laminar viscous flow.

The conductance value of the laminar viscous flow in the piping element is calculated as per (Vacuum 2007). The conductance value depends on pressure and geometry of conducting element in the laminar flow. Axial length of the element is considered for straight-line elements while the effective length is considered for bends and elbows.

The designed hose has a straight-line length of 0.67018 m while the effective length for the bends is found by Equation 6.

$$l_{eff} = l_{axial} + 1.33 \frac{\theta}{180^0} d \qquad (6)$$

Where, l_{eff} – effective length of the line, m

l_{axial} – axial length of the line, m

d – inside diameter of the line, m

θ – angle of the elbow/ bend, deg

The designed hose has three elbows each with an angle of 85^0, 56^0 and 90^0 respectively. After finding the individual effective lengths, the obtained total length which is the addition of straight-line length and effective length is around 1.68 m.

The conductance for a hose in laminar flow is given by Equation 7.

$$C_{hose} = 1350 \frac{d^4}{l} \bar{p} \qquad (7)$$

$$= 64.87 \text{ m}^3/\text{s}$$

Where, C_{hose} – conductance in the hose for a laminar flow, m^3/s

d – inside diameter of the line, m

l – length of the line, m

$\bar{p}$ – average pressure in the system, Pa

3.2.3 Filter or dust bag

The function of the filter is to entrap all the dust and allergens from the airstream before re-entering it to the surrounding. In this way, the surrounding and the motor unit gets clean air. The filter can be disposable or reusable one. The disposable ones are the dust bag wherein the bag material is a type of filter. The bag collects the dust while the clean air passes through its material. The choice of filter bags is very important because any dirt present in the air can erode motor parts, clog the system and reduce the suction and airflow. The different types of filters are cloth filter, paper bags, treated paper bags, fleece, etc. The use of HEPA filter in the vacuum cleaner assures a clean exhaust air (Dijk 2010). The capacity of the bag depends on the quantity of dust that must be collected. The selected disposable dust bag has a dimension of 318×330 mm wherein the expandable height is up to 318mm. The diameter of the opening of the bag is 80mm. its average capacity is 3.5L.

The conductance value through a dust bag is calculated as per (O'Hanlon 2005) considering it has a rectangular structure. At room temperature, the conductance value for a rectangular, slit-like or short structures are given by

$$C_{dust\_bag} = 116(\mathrm{aA}) \qquad (8)$$

$$= 8.43\ \mathrm{m^3/s}$$

Where, C_{dust_bag} – conductance through a dust bag, m^3/s

a – transmission probability for the structure

A – area of the structure, m^2

The ratio of l/h for the dust bag was 1.03 and it's corresponding 'a' value is 0.68438 and area is the product of breath and height(O'Hanlon 2005). The obtained conductance value through the dust bag was 8.43 m^3/s.

3.2.4 Nozzle

Its function is to pick up several types of dust from the surface. Here the surface can be anything such as the wooden floor, tiles, carpet or an uneven floor surface. There are different nozzles for cleaning hard surface and carpets but generally, the combination nozzle for all surfaces are used.

The combination nozzles can be divided into two kinds as seen in Figure 12.

- **Passive nozzle** – they have no motorized parts in the nozzle instead they have static brush or rubber strip to seal against the floor surface. This helps in achieving higher airspeed.
- **Active nozzle** – they have mortised rotating brush or agitator powered by an air-flow turbine or small electric motor. The rotation of this brush improves dust pick up ability majorly on the carpets (Leffler, Sörmark 2013).

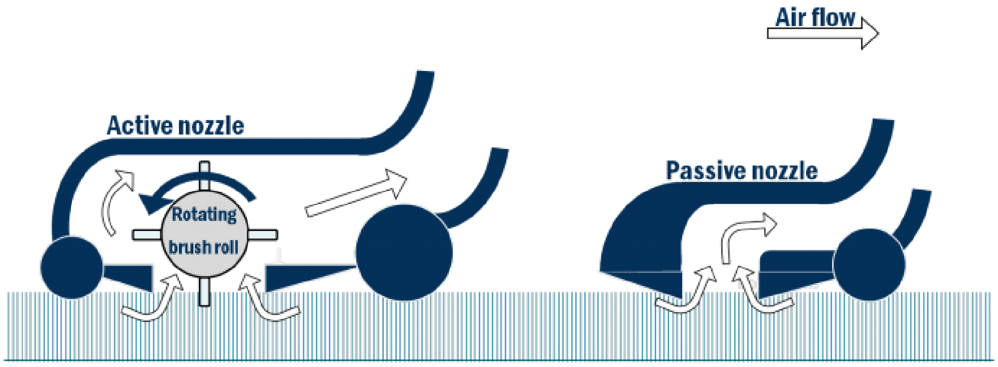

Figure 12. *Principal sketch of an active and passive nozzle (Leffler, Sörmark 2013).*

The selection of the nozzle depends on the surface of the application. Large carpet areas demand active nozzle while a non-carpet area can be cleaned effectively using a passive nozzle. Generally, the classrooms do not use carpets. Hence, a passive nozzle will serve the purpose for this thesis work. This also helps in cutting down the additional electrical parts and power requirements when compared to an active nozzle.

The dust is the combination of different kinds of particles found in classrooms. They usually comprise of sand, bits of paper, the fur of animal or textile, fibers and some fine particles. According to (Larsson, Petersson 2009) the mass of the dust varies depending on the combination of different particles but the average density is considered around 10 kg /m3 to 10000 kg/m^3. The size ranges from 0.01 µm to 1 cm.

The nozzle must have sufficient lifting forces to lift and pick up dust from the surface. This lifting force is a combination of vacuum and airflow. The airflow measures the amount of air that flows from floor to dust collection unit. It can be designed in unlimited designs based on the surface of use (Leffler, Sörmark 2013). The factor influencing the dimensions of the nozzle in this application is the robot chassis.

The Pulu M has a width of 470 mm, this means the selected nozzle must have a width of at least more than half of the width of the Pulu M. 270 mm is the nearest available width of the nozzle (300 mm is better but 270mm will have more options) while the remaining 200 mm width can be covered by the use of side brushes.

Selecting a nozzle with a cleaning width of 270 mm provides a cleaning length of 25 mm. Larger cleaning width nozzle (350 mm) has a narrow length of 14 mm which is not acceptable in this application. As the cleaning slit must be large enough to pick up large objects such as organic waste, pebbles or bigger bits of paper that are commonly available in classrooms. Choosing anything below 270mm will affect the efficiency of cleaning and requires higher cleaning time duration due to the short width. Hence the only choice is higher cleaning length nozzle.

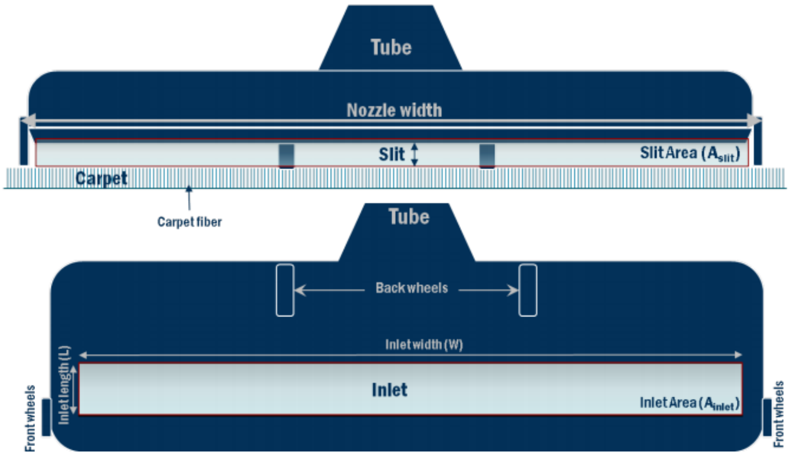

Figure 13. *Parts in a nozzle (Leffler, Sörmark 2013).*

The final selected nozzle has a cleaning width of 270 mm and cleaning length of 25 mm and a cleaning height of 50 mm (considering the height for dust flow and the gap between the floor and nozzle). It has a wire floor tool and the elbow holder with a diameter of 32 mm has an inner diameter of 30.5 mm. The parts of the nozzle can be visualized as seen in Figure 13.

Since the nozzle is a rectangular structure, its conductance value is calculated similarly to the dust bag. At room temperature, the conductance value for a rectangular, slit-like or short structures are given by

$$C_{nozzle} = 116(\mathrm{aA}) \quad (9)$$

$$= 1.26\ \mathrm{m^3/s}$$

Where, C_{nozzle} – conductance through the nozzle, m^3/s

a – transmission probability for the ratio of l/h of the structure

A – area of the structure, m^2

The ratio of l/h for the nozzle was 0.5 and it's corresponding 'a' value is 0.80473 (O'Hanlon 2005). The obtained conductance value through the nozzle is 1.26 m^3/s.

Now the total conductance of the system considering the hose, dust bag and nozzle is given by

$$\frac{1}{C} = \frac{1}{C_{hose}} + \frac{1}{C_{dust\_bag}} + \frac{1}{C_{nozzle}} \tag{10}$$

Where, C – total conductance, m^3/s

C_{hose} – conductance through a hose, m^3/s

$C_{orifice}$ – conductance through an orifice, m^3/s

C_{nozzle} – conductance through a nozzle, m^3/s

The total conductance value obtained is 1.077 m^3/s.

Figure 14 represents graph plotted from Table 4 values. i.e. for orifice loading. The obtained conductance value is equated with the calculated conductance values for different orifice loading. From the graph, the designed system with a total conductance value of 1.077 m^3/s has a flow rate of 0.0335 m^3/s and generates a vacuum pressure of 3.878 kPa.

