AUTOMATED SHOPPING CART

A Final Year Project Report

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

by

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ABSTRACT

The project follows developing a shopping cart, a robot, that can follow a certain path once defined to it. The path can be obtained through different ways, either directly defined in coordinates, or from image, from map reference. The path following mechanism involves running the robot in a steering system that overcomes all the difficulties faced in automated steering. The project goes through finding a proper torque for the cart to run smoothly, and without any jerks. Using principles of mechanics, and kinematics. Then choosing proper steering mechanism that can be implemented for the robot control on the software, and can be modeled easily in kinematics as well as inverse kinematics. Then determining the radius of turn, and whether it is small enough to be used inside a shopping store. Then finally manufacturing the cart and placing the motors and sensors in place, and write the software able to guide the robot through the path.

ACKNOWLEDGMENTS

It was an honor to work under the supervision of the leading face of robotics and artificial intelligence in South Asia, Dr. Yasar Ayaz. Without Dr. Ayaz's guidance throughout the project, we would definitely have been unable to complete it before the deadline. Despite his busy schedule and many commitments, he gave us more than enough time for the fulfillment of this project. Here, the special mention to our committee member, Mr. Hamza Asif is quite necessary for his presence and availability through every single phase of the project from the start till the very end. Mr. Asif is very approachable and this quality of him led us to being under his supervision all the time. The contributions made by Dr. Jawad Khan are also commendable. Dr. Khan specializes in mobile robotics and his guidance was very necessary for the completion of the project. The efforts made by Mr. Abdur Rehman, our FYP coordinator, are also acknowledged. Lastly, SMME deserves the praise for the working environment which it provided throughout the completion of the project.

ORIGINALITY REPORT

We hereby declare that no portion of the work of this project or report is a work of plagiarism and the workings and findings have been originally produced. The project has been done under the supervision and guidance of the supervisor and has not been a support project of any similar work serving towards a similar degree's requirement from any institute. Any reference used in the project has been clearly cited and we take sheer responsibility if found otherwise.

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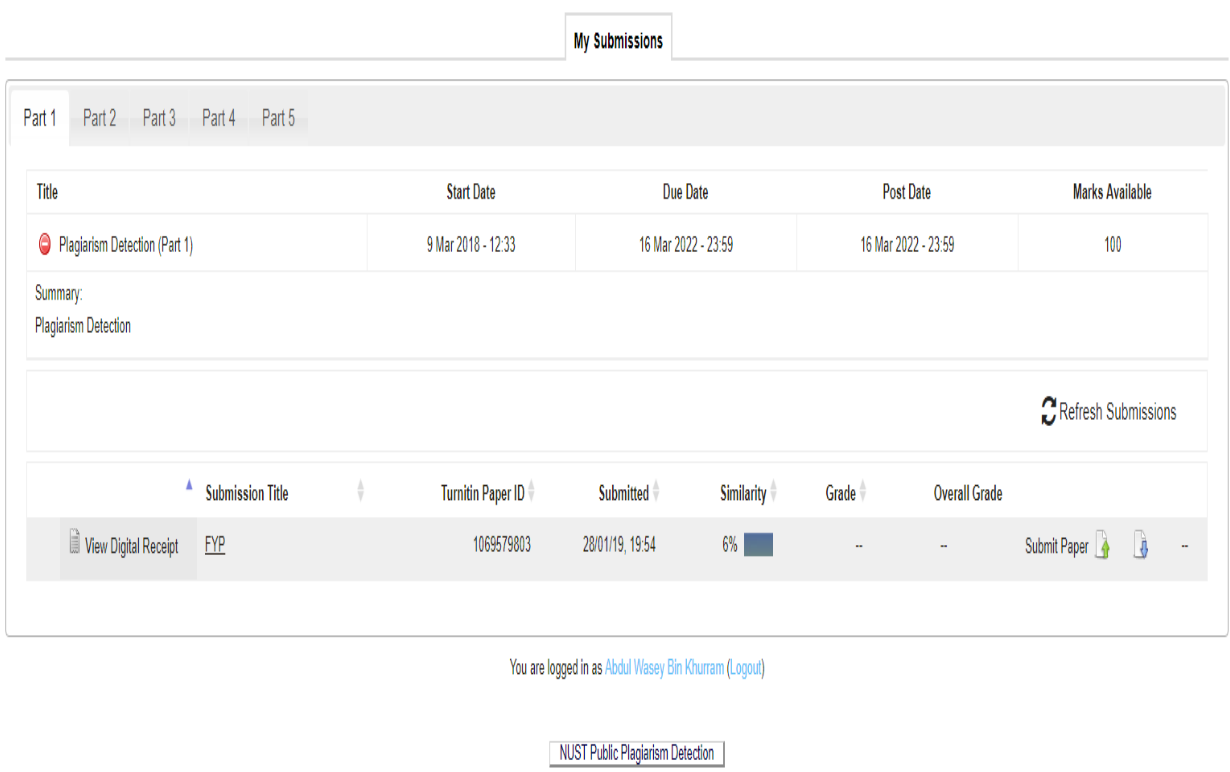

