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Rover wheel mobile robot assisted by vehicle dynamics

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Abstract

This project mainly aims to propose an educational approach in apply the vehicle dynamics in the field of Wheeled Mobile Robotics (WMR), which has lots of applications and visions of development around the world, this project would be a very helpful insight to make. The statement of the desired results behind the project is to apply various educational experiments involving the act of supporting the designed vehicle with or without a control algorithm of vehicle dynamics principles and equations then compare the results and show the difference between the two cases. Furthermore implementing a given number of control logics and expressing it's responses; to find the best optimal output for the system to be applied on a real-time application leading to the widening and understanding of the advanced engineering concepts of this project, and to teach more advanced engineering concepts more closely related to the students educational field, also recognize the change such an application can make and accomplish when it's supported with the right math. Were the experimental results at the end illustrated the differences between the three desired modes, and confirmed the fact that the more the value of the acceleration the more the slope increases and vice versa.

ملخص

يهدف هذا المشروع بشكل رئيسي الى القيام بعمل تطبيق منهج دنميكا المركبات في مجال الروبوتات المتنقلة بالعجلات من اجل اهداف تعليمية وبالاخص في حالة مركبة روفر التي تتوافر بشكل عام على انها مركبة مصنوعة من الالمنيوم للاستخدامات الترفيهية في الهندسة، والتي لديها العديد من التطبيقات ومجالات للتطوير عليها حول العالم ، فسيكون شيئاً جيداً وهدافاً للمساعدة في مثل هذا النوع من المجالات، إن النتائج المرجوة من وراء هذا المشروع هو تطبيق اجراءات مختلفة باستخدام نظام التحكم بالمركبة على اساس المدخلات الواردة من مختلف اجهزة القياس واجهزة الاستشعار على المركبة ، ثم محاكاة نواتج النظام للعديد من التطبيقات وذلك من خلال عمل محاكاة لعمل المركبة دون استخدام قوانين ديناميكا المركبات ورؤية كيفية تصرف النظام ، ثم بعد ذلك رؤية كيفية تصرف النظام بتطبيق قوانين ديناميكا المركبات عليه ، ثم المقارنة بينهما من اجل إيجاد افضل أداء ممكن للمركبة و التعرف على التغيير الذي يمكن لدنميكا المركبات تحقيقه عند تطبيقها في هذا المجال، حيث بينت النتائج العملية الفرق بين الثلاثة حالات المنوي تشغيل النظام بها، وأكدت على حقيقة أنه كلما ازداد التسارع كلما زاد ميل المنحنى المرصود والعكس صحيح.

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Chapter 1

Introduction and background

1.1 Introduction

1.2 Recognition of the Need

1.3 Chapters Overview

1.4 Project Management

1.1 Introduction

In the recent years, Wheeled Mobile Robots (WMR) have had a massive evolution of interest in them and now a days mostly plays a role in every field humans think and try to develop, from military sides, scientifically exploration vehicles, aero spacing and education to the dominancy in the entertainment field with its wide spreading in the Lego games and a lot of other sides and examples aroused the popularity of it and gained much more interest in it from many young engineers all around the world, to study, design, create and get involve in a lot of various competitions around the world related to the control of WMR and challenges.

One of the most attractive engineering concepts and educational material that mainly took us to think and do this project was vehicle dynamics, due to its wide range of analysis and strong concepts of developing vehicles. So the approach is to support a WMR with these engineering concepts of vehicle dynamics. By looking at the field of WMR, it's noticed that there are a lot of types, shapes and categories of sorting them, most are known as intelligent WMR and non-intelligent WMR, the main difference between both those two categories is sensors and intelligent control.

In order to apply and experiment the vehicle dynamics algorithms and concepts in the field of WMR, it was first needed to design an appropriate vehicle to start with, which in the case of this project is Tetrix Rover Kit, which is a Lego robotics kit with a common practice of having the students assembling it's components and operate it as a remote controlled vehicle for the enrolment in engineering robotics challenges such as World Robot Olympiad (WRO) and others.

1.2 Recognition of the Need

The scope of this project is beyond taking the kit and use it not only as a remote controlled toy, but to teach more advanced engineering concepts more closely related to the students educational field and widening the understanding of what happens when vehicle

dynamics is applied or used in such a field and what serious enhancement in the performance of the WMR that might happen and be achieved thereafter.

1.3 Chapters Overview

Chapter One mainly explains the problem and introduces why it was selected and proposes the methodology of solution, meanwhile chapter Two focuses on the literature review and a brief historical background about the used vehicle in the project and some other factors, later in the chapter a conceptual design is made with the mention of the used components and a simple principle of connection and other factor. The followed methodology and modelling and the mathematical approaches done are mentioned and justified in chapter Three. Later on chapter four presents the control principle of the vehicle and what modes to operate in depending on vehicle dynamics algorithms and what concepts made in chapter Three before. Chapter five illustrates the data collected in the experimentation process for the project and the proof of principle. At last chapter six shows what I concluded at the end of the project.