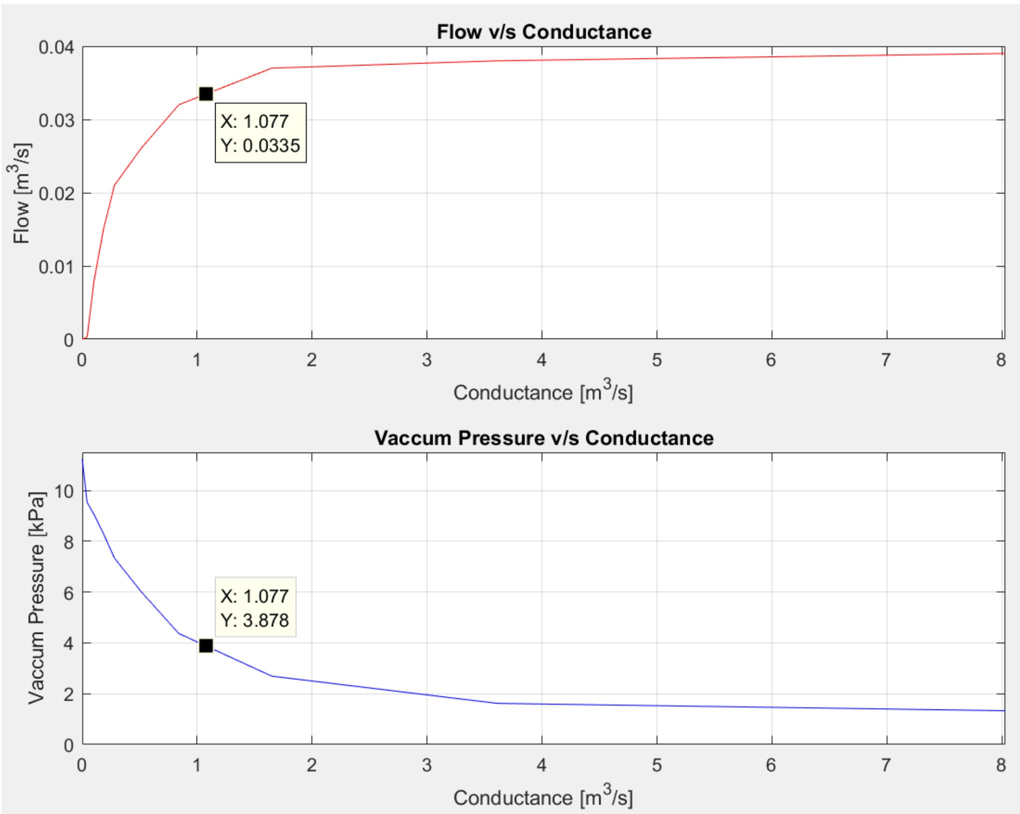

Figure 14. *Plot of Conductance v/s flow, conductance v/s vacuum pressure for different orifice loading.*

The effective pumping speed required to create suction or suck dust is calculated using Equation 11. As per, (Vacuum 2007, O'Hanlon 2005) the pumping speed is equal to the volumetric flow through the pump's intake port which is same as airflow of the system and the value is 0.0335 m^3/s. The effective pumping speed will be equal to the pumping speed of the pump if there are no intermediate elements. However, there is always intermediated piping elements which resist the flow thereby reducing the effective pumping speed less than the pumping speed of the pump.

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C} \quad (11)$$

= 0.032 m^3/s.

Where, S_{eff} – effective pumping speed, m^3/s

S – pumping speed, m^3/s

C – conductance of the system, m^3/s

The net force or the lifting force for the nozzle F is the product of pressure and area of the nozzle. it is given by

$$F = \Delta p A_{nozzle} \quad (12)$$

= 26.16 N

Now, to find the mass from the obtained force value

$$m = \frac{F}{9.81} \quad (13)$$

= 2.67 kg.

For which the volume of air sucked is given by

$$V = \frac{m}{\rho_{air}} \quad (14)$$

= 2.18 m^3

Where, V – volume (m^3)

m – mass (kg)

ρ_{air} – 1.225 (kg/m^3)

The obtained volume is for air, but the designed vacuum system is supposed to suck dust. The density of dust is higher, around 1490 kg/m^3 hence the volume reduces. The obtained volume for dust is 0.0018 m^3. If iron scraps or pebbles are considered the dust the density will increase further.

The velocity, v of inlet air can be found by the ratio of flowrate and area of the nozzle as in Equation 15.

$$v = \frac{Q}{A_{nozzle}} \quad (15)$$

$= 4.97$ m/s

Nozzle placement

For a good cleaning process, the vacuum cleaner must be effective enough to suck the dirt from the floor. This depends on the speed of airstream along the floor. Placing the nozzle at the maximum speed location will improve the efficiency of cleaning. This point on the floor must have the highest speed along the floor and at the same time have the lowest pressure along with it. This point can be calculated using the velocity components applied for laminar flow through the nozzle as per (Cengel A., Cimbala M. 2014). Based on these velocity components, placing the nozzle right on the floor creates a stagnation point as the flow becomes rotational at this point. So, placing the nozzle at a point above the floor and not closest to the floor improves the performance of cleaning. This is dependent on the dimensions of the nozzle and flowrate. Finding this point involves the application of Bernoulli's theorem, plotting and analyzing flow vectors, this is not in the scope of this thesis. However, the point of maximum speed can be found manually by experiment. Some amount of salt or sugar can be placed on the floor and the nozzle can be tested for the height of best performance. Since in this project there is no manual back and forth movement of the nozzle, it is important to have the right placement for efficient cleaning.

3.2.5 Side brush

A pair of rotating side brushes are mounted on to the front end of the chassis supported by a stationary frame. Motors power them. The use of side brushes aids in the effective removal of dust from the sides. The dust swept by these brushes are sucked into the vacuum cleaner by a tangential force to the nozzle. Above all, these brushes can substitute the gap left short due to the limited size of the nozzle. Of the 470mm of width at the front end of PULU, the nozzle will cover 270 mm in the center. Therefore, a width of 100 mm on each side must be compensated for cleaning by side brushes. The brush must be larger than the 100mm gap to reach out to places outside the perimeter of the platform. So, leaving an allowance of 50mm outside the Pulu and 50mm towards the nozzle (for the tangential flow of dust), the brush diameter must be around 200mm. After reviewing the existing side brushes available in the market. The torque required for the side brush must be known to calculate the power required to run them.

Torque is given by the product of moment of inertia and angular acceleration

$$T_s = I\alpha \tag{16}$$

Where, T_s – torque, Nm

I – inertia, kgm^2

α – angular acceleration, rad/s^2

At first to find the inertia the circular brush is considered to be a solid disk or cylinder about an axis through the middle, perpendicular to the plane of the disk. The radius and the mass of the selected side brush are 100 mm and 25g respectively. The equation to calculate inertia is given by.

$$I = \frac{1}{2}MR^2 \tag{17}$$

$= 1.25e^{-4} kgm^2$

Where M – mass of the brush, kg

R – radius of the brush, m

The angular acceleration is calculated using Equation 18. It is considered that the device reaches 40 rpm in 0.1 sec

$$\alpha = \frac{\omega}{t} \tag{18}$$

$= 41.89\ rad/s^2$

Where, ω – angular velocity, rad/s

t – time taken, s

Using the obtained inertia and angular acceleration value in Equation 16, the calculated torque value is $5.24.10^{-3}$ Nm. This is the starting torque value. Next, the torque required to keep the brush in constant operation is calculated. The frictional coefficient between the plastic bristle and concrete floor is taken as 0.6. For a brush of 25g and 100 mm radius, the obtained operational torque value is

$$T_o = \mu F R \tag{19}$$

$= 0.014715$ Nm

Where, T_o – required operational torque, Nm

μ – frictional co-efficient value

F – force, N

R – radius of the brush, m

The total torque is the sum of starting and operational torque which is $0.02Nm$.

Power P, is given by

$$P = T\omega \tag{20}$$

= 0.084W

Where, T – torque (Nm)

ω – angular velocity (rad/s)

the obtained power value is $0.084W$ while the selected motor (Pololu b) can produce 1.2W which meets the requirement with room for further modifications.

3.2.6 Battery

One of the advantages of having PULU platform is its battery capabilities. The currently developed platform can accommodate the smallest capacity being 420Wh and the biggest being approximately 1.5kWh. The platform can also house 3kWh of a battery. There is no limit in terms of the battery capacity that can be connected to the robot platform's internal power system. The model charges at 500W, using a fast 48V station, or at 200W, using a slower 36V station.

The idle mode consist of Raspberry Pi – 3W, LIDAR – 1W, 3D TOF sensors – 3W, total ~7W (Pulurobotics Oy Ltd). Now calculating the possible operation time for the given battery.

Table 5. *Table to represent the calculation of power consumption*

Device	Power Consumption
Sensor array and raspberry pi	~7W
Wheels	300W
Vacuum cleaner motor	500W
Side brush DC motor 1	0.063W
Side brush DC motor 2	0.063W
Total	**807.13W**

The maximum operation time available before next recharge is calculated using Equation 21.

$$Time = \frac{Battery\ capacity}{Total\ power\ consumption} = 1.86\ hours \quad (21)$$

So, the robot can work continuously for 1.86 hours with a battery of 1.5kWh and 3.7 hours for a battery of 3kWh for one complete recharge. This is a good operating time in comparison to the existing products that last just for 40-60 min. They also have lower suction power. Another added advantage with the Pulu platform is the self-charging ability when the battery depletes.

However, the vacuum cleaner motor operates at 24 V, but the side brush's DC motor operates at 3V. So, there is a requirement of voltage step down for the side brush (similar to sensor array which operates at lower voltage).

3.3 Mechanical design of autonomous floor cleaning robot

3.3.1 Mechanical design of vacuum cleaner

The modelled vacuum cleaner design is seen in Figure 15. The mechanical design software used was SOLIDWORKS. The vacuum cleaner was designed to house the motor, the dust collection unit, hose inlet and some electronics.

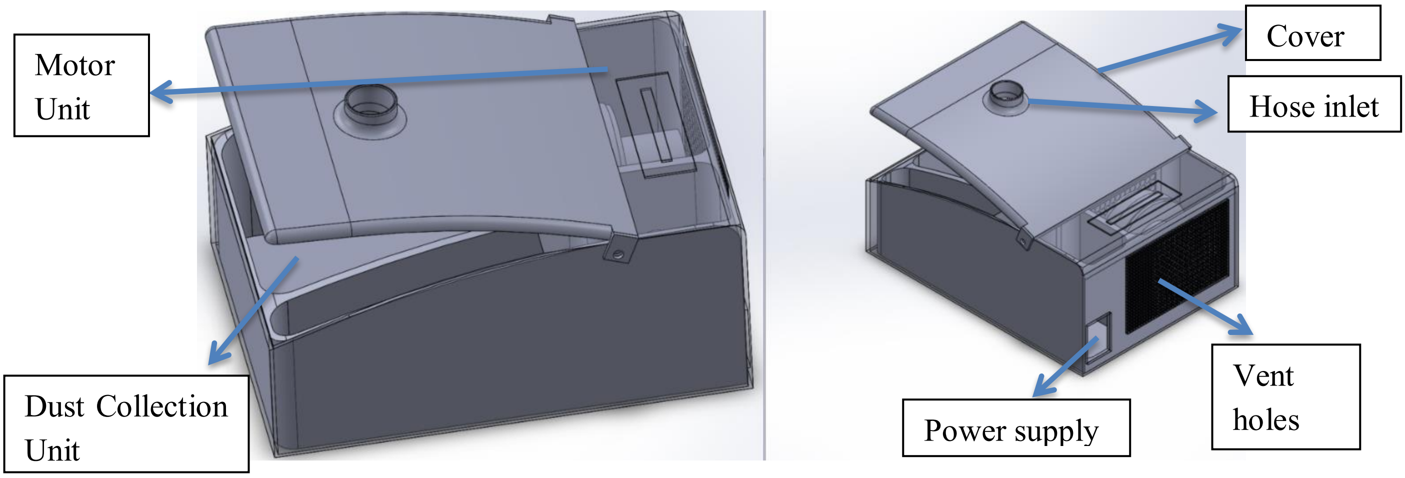

Figure 15. *3D modelled vacuum cleaner.*

The dimensions of the cleaner are around 432×185×130mm. There is no limit on the design type or dimensions of the vacuum cleaner. However, it must fit within the platform dimensions. Dimensions of the compartments must match with the dimensions of their respective parts. The top cover's hose inlet diameter must match the dust bag inlet and hose diameter, such that there is no leakage. The vacuum cleaner is modelled in two parts comprising of the base compartment (Figure 15) and top coverlid. The base compartment houses the motor, dust bag and the controller, Figure 16.