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ABBREVIATIONS

NUST	National University of Sciences and Technology
AC	Alternating Current
DC	Direct Current
SMME	School of Mechanical and Manufacturing Engineering

NOMENCLATURE

F	Force
R	Rolling resistance
r	reaction force
l	distance from front wheel
h	height of center of gravity
m	mass
α	inclination
V	Velocity

CHAPTER 1: INTRODUCTION

The motivation of work, problem statement and objectives of the project are detailed below.

1.1 Motivation

Robots have become an integrated part of our society in the modern era. The need of automation is continuously increasing for the human comfort and ease. The search of man for his facility and to save his time has gradually set his direction towards manufacturing and programming of robots as assistance to him, so that he might not put much effort in things which can be done with lesser time and effort through automation and robotics.

The automated shopping cart is also a link to the search of man for his ease during shopping at a grocery store or a mega mall where he has to push and steer a rolling cart throughout his shopping time.

Conventionally, a customer at a shopping mall takes a manual four caster wheeler shopping cart and push and steer it throughout his expedition to the shopping mall as it becomes heavier and heavier on its way. The automated shopping cart not only finishes the need to push it all around the shopping mall but can also serve as a guide to the human being through its pre-defined path following feature as it ‘knows’ where the required items are, in a shopping mall which are needed by the human being. The data of a certain shopping mall can be stored in the shopping cart including the quantity and the exact location of the goods available in the market. This can then be utilized by the customer if he is new to that shopping mall and this function as a whole can save much time for the customer. Even for the older customers, it can save time by choosing the shortest path in the mall to the required goods.

1.2 Problem Statement

The objective of the project is defined as:

"Building an automated shopping cart that should be able to follow a path in an environment, once the path is defined to it."

1.3 Objectives

The above problem for the automated shopping cart under consideration can be solved by breaking it down into the following three main objectives.

- Mechanical Model
- Instrumentation and Electronics
- Kino-dynamics and Path Following

1.3.1 Mechanical Model

In mechanical model, the mechanical aspects of the project are undertaken for consideration and working. This includes the design and model of the shopping cart in modeling software such as Creo or SolidWorks. Also, it includes performing different analysis on the finalized model including stress analysis and vibrational analysis and ensuring its stability for the extreme cases of unbalanced weight distribution on the cart or movement of the center of gravity due to the mentioned reason.

Torque requirement is also found for the mechanical design part as of how much force and speed (in RPM) is required by the motors for the cart to move in a normal way.

1.3.2 Instrumentation and Electronics

Instrumentation and electronics include all the circuit and sensor requirements of the shopping cart for its automation. This includes the use of the micro-controllers including arduino and raspberry pi and the sensors including SONARs and camera used for vision. Circuit design incorporates the motor control system including the use of H-Bridge and other minute complexities for the required output. Display screen for the interaction of robot with the customer is also included in this category.

1.3.3 Kino-dynamics and Path Following

This kino-dynamic model includes the robot's stability in moving and maneuvering. It deals with the limitations related to the Newtonian physics of the shopping cart including the equations of motion and resistances including all the frictions and slippage. The path following part of the objective includes the software implementation in the raspberry pi and arduino for the cart to move perfectly on the required path with no deviations from the original path.

CHAPTER 2: LITERATURE REVIEW

The robots which can move or is capable of locomotion is known as a mobile robot. A mobile robot has far more complexities than a fixed robot as it has to be aware of all of its surroundings and react to the environment according to it. This includes many small systems and controls. Some of which are detailed below:

2.1 Movement

The first and the very basic concept that is to be fulfilled by the mobile robots is its movement. For the correct steering and speed of a mobile robot according to the amount of weight that it has to bring along, an ideal motor and its assembly is required which is not only able to drag all of the weight that is carried by that mobile robot but also caters all the frictional forces and resistances that are offered by the environment. For the purpose DC motors are used because an AC power supply cannot be provided to a mobile robot as it is continuously in motion.

There are different types of DC brushed motors that can be used for the purpose such as:

- Permanent Magnet DC Motors
- Series DC Motors
- Shunt / Parallel DC Motors
- Compound DC Motors

2.1.1 Permanent Magnet DC Motors

A field flux is produced by a permanent magnet in this type of the DC motors. It provides a high starting torque but it remains limited afterwards. Hence, it is used in applications which requires low horsepower.

2.1.2 Series DC Motors

A series DC motor has its field wound by a large wire through a few turns which contains the full armature current. The starting torque of these types of motors are typically very large but it comes with some setbacks which includes non-regulation of speed and being damaged by no load conditions.