1.4 Project Management

1.4.1 Time Table

Table 1: Timetable for the Project time (Weeks) in the First Semester:-

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Selecting the project idea																
Data Collection																
Conceptual Design																
Modelling and Control																
Documentation																

Table 2: Timetable for the Project time (Weeks) in the Second Semester:-

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Collecting the Components																
Verification and Control																
Experimental Work																
Documentation																

1.4.2 Cost Table

Table 2: The budget of the project:-

Cash Flow	Description	Number of Units	Unit Cost [\$]
Components of the Project	Pitsco TETRIX PRIME student Kit	1	750.00
	Arduino Mega	1	40
	6V 210RPM Encoder DC Gear Motor	2	90
	L298n Motor Driver	2	20
	Tracking Path	1	88
Total			988

Chapter 2

Proposed System Design

2.1 Literature Review

2.2 Conceptual Design and Component Selection

2.3 Component Selection

2.1 Literature Review

As it was mentioned earlier, the used vehicle for the project is a Rover Lego Kit designed and published by the Tetrrix Robotics Company. Rovers have several advantages: they examine more territory, and they can be directed to interesting features, they can place themselves in a lot of positions humans can't reach, moreover, they can advance the knowledge of how to perform very remote robotic vehicle control, which is mainly happening in nowadays use of the Tetrrix Kit of robotics[1].

A first recognition for the rover vehicle was done by Tetrrix Robotics which was mainly intended for educational purposes and competitions such as the first tech challenge which was first founded in 1989[2], and developed further more for the involvement into the World Robot Olympiad (WRO) competitions known nowadays[3].

The first Tech Challenge grew out of the existing first Robotics Competition and the IFI Robovation platform. First, RadioShack, and Innovation First collaborated to develop an improved version of the IFI Robovation kit. The kit was significantly upgraded and called the "VEX Robotics Design System"[4]. For the 2008 season Pitsco developed a platform that uses the "NXT brick" along with additional hardware and a new structural framework under the new name of Tetrrix. Using Aluminum parts that will allow participants to add Lego parts and sensors. In addition to hardware changes, the system was programmed with LabVIEW or RobotC [5].

As for the programming language mentioned Arduino is an open source computer hardware and software company, project, and user community that designs and manufactures single-board microcontrollers and microcontroller kits for building digital devices and interactive objects that can sense and control objects in the physical and digital world.

Arduino board designs use a variety of microprocessors and controllers. The boards are equipped with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards or Breadboards (shields) and other circuits. The boards feature serial

communications interfaces, including Universal Serial Bus (USB) on some models, which are also used for loading programs from personal computers. The microcontrollers are typically programmed using a dialect of features from the programming languages C and C++[6].

So it reached an acceptable level of satisfaction to be used in this project for it is universally accepted, industry recognized hardware/software scheme method, in the hands of learners.

For the use of this corner of Microcontrollers and electronics in the project, learners can learn this technology at a level suitable for them while educationalists increase the buoyancy that this instrument can convoy learners from preliminary to progressive developments, as it is happening around the world with the massive support of exponential growth of this field in today's world to reach some of the most necessary field of living and apply it in their daily life [7].

Were when it comes to the system and illustrating it form the real world to the theoretical one an accurate modelling and control for WMR relies upon the basic understanding of why it's used, what for and the study of its motion in the sight of Kinematics and dynamic models. WMRs require fewer and simpler parts than other types of robots of vehicles, and are thus easier to assemble and build, Moreover, Wheel control is less complex than the actuation of multi-joint legs for example in other category of robots, and wheels cause minimal surface damage in comparison with legged robots and other types[8].

In order to build the model and run it under experiments, kinematics and dynamics of WMR are needed to be studied and well understood, for example the concept of theoretical instruction is shown in (Fig2.1) :-