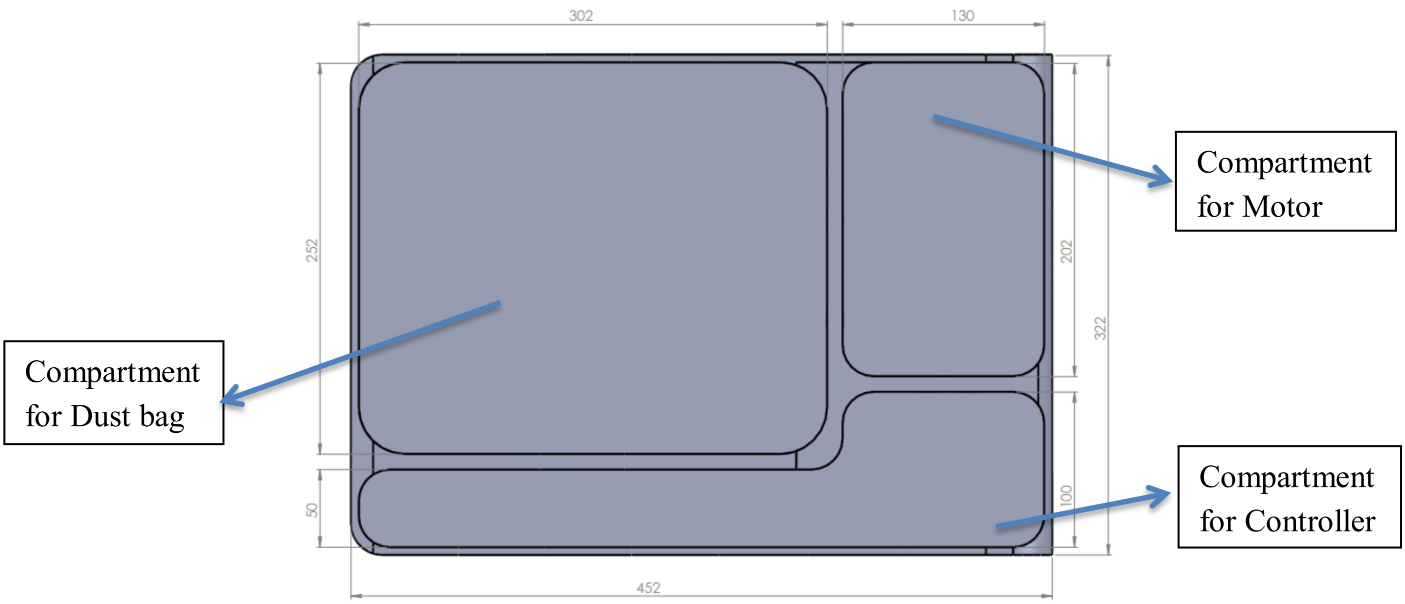

Figure 16. *Top view of the vacuum cleaner compartment to house motor, dust bag and controller.*

The selected motor has the outer diameter of 155mm and a height of 118.3 mm. It is housed in the motor compartment of 202×130mm. The extra space is utilized for electrical wiring. The selected dust bag has the dimensions of 318×330mm and its capacity is 3.5L. It is housed in a compartment of dimension 252×302mm. The compartment space for the controller is 50×432mm. The top view of the designed vacuum cleaner is as seen in Figure 16. It has vent holes at the back for the outlet of clean air. The top lid can be flipped for easy removal of dust bags. It has a hose inlet with a diameter of 80mm to match the inlet diameter of the dust bag. It is further tapered to match the hose piping diameter.

3.3.2 Mechanical assembly of vacuum cleaner and robotic platform

The modelled vacuum cleaner is connected with hose and nozzle on the PULU platform (Figure17), Figure 18. The outer covering on the PULU is modelled as a mini truck to improvise its appearance. The truck design provides space at the back to house autonomous board cleaner robot, which is explained in Chapter 4. The outer cover can be implemented easily using the body of any RC cars of scale 1:5 or 1:8 whose dimensions match that of Pulu.

The parts are assembled on top of the PULU-M robotic platform. The nozzle is placed at the front end at the center. The back end of the vacuum cleaner is in parallel with the front face of the robot. In this way, the vent holes of the vacuum cleaner will be in line with the radiator vent holes of the mini truck. The hose is taken from the top of the platform and not from the bottom due to the presence of the LIDAR sensor in between. The location of the LIDAR can be seen in Figure 17. Therefore, connecting the hose to the nozzle in the front will obstruct its view and connecting the hose from behind the platform will use the complete space. Space is needed to house an autonomous board cleaning robot. Hence, the hose is attached to the nozzle through the sides. The side brushes are placed at the front extreme ends of the platform. Figure 19 shows the various views of the mechanical assembly of the autonomous floor-cleaning robot.

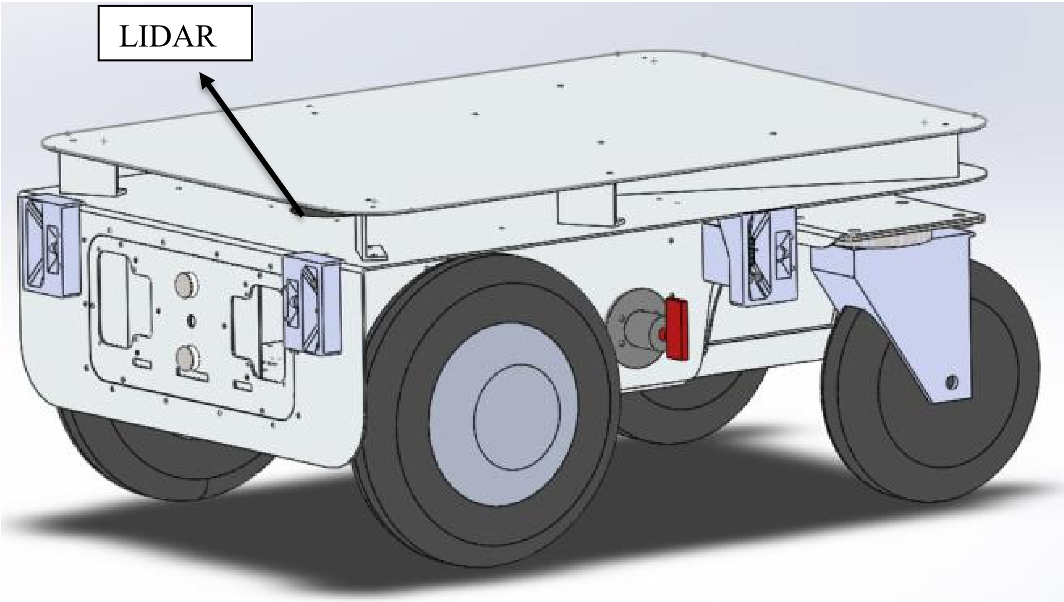

Figure 17. *Computer aided design (CAD) model of PULU-M robotic platform (Pulurobotics Oy Ltd).*