2.1.3 Shunt DC Motors

Also known as parallel DC motors, shunt DC motors contains the field connected in parallel with the armature windings. These motors not only offer great speed regulation but also the simplified reversing controls.

2.1.4 Compound DC Motors

The compound DC motors offer a separately excited shunt field like the shunt DC motors. It provides great starting torque but may show a little inability during variable drive applications.

Each motor has its own advantage and disadvantage and can be used for different applications ideally for which the other type is not ideal.

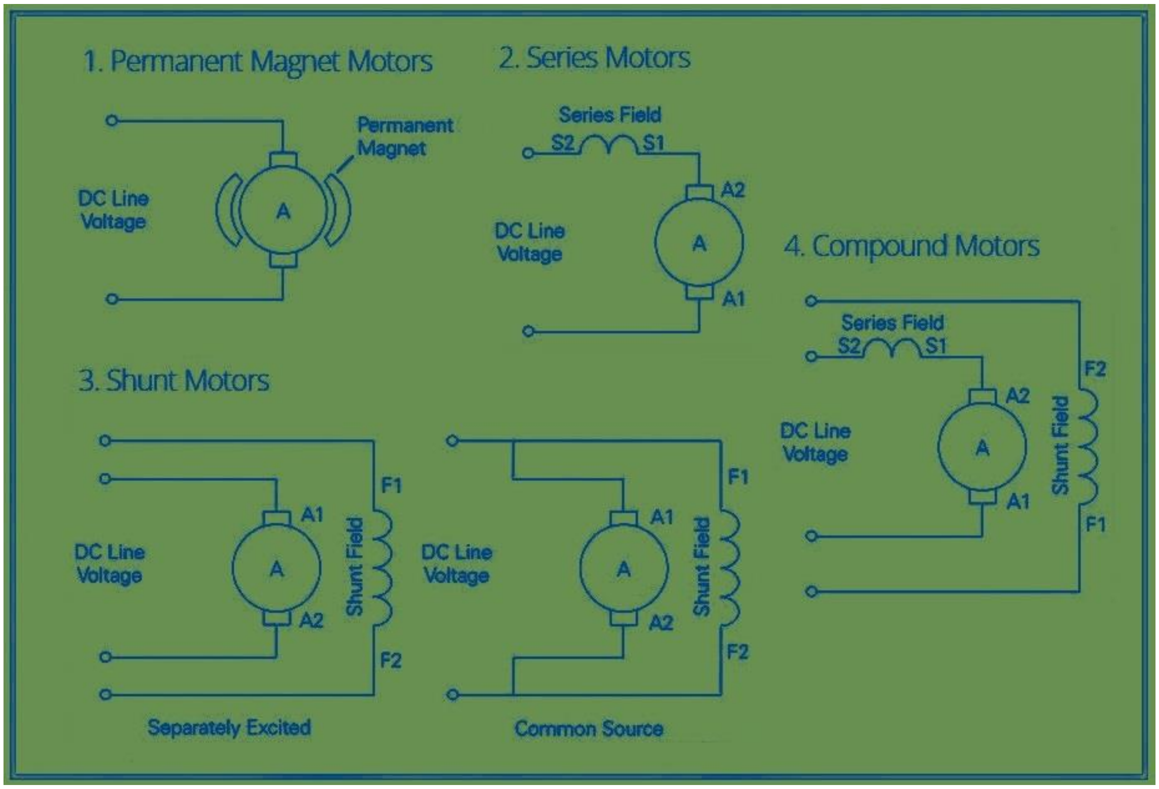

Figure I - Types of Brushed DC Motors

2.2 Navigation

The question by a mobile robot, "Where am I?" forms the basis of the majority of the tasks performed by a mobile robot. To achieve the answer to that question, four building blocks of navigation should be achieved.

- Perception – Use of sensors to extract a meaningful data

- Localization – Determination of position of robot in the environment
- Cognition – Response of robot to achieve its tasks
- Motion Control – Control of the motors to achieve its trajectory

There are several methods to achieve these building blocks. A satisfactory localization system uses multiple sensors and employs the robot odometer, a digital compass with an integrated tilt sensor, a global positioning unit and a camera mounted on a pan-tilt head in two complementary ways.

- The open localization method – Uses odometer, digital compass and GPS by extended Kalman filter
- The visual localization method – Depends heavily on the camera using intense computational power by matching the image with a simple or compact model.

2.3 Kinematic Model

The kinematic model defines the theoretical aspects of the path following of the mobile robot. The kinematics of a differential drive robot described in the inertial frame {X_i, Y_i, θ} is given as:

$$^{I}\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$

Where $\dot{x}\ and\ \dot{y}$ are the linear velocities in the direction X_i and Y_i of the inertial frame.