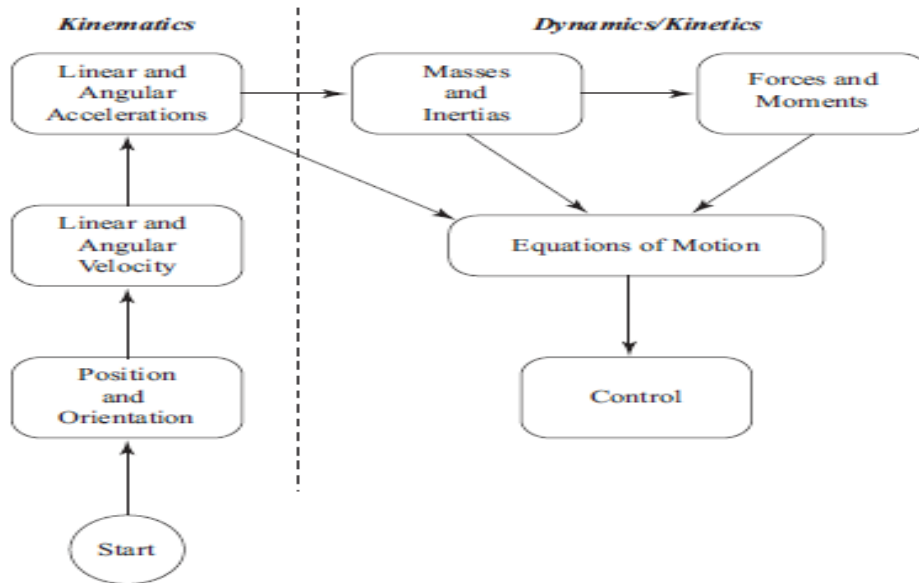


Figure 2.1: The analysis of robot dynamics and control schematic.

As it is mainly categorized the following are the main five stages needed to acknowledge the building of a WMR system:-

1. **Position and Orientation:** This module discusses points, directions, and reference frames, and how they are used to compose a description of position and orientation described by position vectors and rotation matrices. These constructs are used to build a description of the position and orientation of the robot. The design elements discussed include visualizing the workspace of the robot in order to choose the number of links and the physical layout of the robot. Constraints on the robot's kinematics are also discussed, which leads to a discussion of the interaction between motors, gears, and links.
2. **Linear and Angular Velocity:** Differentiation of position and orientation yields descriptions of the robot's translational and rotational velocities.
3. **Linear and Angular Acceleration:** The descriptions of velocity can be differentiated to obtain the accelerations needed to develop the equations of motion.
4. **Equations of Motion:** The derivation of the equations of motion shows how many of the robot components come together to produce motion

5. Control: Model based control, particularly the state space control, is discussed along with concepts of vehicle dynamics and how to integrate these two together to come out with a firm control procedure and output.

Generally when speaking about the kinematics and dynamics of WMR most of the studying field and research is about its modelling and mathematical study, the reason is for the importance of understanding of such an address, in order to be able to understand the motion and performance of the WMR and what constrains and limits it has.

"However, while the subject of kinematic modeling of WMR is well documented and easily understood by students, the subject of dynamic modeling of WMR has not been addressed adequately in the literature. The dynamics of WMR are highly nonlinear and involve non-holonomic constraints which makes difficult their modeling and analysis especially for new engineering students starting their research in this field. Therefore, a detailed and accurate dynamic model describing the WMR motion need to be developed to offer students a general framework for simulation analysis and model based control system design"[9].

As for the description of how and where the system is going to move a two methods described as follows, two types of control algorithms for mobile robots are investigated: (a) trajectory tracking, and (b) path following. In each case, a smooth nonlinear feedback is obtained to achieve asymptotical input-output stability, and Lagrange stability of the overall system. Simulation results are presented to demonstrate the effectiveness of the control algorithms and to compare the performance of trajectory tracking and path following algorithms[10].

The main known problem the vehicles suffer from in their performance on the paths followed, "there are many examples of mechanical systems which require rolling contacts between two or more rigid bodies. These include wheeled vehicles such as conventional automobiles, unconventional actively coordinated robotic systems such as planetary rovers, manipulators grasping an object , and legged locomotion systems"[11]. In this project, the focus is on systems in which the rolling contact is maintained passively through external forces such as gravitational forces. This is true of almost all wheeled vehicles[10].

2.2 Conceptual Design

It's highly needed to justify and detail the appropriate scheme describing the project and what it holds in its logic, so the next explanation of the connection of hardware, parts and software is discussed as shown in (Fig.2.2) :-