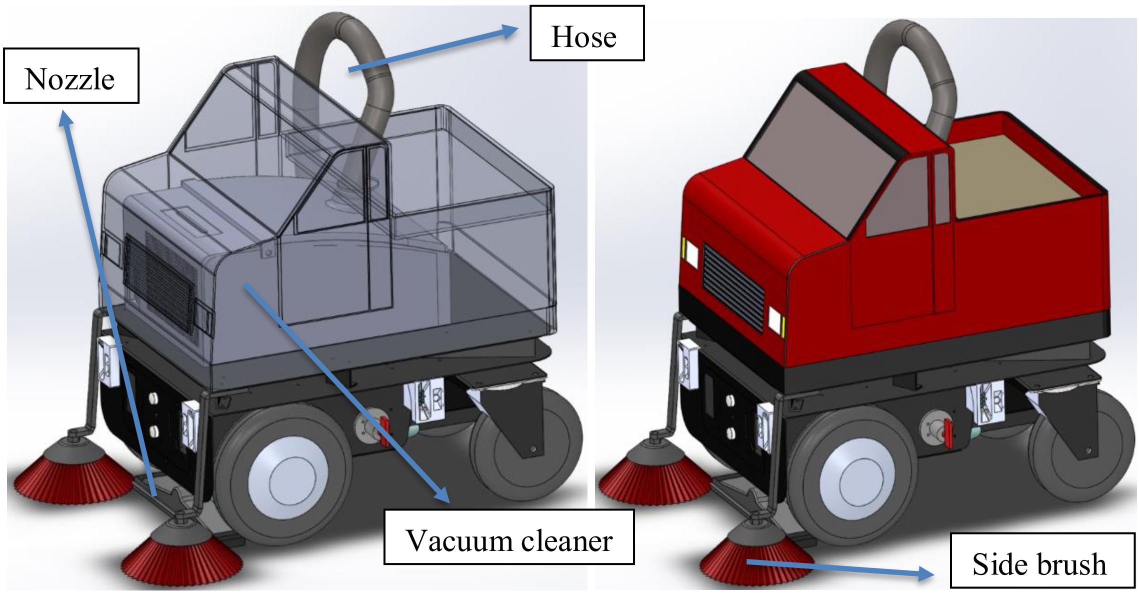

Figure 18. *3D model of robotic vacuum cleaner.*

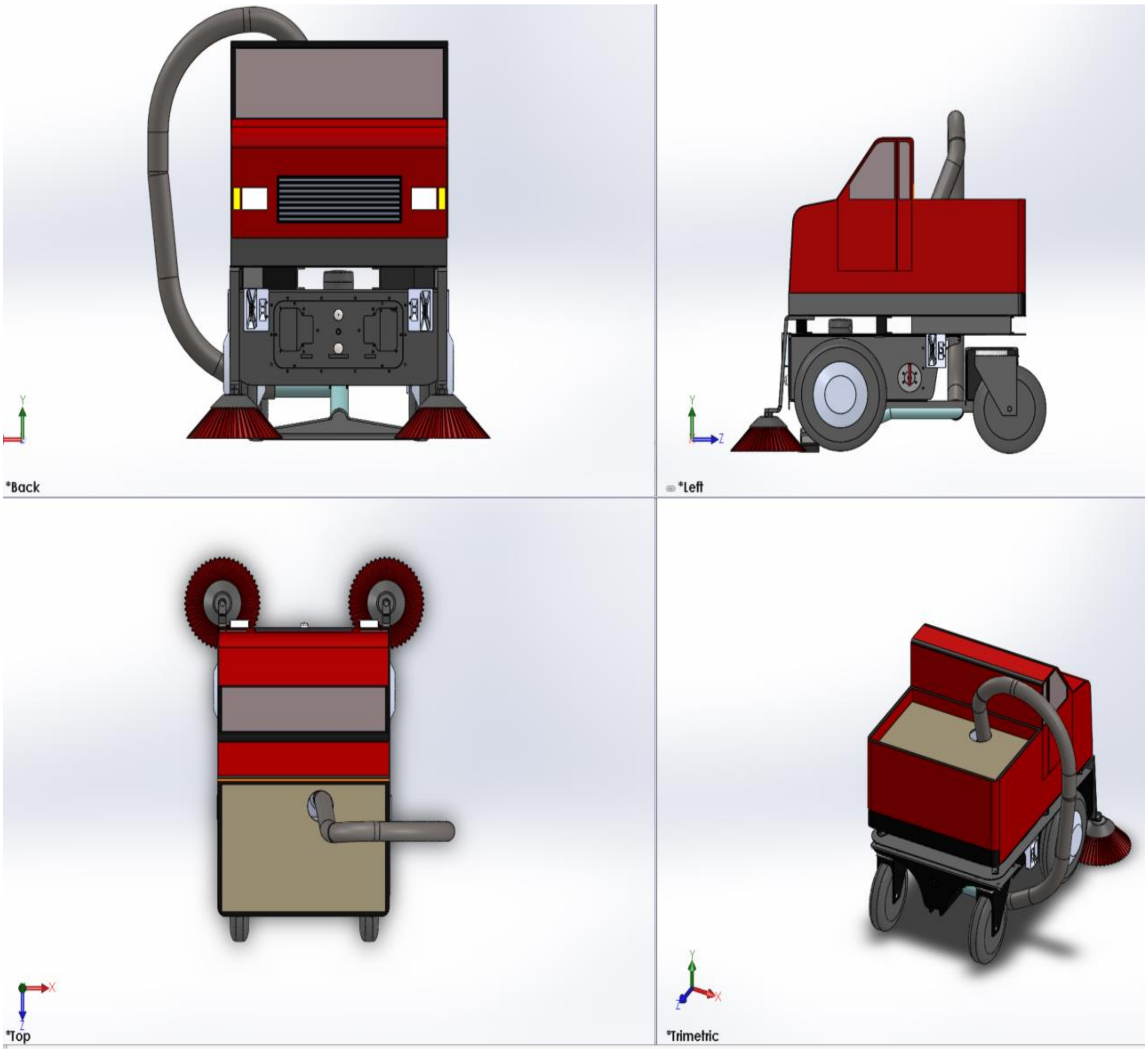

Figure 19. *Starting from top left to right and bottom left to right, back view, side view, top view, and isometric view of autonomous floor cleaner.*

4. CONCEPTUAL DESIGN OF AN AUTONOMOUS BOARD CLEANING ROBOT

4.1 Overview of the autonomous board cleaning robot

The board cleaner robot has been designed to perform the tasks of autonomous board cleaning in classrooms. The robot's function is to maneuver and clean over the vertically placed boards in classrooms.

The elements required for designing the board cleaning robot are –

1. **Adhesion mechanisms** – as the application surface is a ferromagnetic material, utilizing magnetic adhesion is a reliable solution. According to (Chang 2015) it is most reliable in terms of robust adhesion and energy efficiency when compared to other methods such as vacuum suction, etc. Magnetic adhesion can be implemented using either permanent magnets or electromagnets or both.
2. **Locomotion mechanisms** – when it comes to mobility the selection of locomotion mechanism for given application and environment is of prime importance. There are several types of locomotion mechanisms such as legged locomotion, tracked locomotion, and wheeled locomotion. Tracked locomotion is considered in this thesis work, as it is relatively fast with less slippage and less complexity. The tracked locomotion mechanism eliminates the need for a steering mechanism that reduces the complexity of the design during turning.
3. **Structure design** – the design must constitute a light and reliable mechanical structure. Lesser the total weight lesser adhesive forces are needed to adhere. The overall mass of the body must be distributed equally over all the parts. Mass concentration at any point causes slippage of the robot at 90^0 vertical inclination. The use of durable plastic material for the construction of the components will further reduce the weight drastically.
4. **Integration of locomotion and adhesion mechanisms** – effective integration of the two is the key to the connection of adhesion and movement. They can be controlled independently or simultaneously. In this thesis work, the locomotion and adhesion mechanism are integrated to make the system simple.
5. **Sensory unit** – it must contain fewer numbers of sensors but robust to noise while reading data and must be economical. A bumper sensor is used to detect obstacles while an inertial sensor (IMU) is used to estimate the position and orientation of the robot.

4.1.1 Locomotion mechanism – synchronous belts

In this thesis work, the locomotion mechanism and adhesion mechanism are integrated into one simple system. This is accomplished by integrating the synchronous belt unit with magnetic adhesive strips. The reason for choosing synchronous belts instead of the continuous tracked mechanism is that the tracks add on to the weight. Furthermore, the boards are smooth surfaces made of ceramic and ferromagnetic substances; the movement of continuous tracks on these surfaces can tamper it.

The transmission method of the synchronous belt is similar to belt drives, but these come with the addition of teeth on the pulleys and belts. The advantage of teeth makes the transmission form dependent rather than the friction dependent. This prevents the belt slippage and provides accurate and repeating motion with low backlash. Further, these belts can provide high speeds without the need for pre-tensioning and lubrication at low noise levels (Svedmyr 2016).

4.1.2 Adhesion through magnetic tapes

The magnetic adhesion is fulfilled using magnetic tapes on the synchronous belt; together it can be called as the adhesive belt. The reason to choose magnetic tapes over the bar or circular magnets is due to the placement issues. Placing magnet at one particular place can cause a shift in forces. Use of magnetic wheels reduces the contact surface area. It is well known that the magnetic strength reduces drastically with an increase in distance between the magnet and adhesive surface. Placing the magnet far from the surface of the board limits its strength. Further, the choice of adhesive belts helps in an easy change of belt and gear for any modifications in the weight rather than changing the whole design.

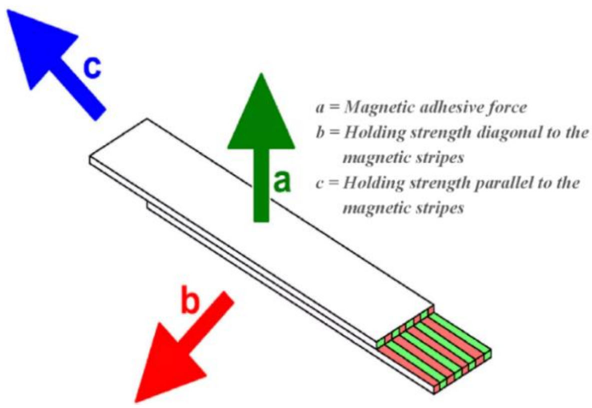

Figure 20. *Force direction representation in a magnetic tape (Supermagnete a).*

The force representation of magnetic tape can be seen in Figure 20. Here the adhesive force value represents the strength needed to separate the magnetic tape from the steel plate. When the tape has to adhere horizontally, the holding strength is around 80 % of the adhesive strength due to vertical strain. For a vertical adhesion, the holding strength is 40% of adhesive strength (Supermagnete a). Furthermore, a good amount of safety margin makes the adhesion resistant for the vibrations and movements as the defined numbers are for static adhesion. In this thesis work, both horizontal and vertical holding strength is necessary, as the robot must manoeuvre in all directions and still be able to adhere to the board.

The magnetic tape available at (Supermagnete b) comes in two types

- **Magnetic adhesive tape ferrite** – has a strength of 102 g/cm^2 and comes in widths of 10mm, 20mm, 30mm, 40mm, and 150 mm.
- **Magnetic adhesive tape neodymium** – has a strength of 450 g/cm^2 and comes in widths of 10mm, 20mm and 30mm. The strength of neodymium is quite strong about four times the regular ones. One-meter length of 20 mm neodymium tape has a strength of 90 kg.

The high holding strength requires a high separating force while the robot is in motion. Hence, the magnetic adhesive tape ferrite is chosen.

4.1.3 Controller

Raspberry pi-3 model B will be used as the controller. The advantages of using raspberry pi are that it is a compact size single-board computer. It runs Debian based GNU/ Linux operating system Raspbian. It comes with general-purpose input/output (GPIO) pins to either send signals to hardware or receive from them to read sensor data. The reason for choosing Pi-3 is the addition of wireless connectivity feature in it. It has onboard WiFi and Bluetooth support. Wireless connectivity is the key to effective communication between two autonomous robots.

Robot operating system or simply known as ROS will be the robot platform. It is a BSD licensed open-source software. This software framework allows applications to operate robotic hardware. It has a set of utilities and libraries to control the robotic components. The ROS system consists of several nodes. Each of these communicates with each other to publish or to subscribe to messages or the state of the robot (ROS.org a).

4.1.4 Sensory unit

Sensors are required to guide the robot in its working environment. They send the acquired data to the controller for further action. They are of several types based on the application. In this application, sensors are needed to estimate the position and orientation of the robot at the same time avoid obstacles and stay within the vertical working environment.

Bumper Sensor

The obstacle detection can be achieved using a bumper sensor in the form of a micro-switch. They are simple and inexpensive. Three of such sensors are required to navigate the robot against obstacle on three of four sides of the robot (the rear end is not included). These switches can trigger signals to the controller and thereby avoid obstacles. These sensors must be placed low on the robot such that it can detect the board edges.

Inertial Sensor

Inertial sensors alone can estimate both position and orientation. These sensors are a combination of accelerometer and gyroscope. They are also known as inertial measurement unit or IMU. They come as a single axis, two-axis or three-axis IMUs. The three-axis is the combination of a three-axis gyroscope and three-axis accelerometer. The gyroscope measures the angular velocity to obtain the robot’s orientation. The accelerometer measures the specific external forces that include acceleration and gravity. The sensor’s position value is measured by subtracting earth’s gravity from the accelerometer value and then double integrating it. The sensor’s orientation must be known to negate gravity (Kok, Hol et al. 2017). This is represented in the form of a block diagram in Figure 21.