2.4 Batteries

For the power supply of a robot, DC batteries are used instead of AC power supply because the robot has to be continuously in motion and a wire cannot be suspended with it at all times.

Batteries can be of 6V-48V depending upon the requirement of the potential difference value by the motors and other instrumentations. Its capacity can be measured in Ampere-hour. Batteries can be attached in series to acquire a certain value required by the motors. For example, for the potential difference requirement of 24V, two batteries of 12V each can be connected in series by joining the negative pole of one battery directly to the positive pole of the second battery.

The main constraint in deciding the capacity of the battery is its weight. Batteries are immensely heavy and cannot be compromised with the capacity of the battery. Weight of the mobile robot is directly related to the torque requirement which in turns requires larger motors.

2.5 Sensors and Micro-controllers

2.5.1 Sensors

Any mobile robot which is built to fulfill a requirement or a goal requires different and specific to that problem or goal sensors. Other than those, some universal or general sensors are also used typically in almost all of the mobile robots.

Some sensors are:

- Ultra-Sonic Sensors - SONARs
- Camera – Vision
- Wireless Beacons

2.5.2 Micro-controllers

The sensors are then controlled by some microcontrollers like Arduino UNO or Arduino Mega which are as a whole controlled by another microcontroller such as a Raspberry Pi.

Mobile Robots are usually equipped with a combination of microcontrollers including Arduinos and Raspberry Pies. These microcontrollers are operated at a very low voltage and should not be exposed to the batteries operating motors directly. For the purpose relay system is used or another set of low voltage batteries is used.

2.5.3 Other Instrumentation

Apart from sensors and micro-controllers, some other equipment is also used for the instrumentation to work efficiently such as:

- H-Bridge
- Relay

CHAPTER 3: METHODOLOGY

3.1 Weight Limitation

The first step was to decide the amount of products that the cart will be carrying in it. So that the total weight of the cart can be determined. It was decided to limit the total weight to 50 kg. The weight of the cart itself was 12 kg and the added equipment took it to near 25 kg. A limit of 15 kg will then be specified, which will leave 10 kg in spare as factor of safety.

3.2 Torque Requirement

Determining the equipment power in designing the wheeled robot, is simply just designing a vehicle for certain target values and determining the required forces and torques. Where the engine torque is replaced by motor torque and mechanical linkages are simplified by using electronic equipment. For example, instead of a gearbox and differential for two wheels on same axes, two separate motors are used in parallel, and are controlled by software. To determine the motor torque, it is necessary to determine the total tractive force on the driving wheel. For a simple vehicle model climbing on a certain angle, the active and reactive forces are taken according to this diagram [1].

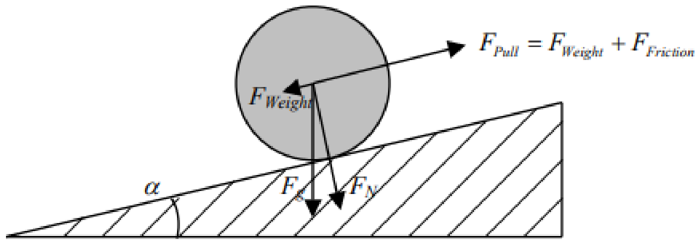

Figure II - Simple Vehicle Model

The tractive force is given as

$$F_{pull} = F_{friction} + F_{weight}$$

Which simplifies into

$$F_{pull} = mg(\sin\alpha + \mu\cos\alpha)$$

The next step is to introduce the rolling resistance for each pair of wheels. Since we are following a six wheel model (explained later in 3.4), there exist 3 rolling resistances. So the equation becomes

$$F_{pull} = mg(\sin\alpha + \mu\cos\alpha) + R_f + R_c + R_r \quad \ldots.. \text{ (A)}$$

Where the subscripts *f*,*c* and *r* represent front, center and rear respectively. For the rolling resistance to be determined, it is necessary for the amount of weight acting on the relevant pair to be found. Which brings us to our model. The force model then becomes:

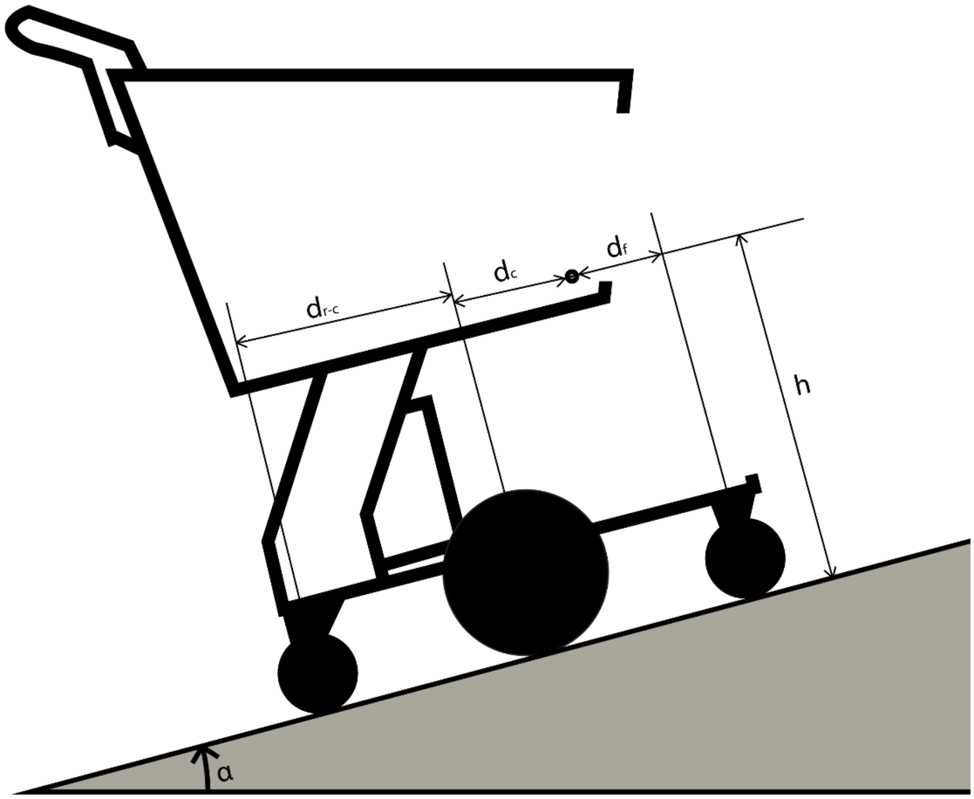

Figure III- Cart Climbing Model

Since the user of the cart is not expected to have knowledge about mechanics, we cannot be certain as to where would the center of gravity lie. For countering this uncertainty, we use the worst case and assume the center of gravity to almost at the edge of the compartment, and then perform our calculations.

To find out the weight acting at each of the wheels, we use statics and determine the moments about front, rear and center wheels [2]. The equations are:

$$W\cos\alpha \times d_f + W\sin\alpha \times h = r_r l_r + r_c l_c$$

$$W\sin\alpha\ \times h + r_f l_c = W\cos\alpha \times d_c + r_r l_{r-c}$$

$$W\cos\alpha \times d_r = r_f l_r + r_c l_{r-c} + W\sin\alpha \times h$$

Where l is length measured from front wheel, which means $l_c=d_f+d_c$, $l_r= d_f+d_c+d_{r-c}$ and $l_{r-c}=d_{r-c}$

When solved simultaneously for reaction forces r, we get :

$$r_c = W\left[\frac{\left(d_r l_c - d_c l_r - d_f l_{r-c}\right)\cos\alpha + h l_{r-c}\sin\alpha}{l_{r-c}(l_r+1)}\right]$$

$$r_f = W\left[\frac{\left\{d_r(l_r+1) + d_c l_r + d_f l_{r-c} - d_r l_c\right\}\cos\alpha + h(l_{r-c} - l_r - 1)\sin\alpha}{l_r(l_r+1)}\right]$$

$$r_r = W\left[\frac{\left\{d_f l_{r-c}(l_r+1) + d_c l_r l_c + d_f l_{r-c} l_c - d_r {l_c}^2\right\}\cos\alpha + h\{l_{r-c}(l_r+1) + l_c\}\sin\alpha}{l_r l_{r-c}(l_r+1)}\right]$$

The rule of thumb for selecting motors is to use $\alpha=15°$ $\mu=0.05$ [1].

The values for our model in *cm* are given. Note that the center tires are placed at exact center such as $l_r=l_{r-c}$. Explained later in 3.4

$h=$ 46.3

$l_{r=}$ 54.7

$l_c=l_{r-c}=d_{r-c}=$ 27.35

$d_f=$ 11.2

$d_c=$ 16.15

$d_r=$ 43.5

wheel diameter= 22

Putting these values in the equations above, along with mass of 50 kg, we get the reaction forces at wheels, and thus the weight acting upon them. Using the rolling resistance coefficient of f=0.05 for rubber central wheels [3], and 0.1 for front and rear plastic castor wheels [4] and the relation R = r x f, all these values in equation A gives us the traction force as

$$F = 196.117\ N$$

From wheel diameter, we have radius of 11 cm, which then gives us the required torque as

$$T = F\ \times radius = 21.57\ Nm$$

Which is for both wheels, thus the torque required on one motor is half of this, which is almost 11 Nm.