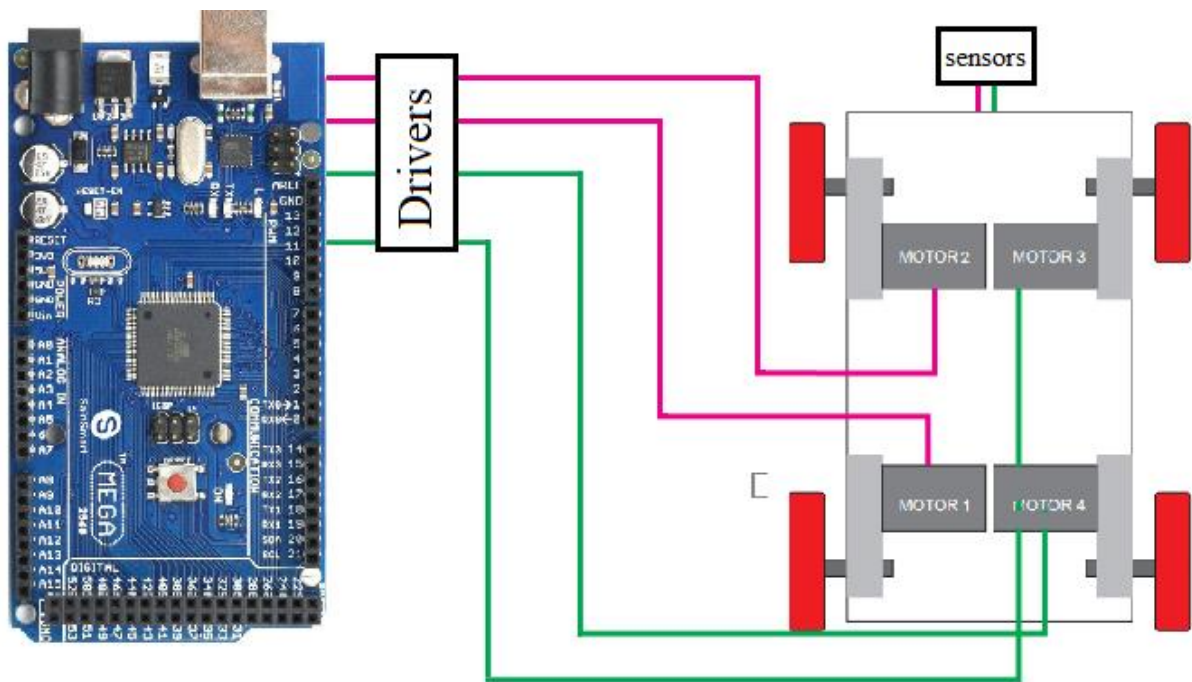


Figure 2.2: Design Scheme for the Project's 4-Wheeled WMR.

A control procedure is set to be done on the 4 wheels of the vehicle, the front two and the rear ones are connected to a DC motor block as it's seen, and the motors are actuated by the Arduino-Mega Microcontroller using a Motor Controller Board 41136 for the sensors and a L298N motor driver for the motors.

A Arduino Mega Microcontroller was used for it's wide number of Input/output pins, also for it's simplicity in programming and open source support. Moreover, it was used for it's low price comparing to other microcontrollers advised to use for this project as the NI-MyRio Microcontroller attached with the Kit of this project that worth's 500\$ more than the Arduino and does the same job