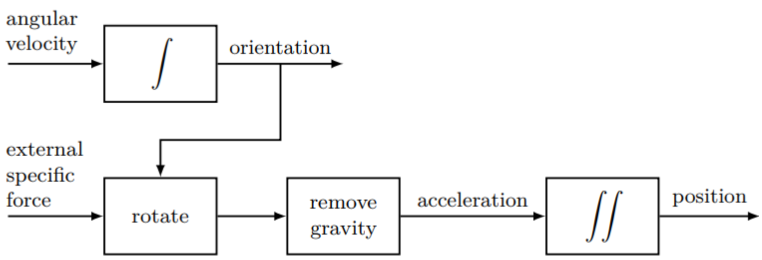

Figure 21. *Schematic illustration to represent position and orientation measurement using IMU (Kok, Hol et al. 2017).*

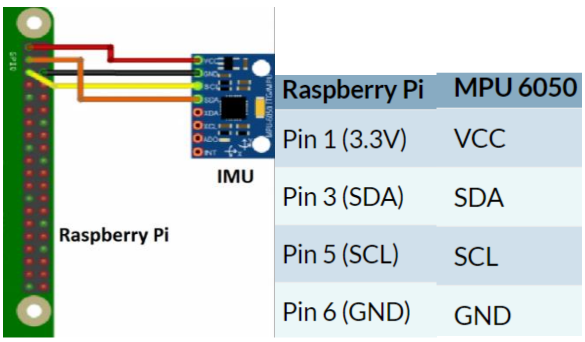

Figure 22. *Pictorial representation of Raspberry pi and MPU 6050 with its pins (RaspberryPiTutorials).*

MPU6050, three-axis accelerometer and gyroscope IMU is used. It uses a 12C bus to interface with the controller board. It is very easy to set up with the raspberry pi to obtain the readings. Figure 22 shows the pictorial representation of setting up MPU6050 IMU with raspberry-pi.

4.1.5 DC Motor for locomotion

It is the main component that moves the robot. In this work, geared DC motor or a DC motor with speed reduction are needed to achieve high torque and low speeds. The motors must have high torque to move the robot on a vertical board. Low speeds are required to maximize the efficiency of cleaning and to achieve easy maneuvering on a vertical surface. The selected motor is as seen in Figure 23. The specification of the selected motor is listed in Table 6. For a wheel radius of 21.5 mm the least velocity obtained is 0.1 m/s. The steering to any direction can be achieved by locking one of the pulleys (no power) and powering the other.

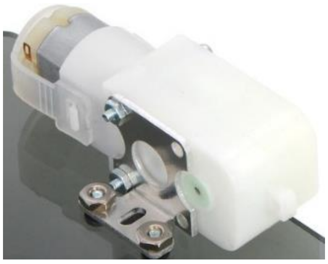

Figure 23. *Selected 200:1 Plastic Gearmotor, 90^0output (Pololu a).*

Table 6. *Specification of selected gear DC motor (Pololu a).*

Size	64.4 × 22.3 × 21 mm
Shaft diameter	7 mm
Weight	32g
Operating Voltage	6V
No load speed at 6V	51 rpm

Table 7 lists the different components used in the CAD assembly (Figure 25) of the robot along with its weight.

Table 7. *List of components of autonomous board cleaning robot along with the weight.*

Part	**Weight**
DC motor	32×4 = 128 g
Raspberry Pi	42g
Sensor (IMU+bumper)	~10g
Cables	~50g
Battery (rechargeable)	31×4 = 124g
Chassis	~350g (from Solidworks)
Top cover	~320g
Duster	40g
Gear and belt	~400g
Total	**~1500g**

4.2 Mechanical design of autonomous board cleaning robot

To understand the importance of adhesive forces on the vertical plane, the force diagram for a wall-climbing robot is studied as seen in Figure 24.

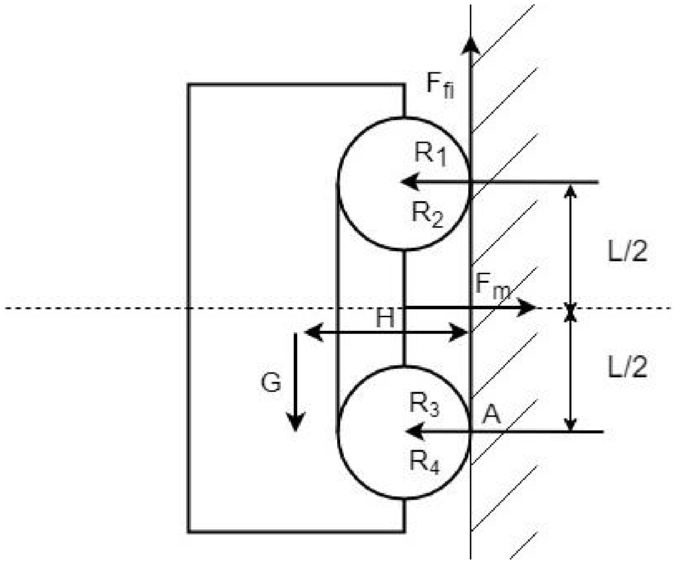

Figure 24. *Force diagram for a wall-climbing robot on a vertical plane.*

Let us consider that, the board cleaning robot remains static on the surface of the board. As the robot is static upon a vertical surface there are various types of force acting upon the robot such as magnetic adhesion force (F_m), force due to weight (G), force due to friction between the surfaces (F_{fi}) and reaction forces or supporting forces on the surface (Ri, where i = 1,2,3 and 4). For the robot not to slip from the board, it is considered that the magnetic adhesion is distributed uniformly. The uniform distribution would balance the force on all the four points as shown in Figure 24. The static friction coefficient is denoted by f_0. The static and dynamic analysis was according to (Chen, Wang 2013).

Resolving the forces into horizontal component, vertical component and frictional forces.

$$\begin{cases} F_m - R_1 - R_2 - R_3 - R_4 = 0 \quad (Horizontal\ component) \\ G - F_{f1} - F_{f2} - F_{f3} - F_{f4} = 0 \quad (Vertical\ Component) \\ F_{fi} \leq f_0 R_i \ (Frictional\ force\ component)\ (i = 1,2,3,4) \end{cases} \tag{22}$$

As the robot is stationary on the surface, to prevent the slip down the reaction forces must be balanced. Therefore, equating $R_1 = R_2 = R_B$ and $R_3 = R_4 = R_A$.

Considering the horizontal components from Equation 22.

$$F_m = 2R_A + 2R_B = R_i \tag{23}$$

Let the vertical components be

$$G = F_{fi} \tag{24}$$

After substituting equation 24 in equation 22, the frictional force component is given by

$$G \leq f_o R_i \tag{25}$$

Now, substituting equation 25 in equation 23.

$$f_o(2R_A + 2R_B) \geq G \tag{26}$$

By using equation 22 and 23 in 26, the condition for the robot to adhere to the vertical structure is

$$F_m \geq \frac{G}{f_o} \tag{27}$$

When the robot is in static position, the magnetic adhesion force must satisfy the condition in the equation 26 to stay upon the board.

Now, considering the rotation about point A. The distance between the center of the rollers is L and the distance between the surface of the board and the center of mass of the robot is H.

$\sum M_A \geq 0$

$$-R_1\frac{L}{2} - R_2\frac{L}{2} + R_3\frac{L}{2} + R_4\frac{L}{2} - GH \geq 0 \tag{28}$$

Where, R1 = R2 = RB and R3 = R4 = RA.

$$-2R_A + 2R_B - \frac{2GH}{L} \geq 0$$

$$2R_A - 2R_B + \frac{2GH}{L} \geq 0$$

$$2R_A \leq 2R_B - \frac{2GH}{L}$$

From horizontal component of equation 22,

$$2R_A \leq (F_m - 2R_A) - \frac{2GH}{L}$$

$$4R_A \leq F_m - \frac{2GH}{L}$$

Dividing by 2

$$2R_A \leq \frac{F_m}{2} - \frac{GH}{L}$$

For the robot to stick to the board it is known that the lower wheels should not rotate around A. For that to happen the force on top wheels $2R_A$ should be greater or equal to 0. The minimum requirement is when $2R_A$ is equal to 0. So, when 0 is substituted in above equation the obtained condition is

$$F_m \geq \frac{2GH}{L} \tag{29}$$

To estimate the magnetic adhesion force, the maximum of the equation 27 and 29 is considered.

$$F_m \geq max\left\{\frac{G}{f_o}, \frac{2GH}{L}\right\} \tag{30}$$

Considering the parameters from the CAD model, for 1.5 Kg payload of the robot, the magnetic adhesion force must be greater than 49 N for the robot to remain static on the board surface. The static coefficient of friction is taken as 0.3. The weight distribution on the two sides of the bot would be 24.5N. The possible least magnetic adhesion through the magnetic strips on one side of the bot considering 40% of total holding strength is 27.3N which is greater than 24.5N. Hence the robot can adhere to vertical magnetic plane.

Next the torque required for the robot movement is calculated. The torque of the motor must satisfy:

$$M_d \geq \frac{k_2.\mathrm{F}.f_o.r}{\alpha_t.\eta} \tag{31}$$

$$M_d \geq 9.629.10^{-3} \text{ Nm}$$

Where, k_2 – is the safety factor, considering it to be 3

F – sum of reaction force and force due to weight, N

f_0 – frictional coefficient

r – radius, m

α_t – transmission ratio

η – efficiency

The obtained value is 0.01 Nm while motor can provide a torque of 0.7Nm which is higher than the requirement to keep the robot moving on the vertical plane.

4.2.1 Mechanical assembly of autonomous board cleaning robot

The chassis is the main supporting structure of the robot. On this, the sensor, controller, and batteries are mounted along with the locomotion parts. The rectangular modelled chassis has a length of 217.6 mm and width of 95 mm. It has a central housing wherein the bottom part houses a duster, while the top housing at a height of 65 mm has provision to stack four AA batteries along with its cover, a raspberry pi, and IMU sensor.