3.3 Steering

For the cart to be able to move in small area, a small radius of turn is desirable. Such is not achievable in using Ackerman's steering mechanism, so we resort to the differential drive steering, in which the driving wheels are given different speeds, and the speed difference determines the rate of turn as well as the radius of turn.

3.4 Radius of turn

First the coordinate system of the robot and the universal system are established, then kinematic analysis is done upon them to determine the radius of turn and turn rate.

For determining the radius of turn, we need to find out the instantaneous center of curvature ICC. Reference image is given [5]

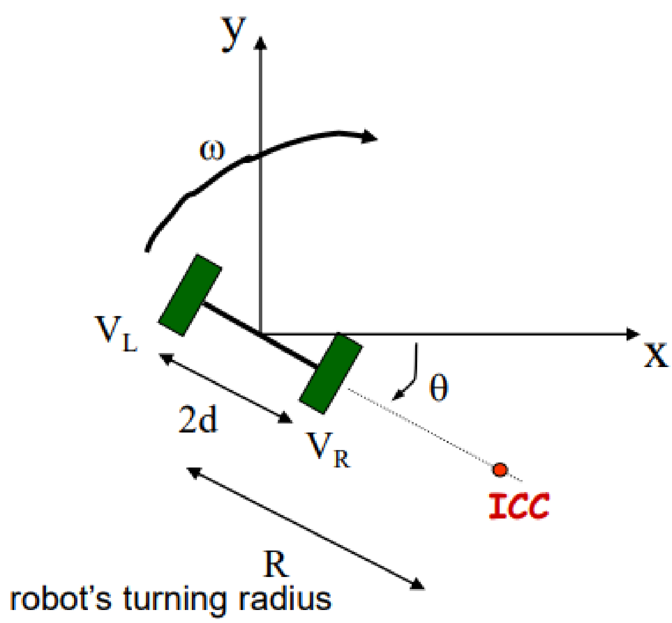

Figure IVdifferential drive parameters

To achieve the no slippage condition, it is necessary that the ICC lies on the same axis as the driving wheels. This means both wheels are turning at the same angular velocity. Note that this is not the wheels' rotation speed, but the rate at which the wheel moves around ICC. This condition gives us the information to write our initial equations of motion:

$$\omega(R + d) = V_L$$

$$\omega(R - d) = V_R$$

Solving these two gives us the location of ICC as

$$R = d\frac{V_R + V_L}{V_R - V_L}$$

And the overall velocity of the robot becomes

$$V = \frac{V_R + V_L}{2}$$

Where the Vx and Vy can be found out using the angle at the given time frame. Where angle is calculated by

$$\vartheta(t) = \int \omega(t)dt$$

In the condition where both the wheels have equal and opposite velocities V, the term V_R+V_L takes the form V-V=0. Which means R=0, consequently the radius of curvature lies between the two wheels, thus achieving a small radius of turn.

But this was the radius of turn on just 2 wheels. The total radius of turn becomes different on 4 wheel, or more. The radius now incorporates the diagonal of the polygon made by the wheels. The easiest way to reduce the radius, is to reduce the length of diagonal.

If the castor wheels have already adjusted, the resulting radii of turn are shown for two configurations.

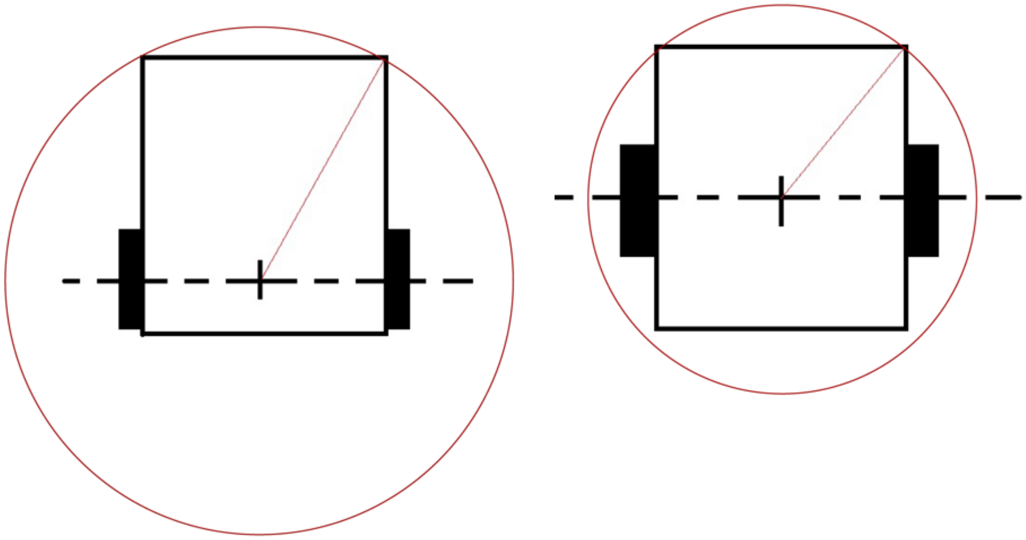

Figure V- Demonstration of diagonal relation with turning radius

The shortest diagonal, and hence the radius, is possible if the differential drive wheels are placed in the center of the vehicle. Therefor the approach to place the driving wheels in center was taken. But such configuration will introduce instability of the center of gravity shifts beyond both the wheel pairs, hence the 6 wheel design, with 4 castors and 2 fixed drivers.