The following in (Fig2.3) is the connection of the components of the Rover WMR:-

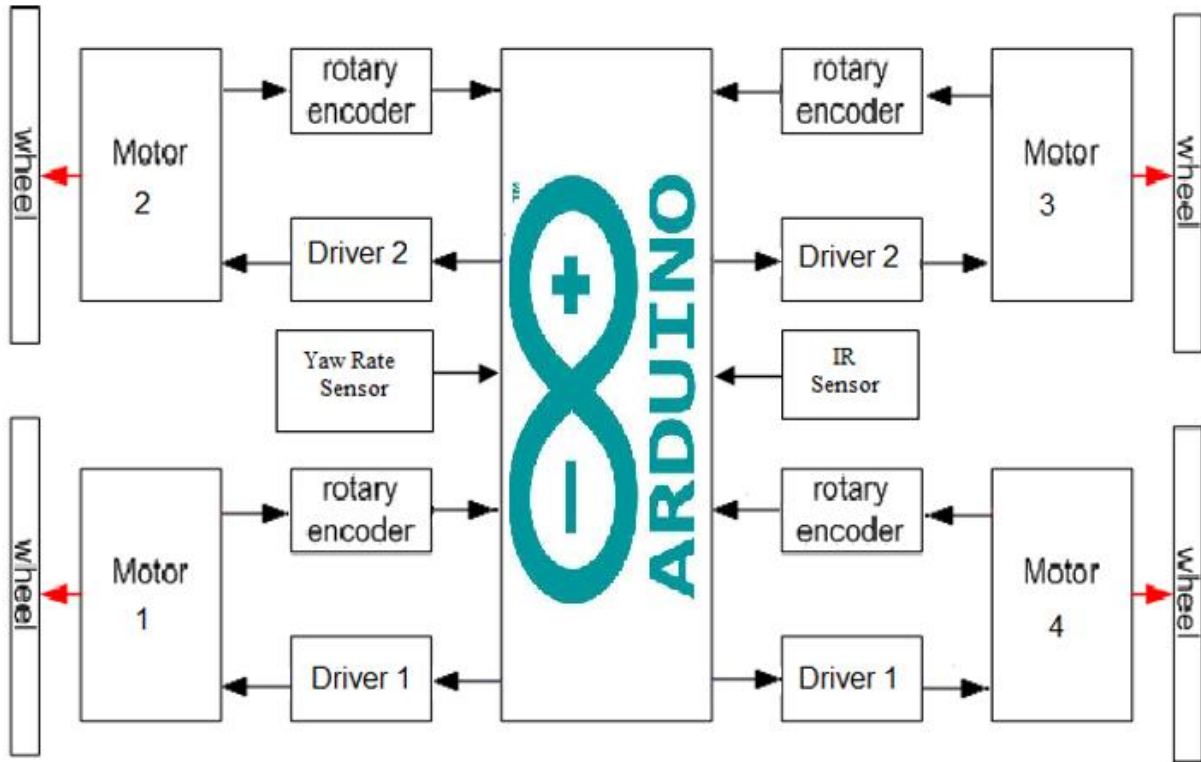


Figure 2.3: Connection Scheme for the Project's 4-Wheeled WMR.

The main control of the system is in the microcontroller shown in the middle, all the components are connected through the microcontroller's input/output ports and giving the programmed commands to the rest of the output drivers, which has the motors connected on them, the feedback of the motors' actions are coming from the four placed rotary encoders on each wheel of the vehicle, also the input signals are detected from the reading of the sensors placed on the hardware of the vehicle, which are the yaw rate sensor reading that detects the angular velocity around the vehicle's vertical axis, moreover, IR sensors are placed for any needed procedure such as line following case or any other.

The following (Fig2.4) shows the path where the vehicle will be moving on, and the experiment of modes that will be done on it; to read and achieve the results and compare it, to find what optimal output is best for the system to be set on.

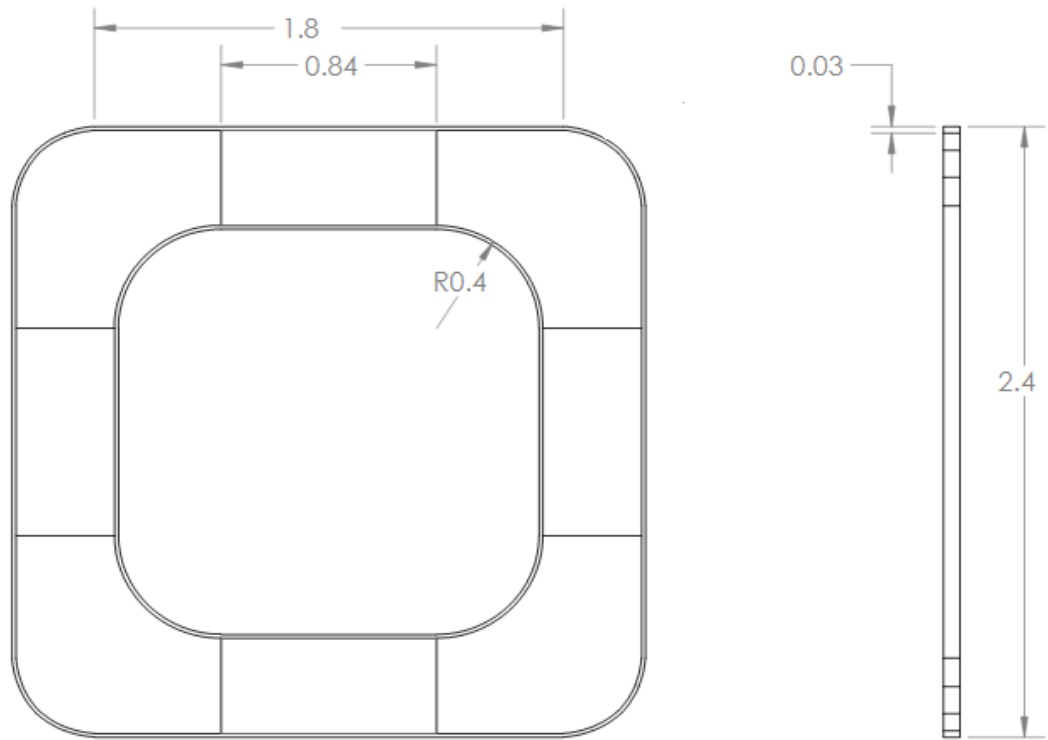


Figure 2.4: Path scheme for the WMR.