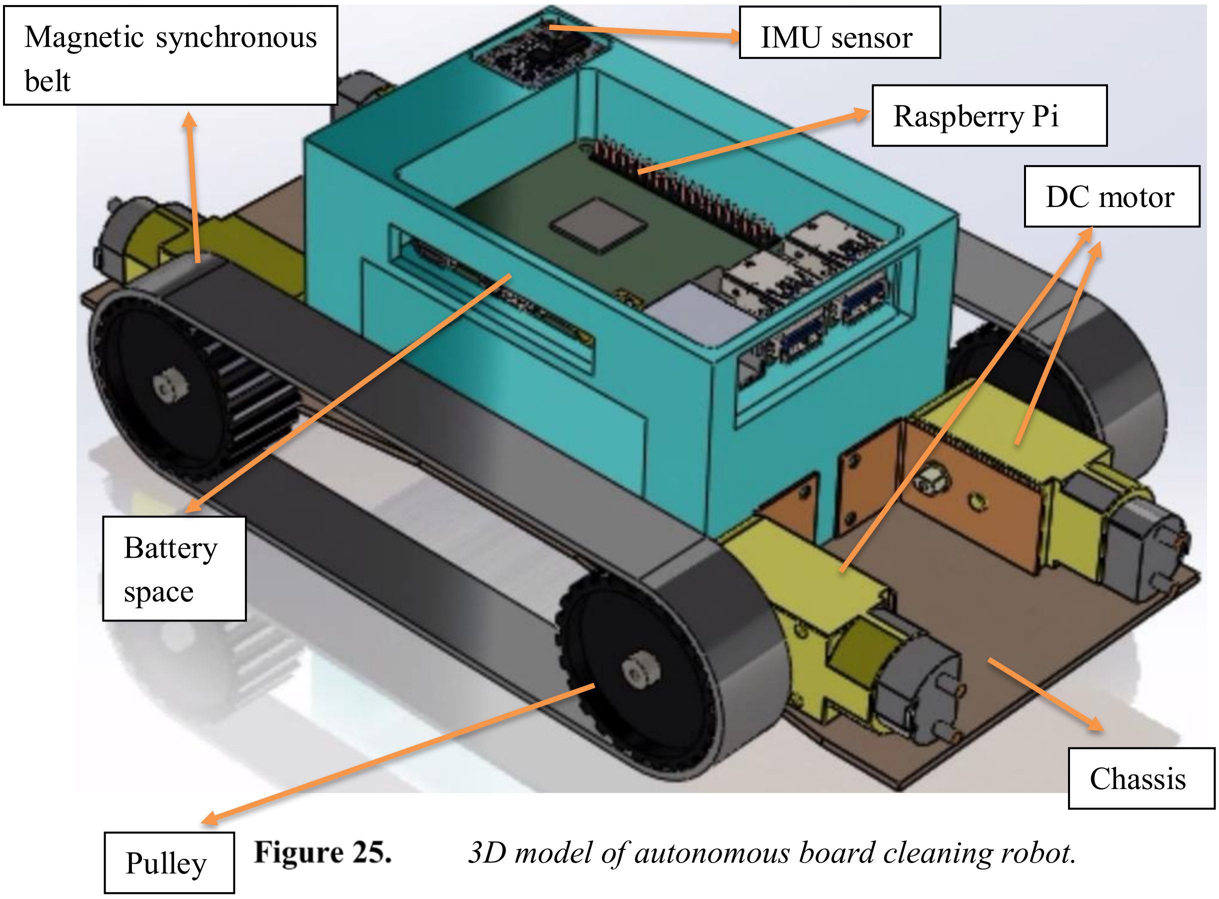

Figure 25. *3D model of autonomous board cleaning robot.*

A standard whiteboard marker duster is considered for the design purpose. It is lightweight and has a dimension of 100×55×23 mm. The bumper sensor along with micro switches will be placed on the surface of chassis at the bottom. Four DC motors are used to run four pulleys and two synchronous belts. Figure 25 is the isometric view of the mechanical assembly of the autonomous board-cleaning robot. The main design consideration in this assembly is that the duster must firmly adhere to the surface of the board. Figure 26 represents the different views of the modelled autonomous board cleaner.

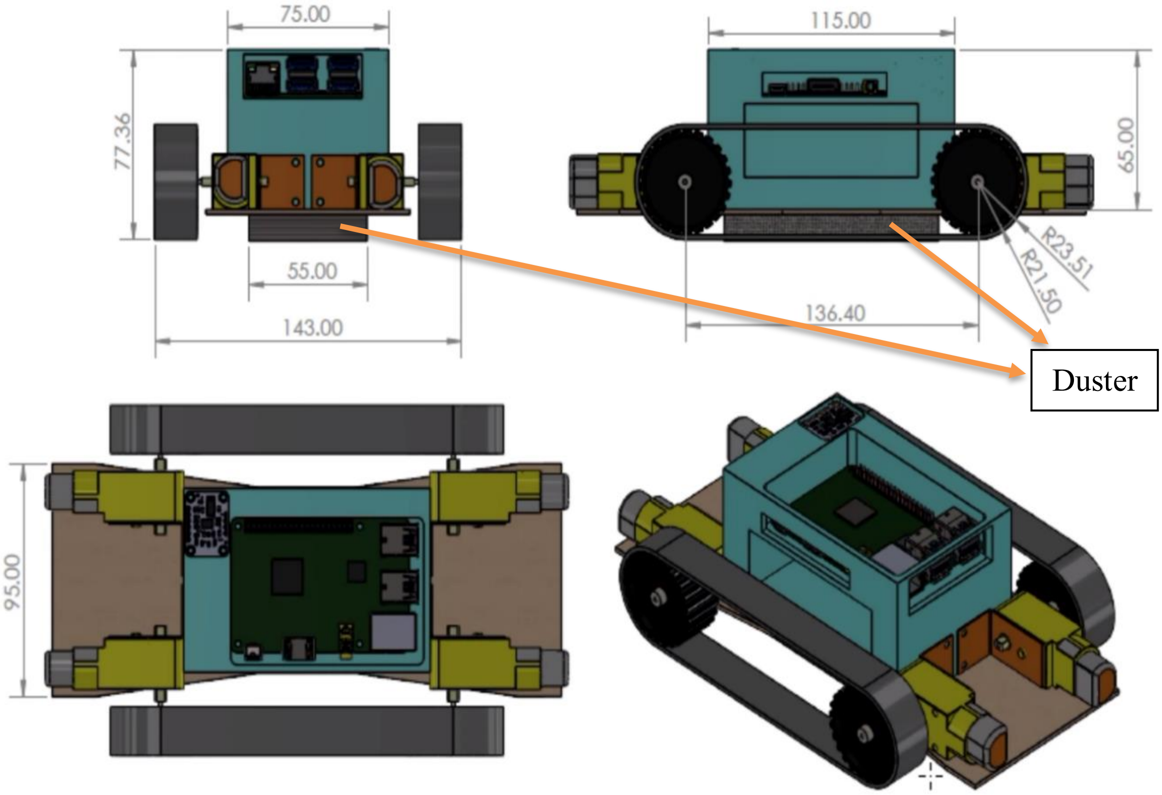

Figure 26. *Starting from top left to right and bottom, side view, front view, top view, and isometric view of autonomous board cleaner.*

Since the product finds its application in school the appearance and aesthetics of robot are very important. Here, an amour tank design is chosen, Figure 27.

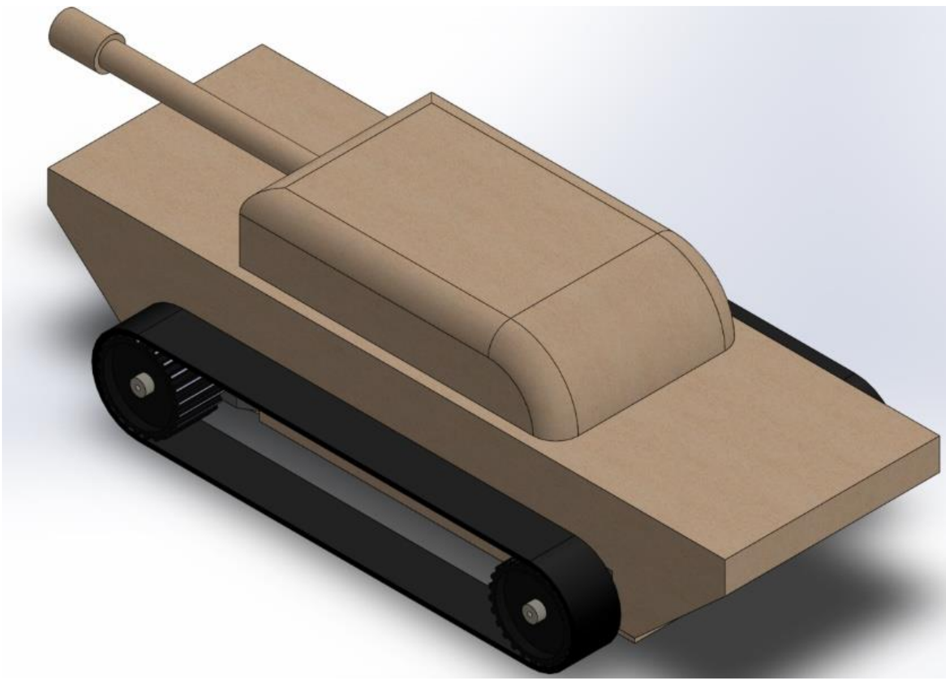

Figure 27. *The autonomous robot with outer covering depicting a tanker.*

5. PATH-PLANNING TECHNIQUES FOR AUTONOMOUS CLEANING ROBOT

Navigation is the combination of a robot to know where it is in its operating surrounding and how to move from one point to another without colliding into obstacles. In short, it comprises of following

- Localization – the robot must establish its position
- Mapping – know its surroundings
- Collision avoidance – must detect and avoid obstacles in its path
- Path planning – must know how to get to goal point from the start point (books.org 2015).

5.1 Localization and mapping technique

Localization is nothing but the robot knowing where it is. It focuses on finding its position and orientation within its operating environment. As the application is indoors, the discussion is on indoor navigation and localization. The dead-reckoning localization uses odometry to know the position for short distances. However, it is not accurate for long distances, must have an estimate of the initial position (books.org 2015). Placing artificial markers for indoor localization is not feasible at least in areas such as schools. Probabilistic localization such as Monte Carlo localization, Markov localization employs sensory data and robot's uncertainty beliefs in knowing where it is. Before choosing any localization algorithm, the nature of the working environment must be decided as it can affect accuracy.

Global and Local localization

In local localization (also known as position tracking), the robot's initial position is known but the disadvantage is, it loses the track of robot once the position is not known. On the other hand, in global localization, the map is given but the robot's initial position is not known. Hence, in global localization, it is possible to localize the robot in an unknown location (Se, Lowe et al. 2001).

Static and dynamic environments

In a static environment, only robot moves while everything else remains in the same location whereas in a dynamic environment other objects (other than the robot) also change their position to time. Example: people, daylight (a robot with a camera). In a dynamic environment, if these changes are not measured then the localization becomes useless (Thrun, Burgard et al. 2008).

In this application, the robot does not know its original position hence it is a global localization problem. It is assumed that the environment is static.

As per (Thrun, Burgard et al. 2008) both Markov and Monte Carlo localization (MCL) apply to both global and local localization but the implementation of the MCL algorithm is most popular in robotics. It is because the implementation is easy, and it works for a wide range of problems.