3.5 Kinematic Model

The kinematic equation of robot is described as [5]:

$$\begin{bmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$

Where ρ, α and β are the elements of polar coordinate system defined on the robot's reference, and ρ is the distance between the wheel center and the target location.

Using the control law [5] the closed loop control equation takes form

$$\begin{bmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} -k_\rho \rho \cos\alpha \\ k_\rho \sin\alpha - k_\alpha \alpha - k_\beta \beta \\ -k_\rho \sin\alpha \end{bmatrix}$$

This will be used in future work when programming the robot.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Model

Figure VI- Model

4.2 Motors

For the robot to be able to lead, it has to be first able to drive. The first thing is to be able to carry the load with it. That's why the first step was to determine the required torque, which turned out to be

$$T = 11\ Nm$$

For each driving motor, when used two at a time. The motors decided were geared compound DC motors. Dc motors are easy to control and provide high rpm at stable current values. When geared, their rpm is lowered down and then a good torque is obtained from them. The motors procured have the following details.

Table 1 Motor properties

rated torque	3.5 Nm
rated rpm	3350
gear ratio	1:15
torque after gear	52.5 Nm
rpm after gear	223.3
Operating Voltage	30 V
Nominal Current	4.9 A

Since the amount of torque provided by this motor has a very decent amount of factor of safety, it is decided that the motors will be operated at a lower voltage of 24 Volts. And also because two motors will be used, this will be compensated for. The other factor of consideration is the motor power. The required power is determined as

$$P = F_{pull} \times v$$

When the velocity is that of an average human at 1.4 m/s, the required power reaches 270 W at worse conditions.

Each motor has a power rating of 95 W at nominal and 170 W at peak, which is expected to be more than enough.

In already existing robots, the main thing that differentiates the motors employed, is the type of accuracy required in motion. Stepper or servo motors offer high accuracy feedback about the angle through which the motor has turned. Such accuracy demands higher economical cost as well. The tradeoff was easy because the extent of accuracy required by our project will be easily achieved using laser or optical encoders.

4.3 Batteries

Since this project involves the development of a prototype, the batteries acquired are of small capacity. Two batteries each of 12 volts and 4 Ampere-hours are acquired. They will be used in series to obtain the 24 volts voltage for driving the motors. A separate battery will be used to power the controller and other peripherals.

The most common battery type used in mobile robots is 12 or 24 volts. The main reason is the weight it adds onto the robot. A very powerful motor may exist that required 48 volts, but is not used because providing a 48 volts battery adds a lot of weight to it. That is why the developers tend to use less voltage batteries and motors.

4.4 Steering Mechanism

The next step was steering mechanism, as described in section 3.3 the decided steering mechanism was the differential drive system. This is the go to system for most mobile robot applications and is not only just easy to use but also has a small radius of turn.

The minimum radius of turn for the vehicle was determined to be

$$R_t = 32.8\ cm$$

Which is the distance from wheel centers to the diagonal castors. The lengthier diagonal describes the radius

The other advantage of the differential drive system is that the mechanics become simpler, because the complexity in controlling the motion are solved in the programming rather than mechanically altering the product. These reason made it to be chosen over the tricycle and the Ackerman arrangement.

4.5 Sensors

The sensors used are SONARs and a camera for vision. There are two types of sonars: low frequency and high frequency. High frequency SONARs were decided due to their higher accuracy. Camera is necessary to determine the robot’s position in inertial frame of reference. Encoders are used to determine the total turned angle for wheel.

4.6 Motion

The next step involves making the controller for the motors for moving and steering. For speed and direction control two H bridges are implemented. The bridges will be connected directly to an Arduino Mega microcontroller. On equipment level Arduino will be used for control and input gathering. Laser encoders will be implemented on each wheel and will be connected to the Arduino for knowing the current wheel speed.

4.7 Intelligence

The current project represents the path following mechanism of wheeled robots through predefined paths in digital soft format. This requires a mean to represent the path to the robot. For such purpose a grid was defined as a function. Following is the image of the grid.