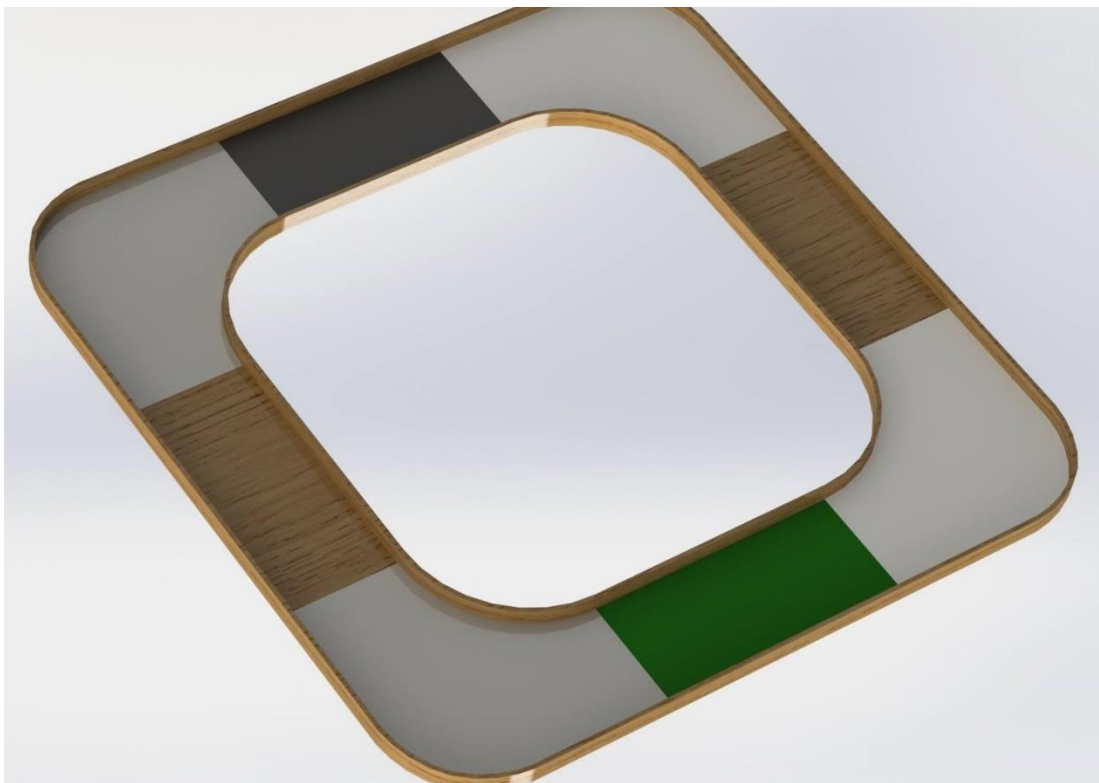


Figure 2.5: 3D Designed figure for the Track.

And the following figure is for the Actual Built Track:-



Figure 2.6: Actual Built Track for the WMR.

The path has four corners, each area of the path comes with different types of surfaces, and each one represents a different type of material for the vehicle to be running on, for example:-

The first one has a friction factor of wood, where the second has the paper type of material, so the friction factors differ and by means the forces where the vehicle will be enduring in the path will differ as well. Moreover, a grassed surface and a rubber one were added to simulate the effect of multiple surfaces and let the track be as close as possible to real time factors and parameters with no neglected effects left behind or off the table.

The following Table illustrates the friction coefficients of the designed surfaces in the track:-

Table 2.1 Coefficient of friction for the designed surfaces

Surface	μ_k
Car tire – Grass ^[12]	0.36
Car tire – Wood ^[13]	0.53
Car tire – Friction added surface ^[12]	0.67

Were it was modified that the vehicle will accelerate and decelerate on those surfaces all taken into account what choice it makes and how it affects the behavior of the vehicle.

2.3 Component Selection

Mainly the components used in the vehicle are from the Pitsco Tetrax Prime student Kit, where it already has the components coming attached in the kit's box and a couple more components were bought from outside the kit which will be mentioned as following:-

Components:-

1. Arduino Mega Microcontroller: used to control the whole procedure of the inputs and manipulate the performance of the vehicle according to the needed adjustments and required output and it can be seen as shown in fig (2.2).
2. L298n Motor Driver Board 41136: used to actuate the motors connected on the vehicle wheels and to make the commands easier to control between the microcontroller and the motors, the following figure shows the driver board:-

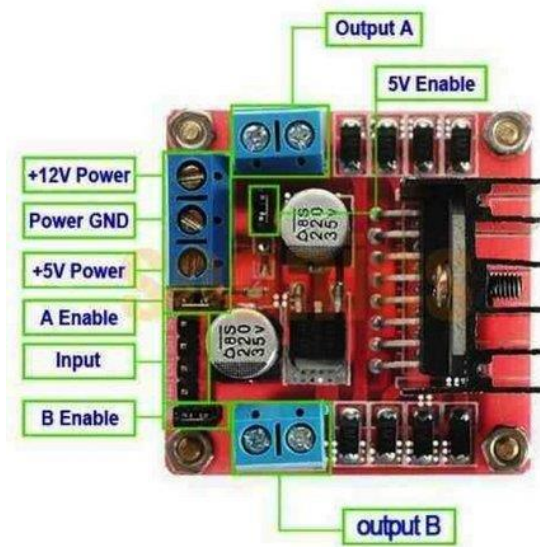


Figure 2.7: L298n Motor Driver Board.