The Monte Carlo localization algorithm uses a particle filter to estimate the robot's position in a given map while it senses the environment as it moves. In the start, the robot has no information about its position, it initiates with the uniform random particle distribution over the surrounding environment and assumes it to be at any point in space. For the distribution of likely states of its position, this algorithm uses particle filter, wherein each particle represents the possibility of the robot being there. As the robot moves, the particles move and are resampled based on recursive Bayesian estimation to predict the new state of the robot. Based on successive resampling of how well the actual sensed data correlates with the predicted position, the unlikely particles are filtered and converge to the robot's actual position. When MCL is used for symmetric environments, it needs some modifications (Thrun, Burgard et al. 2008).

In the above localization, it is assumed that the map is given. It can be acquired using the blueprints of the buildings or a CAD model (Thrun, Burgard et al. 2008). However, that just gives information about the shape and size, doors and walls but not about other objects such as furniture inside the building. To construct a map from the sensors the position of the robot must be known. To localize there must be a map. What comes first? The map or position? Well, the answer is both. This can be achieved by simultaneous localization and mapping (SLAM). This process builds the map and at the same time estimate the robot's position. It considers the uncertainty in robot's position while building the map. It correlates between the estimated robot position and the constructed map (Kudan 2016). This modelled map can be used for further applications.

The Pulu platform has LIDAR for long-distance navigation and mapping. Four 3D Time of Flight (TOF) cameras to see in direct sunlight or at night and to sense obstacles lower or higher than the 2D LIDAR plane. SONAR for detecting transparent obstacles such as glass doors, etc (Pulurobotics Oy Ltd).

The robot performs SLAM using the 2D plane LIDAR, this creates the map of the surrounding, but it is not useful for obstacle detection. The LIDAR creates the 2D map around its line of view. It cannot detect objects that are below or above its line of view as seen in Figure 28 A. However, the 3D TOF sensors can view all the obstacles at once Figure 28 B; it can analyze the floor levelness. Hence, the LIDAR sensor is used for localization and mapping while the 3D TOF sensors are used for obstacle detection in 3D. Both LIDAR and TOF sensors work on the principle of light. If in case, there are any transparent obstacles such as glass it will not be detected as the light passes through it. To solve this problem, SONAR sensors are used. They detect transparent objects.

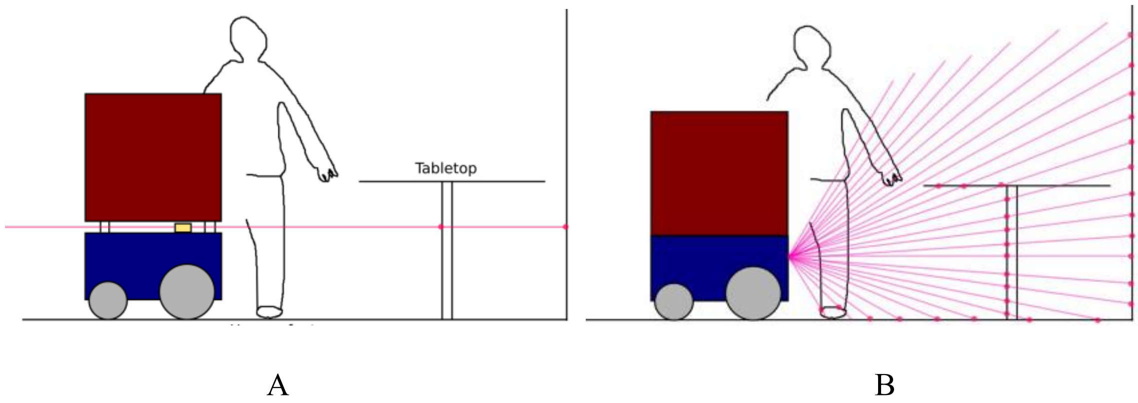

Figure 28. *A – The 2D LIDAR cannot provide complete picture of the obstacle as it cannot see the human foot in the way and the tabletop that is above its sight, but it is useful for localization and mapping. B – The 3D TOF sensors can see all the obstacles at once; hence, they provide details for obstacle avoidance (Pulurobotics Oy Ltd).*

5.2 Techniques involved in autonomous path planning

For an autonomous robot, path-planning aims at finding a collision-free path from the start point to the goal point. When it comes to robotic vacuum cleaners the path-planning gets complex, as it must aim at providing complete coverage of the surrounding for cleaning.

Various motion algorithms can be designed for path planning depending on the sophistication needed. Some are sophisticated demanding expensive sensory unit and heavy computation while some simple algorithms can be implemented with just bumper and IR sensor. The motion algorithms that are simple and yet provide complete coverage of the area are

- **Random coverage** – in this the robot follows a random travel motion wherein it travels straight until it hits an obstacle. Once it hits the obstacle, it changes its orientation to any random direction and moves along until it encounters the next obstacle and repeats. It is time-consuming, but it is possible to completely cover the surrounding. Though it is simple, it requires more time for complete coverage. There is a possibility for the robot to repeat the already traversed areas unless programmed no for it. This is only suitable for domestic cleaning with small areas where time is not a priority.
- **Systematic/ pattern coverage** – this involves a predefined pattern path or combination of them to manoeuvre the robot. Since the paths are already predefined, it is simple and not computationally heavy. The systematic coverage will be used in this project.

The use of random motion is advantageous for homes as the coverage area is too small and time is not of much importance. However, when it comes to larger environments like school, time becomes a priority. The school consists of several classrooms. Random motion cleaning of all the classrooms is time consuming and uncertain. Hence, pattern motion is preferred. Here the robot can systematically cover the entire room within the predefined time. The Pulu platform has a velocity of 0-7km/hr that is nearly 1.9 m /s. This is too fast for a cleaning robot. The velocity will be limited to around 0.3 m/s for safe and effective cleaning.

The choice of pattern motion algorithm for path planning has several advantages

- It is able to generate paths to cover the complete area
- Not necessary to have complete knowledge of surrounding if it has the obstacles data.
- It also has the advantage of contour follow such a wall follow or object follow. Much of dust is near the wall; wall follow pattern increases the efficiency of cleaning.
- It does not have to save any data and it is computationally cheap.

Following are the motion patterns selected for path planning for this project namely, wall follow, zigzag, spiral etc. Each one is unique for a specific task.

5.2.1 Spiral motion

The robot moves outwards or inwards to form a spiral motion. For an outward motion, the robot will start from the center of the room and go around in circles of increasing diameter.

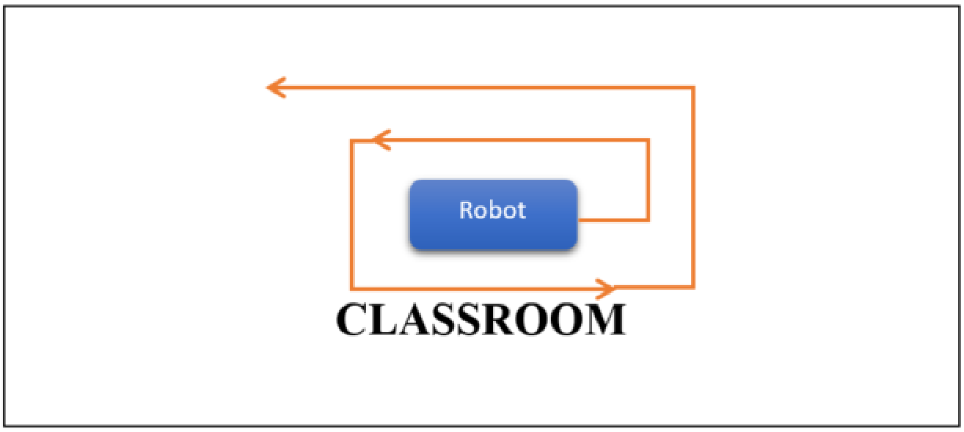

Figure 29. *Path generated by squared spiral motion algorithm.*

For an inward motion, it will start from the corner of the room and form circles of decreasing diameter. Both circular and square spiral motions are possible. In this application, squared/rectangular spiral motion is considered, as the robot platform and environment (classrooms) are rectangular. The robot moves in a straight line turns 90^0 at the end of the line and then continues as seen in Figure 29. The outward spiral motion is chosen in this application because at the end of this pattern the robot reaches the corner of the room. This reduces the time needed to execute the next pattern in the cleaning cycle as it also starts from the corner of the room.

5.2.2 Zigzag algorithm

Here the robot moves in a straight line and at the end of the path, it takes a turn to get in parallel with the previous traversed straight line. The generated motion will be similar to 'L' shape. At first, the robot starts from any corner to form the letter 'L' and then turns to form an inverted 'L'. The robot continues this pattern until it has covered the entire surrounding. Figure 30 shows the path generated by a zigzag motion algorithm.

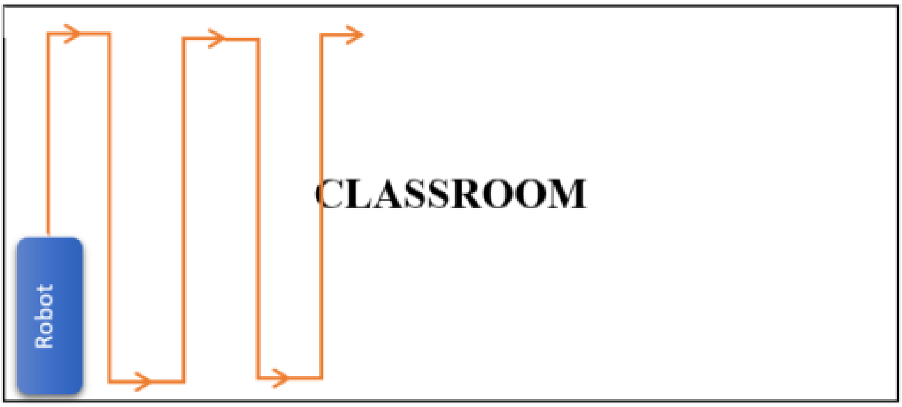

Figure 30. *Path generated by Zigzag motion algorithm.*

5.2.3 Wall follow algorithm

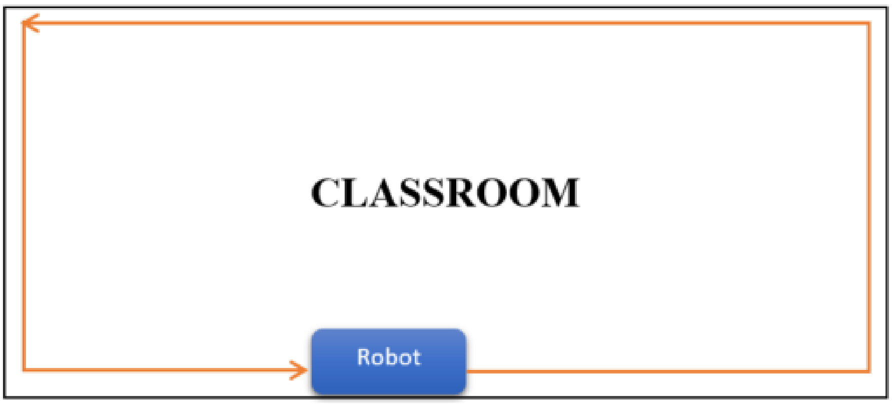

Figure 31. *Path generated by wall follow motion algorithm.*

It is known that dust tends to accumulate much at the corners and along the wall. The wall follow algorithm allows the robot to move along the walls; furthermore, the advantage of having a side brush will help in effective removal of dust from the corners and along the wall. Figure 31 shows the path generated by the wall-follow algorithm.