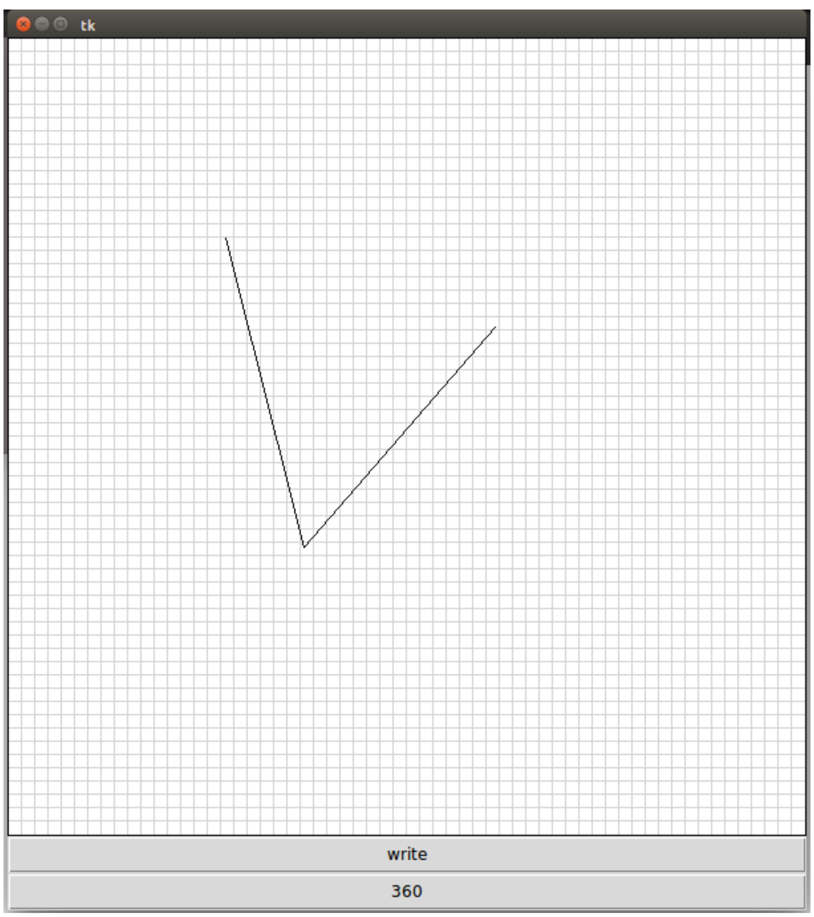

Figure VII- Grid

All this AI will be implemented on a higher level microcontroller. The device of choice is a Raspberry Pi 3 B+ with the OS Raspbian installed on it. This grid converts the drawn figure into section of small lines and turns, which is fed to the Arduino to control the motors in a set of sequences based on the path drawn. This can be useful in future advancements as the layer of path defining can be done through another independent AI that can then use the path extraction feature and implement on a predefined map.

Our current project was limited to cornered paths as the mathematical models defining functions for curvatures require instant feedback which can become very costly as this requires internal GPS systems.

The control software for robot will be ROS (Robot Operating system). The camera will be coupled directly with the Pi, while the others sensors will send the information to the Arduino. ROS Serial will be used to connect Arduino to the Pi, and it provides the control interface for Arduino from within the Pi.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

This report covers how the mechanical model of the robot was established, and how will it be used in future, when programming the robot. The theory of road vehicle in general is used to first determine the requirements of the robot as a vehicle. The principles of statics and dynamics are used in combination with knowledge of physics to determine the motor torque required to run the cart, given a specific weight on it. Then the information was used to purchase the motors along with its batteries and sensors. The kinematic equations for robot controlled were looked at, which will be further used in the mentioned software to describe to the robot its path, and how to follow it.

5.1 Application and Uses

The automated shopping cart is capable of path following which can be used in any mega mall or shopping / grocery store where a new customer is unfamiliar with the whereabouts of goods he needs. The cart can guide him to his required area by the application of its path following feature. The data of a certain shopping mall of the amount and exact position of each item can be stored in all the carts which can be updated through a central control system. Even for the older customers, it can guide you through the shortest path available and save time of people in both the scenarios.

Moreover, other than shopping malls, this mobile robot finds its application at airports and other luggage carrying places, even for simple hospitals, schools or offices.

5.2 Future Advancements

Next step in motion control is determining the present location of the robot. For this purpose the proposed method to be used is vision. When the occupancy grid is fed to the robot, it will use the camera in combination with sonars to determine its location on a provided map. The allothetic and the idiothetic information will be compared and run through a Kalman filter for deciding the instantaneous path.

Finally, when the path is defined it can be divided into lines and arcs for the robot, based on the map information available of the occupied and available cells in the environment.

The automated shopping cart is an upgradable project and several features can be added into it for the human ease and market production cause. Some of the advancements that can be looked into for this cart are:

- Human Following Mechanism
- Obstacle Avoidance Mechanism
- Human User Interface
- Voice Control and Interactive interface

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