3. 6V 125RPM Diligent DC gear Motor: used to steer and drive the wheels, each wheel has one placed on it and of course each motor has a built-in encoder used to support the feedback control in its speed, it can be seen as follows:-



Figure 2.8: 6V 125RPM Diligent DC Gear Motor.

4. 6V 210RPM Encoder DC Gear Motor:- a stronger type of motors brought from outside of the Kit and was used for the rear and front experiments also shown as follows:-



Figure 2.9: 6V 210RPM Encoder DC Gear Motor.

5. Gyro Sensor: which mainly measures the angular velocity ranges, and the measured orientation around the axis of rotation through integrated operation done in the CPU of the microcontroller, shown in it's board connection as follows:-

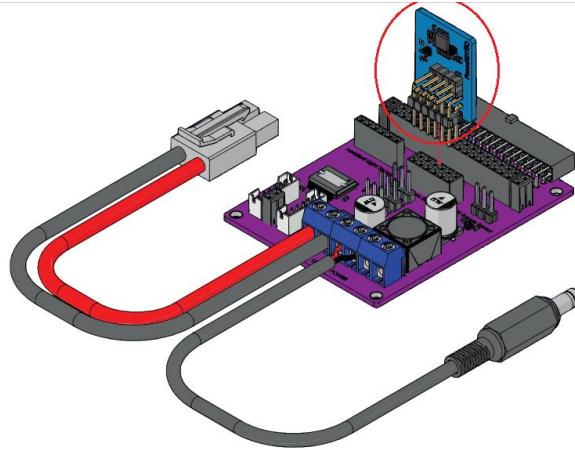


Figure 2.10: Digilent Gyro Sensor4114.

6. Gp2s40 Color Sensor: used for the tracking aim for the microcontroller's input to determine when there is a curve starting and when it ends, in order for the microcontroller to adapt it's output for the drivers of the motors.

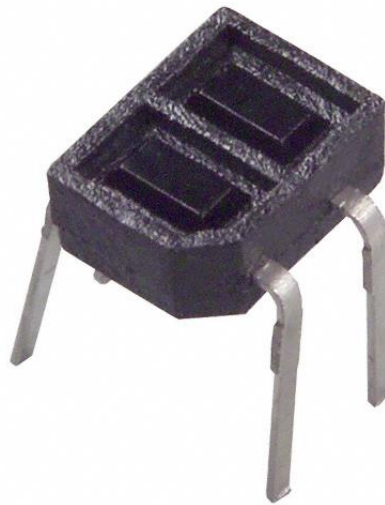


Figure 2.11: Gp2s40 Color Sensor

The following figure shows the connection of the Arduino mega to one motor through the motor driver L298n as follows:-