The combination of spiral, zigzag and wall follow patterned algorithm proves to be more advantageous in overcoming the drawback of a single patterned algorithm. Hence, the combination of the three above-mentioned algorithms will constitute one full cleaning cycle. The onboard sensor unit will detect the obstacles while the obstacle avoidance program will command the robot to turn or change direction when an obstacle is encountered.

5.3 Collaboration of autonomous robots

A robot is specialized in one particular task. If there is a need to automate two or more tasks, then there is a need to employ two or more robots for the completion of the task. However, when two or more robots are built to co-ordinate together with minimal supervision, they make the task easier. In this thesis work, the objective is to collaborate and co-ordinate the autonomous board-cleaning robot with the autonomous floor-cleaning robot. However, the design and implementation of it is the next stage of work (mentioned in future work) the basic concept will be described in this subsection.

As mentioned in the introduction, in a school classroom the most important cleaning tasks are vacuuming of floor and cleaning of the board. The autonomous vacuum cleaner is easier to implement and reaches a bigger area because of the presence of wheels. However, the implementation of the autonomous board cleaner is not as easy as the robotic vacuum cleaner due to reasons stated below

- The operating environment of the autonomous board cleaner is at a vertical inclination of 90^0 and at a height of few meters from the ground.
- An individual robot in order to reach the board has to climb on the wall. This is easier to be said than implemented because climbing against gravity is complicated. The wall does not have magnetic adhesion. Hence, special grippers or any other forms of adhesion must be designed making the system complicated.
- The crossover from the wall to the board is difficult as the robot will use adhesion during the crossover.
- Above all, this is dangerous, complicated and time-consuming.

What is the best solution over here? Well, the best solution would be collaborating the two robots together. The robotic vacuum cleaner designed has a back compartment that can house the robotic board cleaner as seen in Figure 32. So, whenever the robotic vacuum cleaner travels to any working environment the robotic board cleaner is accompanied along. Now the question arises regarding the placement of robotic board cleaner from the platform on to the board. It can be fulfilled using a simple 4-DOF manipulator. Precision and accuracy of placement are not of prime importance (the robot can be placed anywhere on the board), this rules out the need for a sophisticated industrial manipulator. The path planning technique for the autonomous board-cleaning robot is simple; it follows the zig-zag motion pattern for path planning. Once the autonomous board-cleaning robot is placed in its working environment it travels straight and down to the board's bottom end corner. From this point, it travels up and down in a zigzag pattern until the other end of the board.

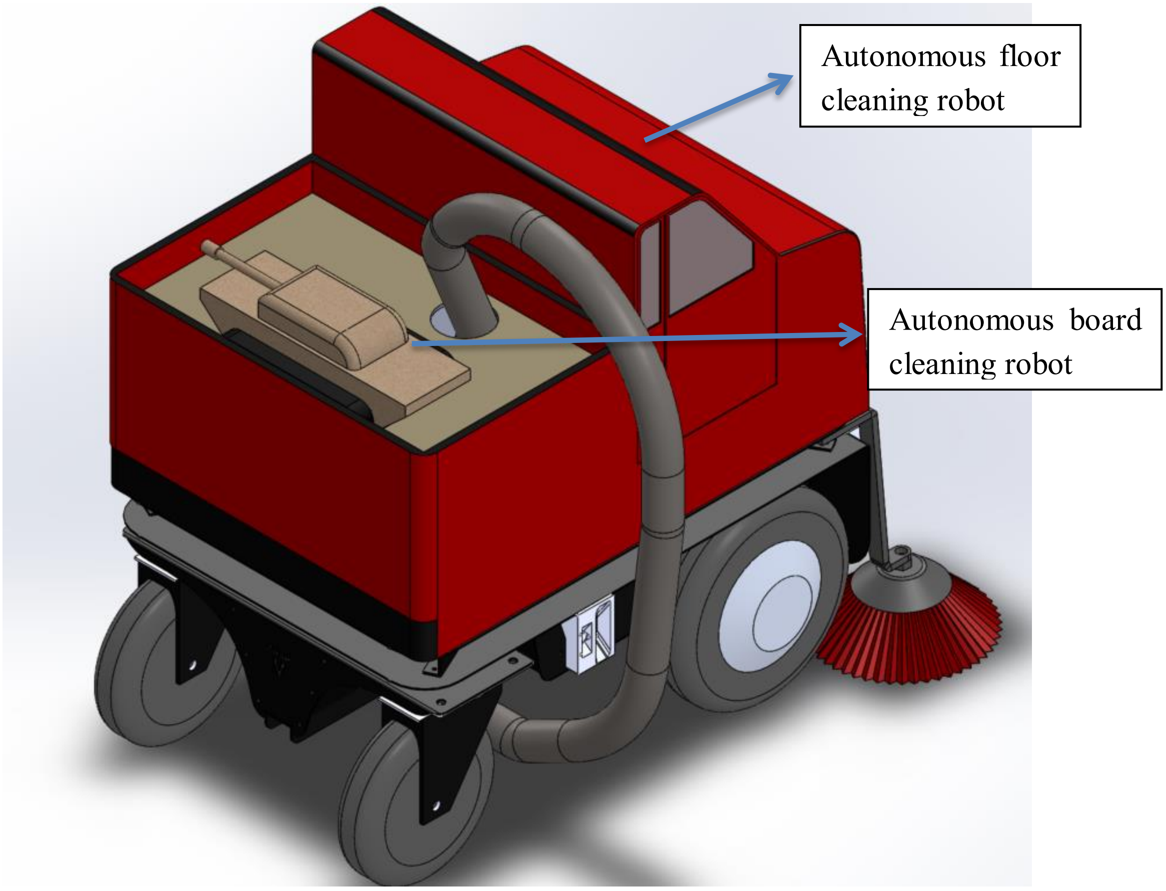

Figure 32. *Image to show the idea of collaboration of robotic vacuum cleaner with robotic board cleaner.*

Robot operating system (ROS) environment

Both the autonomous floor-cleaning and autonomous board-cleaning robot will operate in the ROS environment. As ROS is open-source software, it has the advantage of code usage from several sources. The ROS system consists of a number of nodes. Each of these nodes communicates with each other to publish or to subscribe to messages or the state of the robot. The nodes are started by accessing and starting the ROS Master core. One ROS master can control both the robots. However, turning off the ROS master due to any unforeseen errors will turn off both the robots, which is undesirable. Hence, the two robots are themselves set as ROS master independent of each other. The two robots communicate with each other via some communication technologies like Wi-Fi (ROS.org b). The combination of ROS environment and Wi-Fi communication technologies helps in collaboration of the autonomous robots.

6. CONCLUSION

The main objective of this thesis work was to design a proof-of-concept for an autonomous floor-cleaning and an autonomous board-cleaning robot. An extensive literature study was done to understand and compare the state of art technologies of these systems. However, the studies concentrating on the methodology of these systems were quite limited. The preliminary design and component selection of the vacuum cleaner system was based on the vacuum and airflow equations along with assumptions. The basis of these assumptions were the analytical skills of understanding, reasoning and comparing the existing models of vacuum cleaners.

The choice of using the existing commercially available robot platform, PULU-M for the robot chassis has eased the design process as it comes with the in-built sensory unit for obstacle detection, locomotion unit and the in-built battery-package along with self-charging capabilities. Furthermore, the in-built batteries of PULU provide about 3.7 hours of working time, which is quite good for large working areas like school. This ability out beats the domestic robotic vacuum cleaner, which has the cleaning cycle of around 30-60 min. By using PULU platform, more focus can be laid on developing an efficient cleaning system. The platform has a maximum speed of 1.9m/s but it will be limited to around 0.3 m/s for the effective cleaning process. The main concerns of navigation in this project are to provide a full area coverage. This is addressed by semi-systematic coverage approach using the combination of patterned motion algorithms namely spiral, zigzag and wall follow. By knowing the dimension of the environment, the time taken for a cleaning cycle can be estimated. The choice of localization and mapping techniques are Monte-Carlo localization and SLAM wherein the environment is assumed to be static with global localization.

Getting a robot function against gravity is quite complex. The choice of magnetic adhesion for the autonomous board-cleaning robot harnessing the board's ferromagnetic attraction makes the system simple, lightweight, and energy-efficient. Further, as the chassis of the autonomous board-cleaning robot is small it can be 3D printed conveniently. Belt drives with magnetic tapes are the preferred locomotion unit over the wheels to increase the surface area of magnetic attraction. The robot weight estimation is important. If weight force is greater than the adhesion force, the robot will fall. There is no safety device designed if in case the robot loses adhesion. The equations show one hundred percent adhesion, but this can be confirmed only with practical implementation. The use of a simple sensory unit for obstacle detection and robot position estimation reduces the complexity of data reading. Rechargeable batteries are preferred for power supply.

Further, the autonomous floor cleaner and board cleaner must be integrated into one system for simultaneously floor cleaning and board cleaning. This can be done using a simple

4-DOF robotic manipulator wherein the manipulator picks and places the board cleaning bot on the board and back on the platform after the completion of the task. Accuracy and precision are not of much importance unlike the industrial manipulator, which also reduces the cost of manipulator implementation.

Robustness, safety, lightweight and cost-effectiveness are the keys for successful implementation of the robot system. Since the area of application of the project is school, appearance and aesthetics of the robot are of much importance. The work has shown that there is a great potential to bring autonomous cleaning robot to schools. The implementation of autonomous service robots to school open new doors of the school to kids. Constant interaction with autonomous robots can ignite innovative ideas among children.

6.1 Future work

Since this is a proof of concept, the road for practical implementation has many stops. The safety concerns of the autonomous board-cleaning robot in terms of a safe and reliable attachment must be worked upon. The motion control methods and graphical user interface are key design requirements for practical implementation. The next stage of this work must focus mainly on developing path planning algorithms. Programs must be developed to establish collaboration between autonomous robots. Use of cameras and machine vision techniques for path planning will improve the mapping techniques for autonomous robots.

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