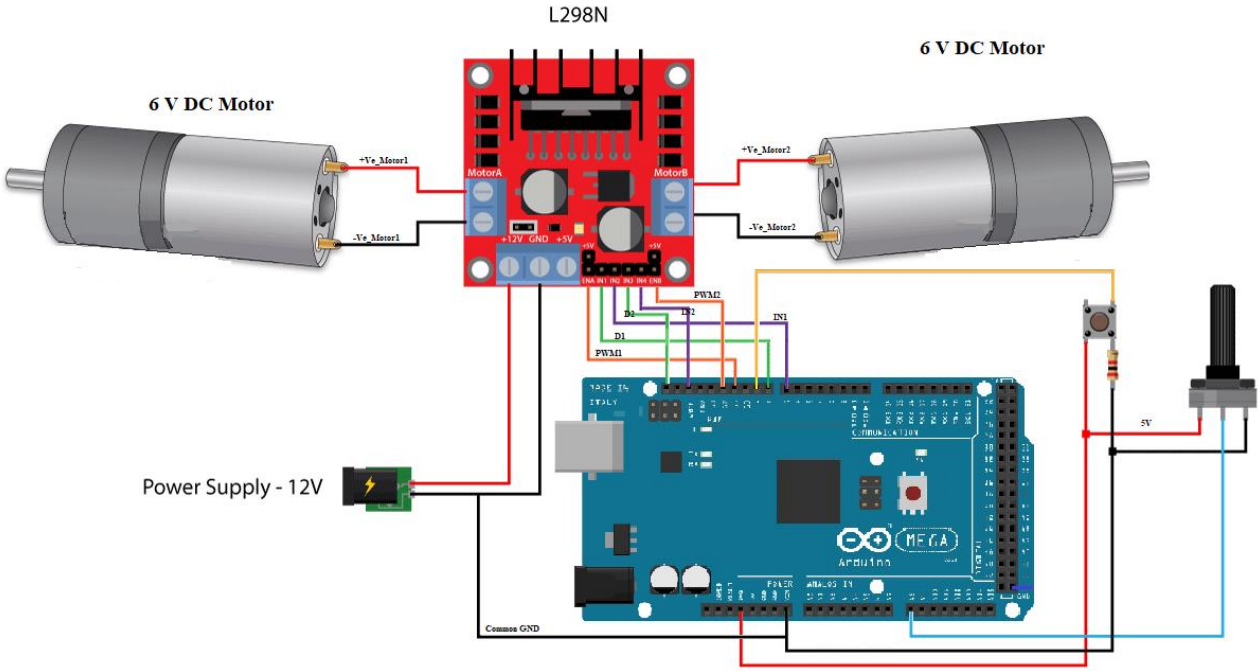


Figure 2.12: Arduino Mega Motors Connection with Manual Control for 2Wheel Drive

Chapter 3

Modeling and Methodology

3.1 Methodology

3.2 Modelling

3.2.1 Kinematic Modelling

3.2.2 Dynamic Modelling

3.1 Methodology

As it was mentioned earlier, a model of a Tetrix kit is needed to be studied scientifically and accurately here.

The aimed purpose of the whole project was to suit a best optimal performance for the vehicle through the support of vehicle dynamics algorithms, this mainly requires a full modeling and understanding of the vehicles body, hardware and what best relation could combine these two together; in order to meet any required results.

When it comes to terms of modeling, generally the main method taken into account is the kinematic modeling, for its simplicity and good providence of prediction and correction of the error in the vehicle's performance, but it's only valid for low acceleration and light loading on the vehicle. "Disadvantage is that it doesn't take any dynamic constraints into account". This leads to errors in pose prediction, especially when significant control signal (translational and rotational velocity reference) changes occur. Problem lies in the fact that mobile robot can't immediately change its current velocity to the desired value and mostly there exists a communication delay between the sensing elements and mobile robot micro-controller[14].

In order to avoid the errors in such a case and taking into account that WMR is desired to operate in high velocities and in some cases required to perform a heavy duty tasks, a dynamic modeling is extremely needed in the modeling procedure and algorithms; to provide flexibility, variety and accuracy in operations required to be achieved and satisfied.

3.2 Modeling

A modeling algorithm of a WMR always follow two main categories, kinematic and dynamic modeling.

A procedure algorithm supported by the two mentioned categories, will always produce and result a firm, strong model and simulation for any prototype needed to be represented as a WMR.

In such a modeling procedure aimed for the project, all the needed variables required in vehicle dynamics will be taken into account, starting with longitudinal and lateral vehicle dynamics, for a constrained set of control algorithms; in order to achieve an optimal output and performance of the vehicle.

3.2.1 Kinematic Modeling

First of all, it's already known that kinematics is the study of the mathematics of motion without considering the forces that affect the motion, and mostly referred to as the "geometry of motion".

In the control sight of modeling, kinematics Deals with the relationship between control parameters and the behavior of a system in state space representation. As for modelling the WMR in Kinematic sight it is considered that the vehicle is executing it's operations and actions on a planer surfaces with a local coordinate frame denoted by (x_l, y_l, z_l) , is assigned to the robot at its center of mass (COM). As shown in the free body diagram in Fig.3.1, while keeping in mind that in this project the plane motion is the only considered motion, so the Z-coordinate of COM is constant ($Z = \text{const}$)[15].

Assuming that the vehicle is moving on a plane surface in the local frame with linear velocity vector $[V_x \ V_y \ 0]^T$ and rotates with an angular velocity vector $\omega = [0 \ 0 \ r]^T$, so the state vector describing the coordinates of the vehicle is donated as $q = [X \ Y \ \theta]^T$ (the COM position, X and Y, and the orientation of the local coordinate frame with respect to the inertial frame), therefore, the vector of generalized velocities can be denoted

as $\dot{q} = [\dot{X} \quad \dot{Y} \quad \dot{\theta}]^T$ the variables \dot{X} and \dot{Y} are related to the coordinates of the local velocity vector as follows in (Fig3.1) :-

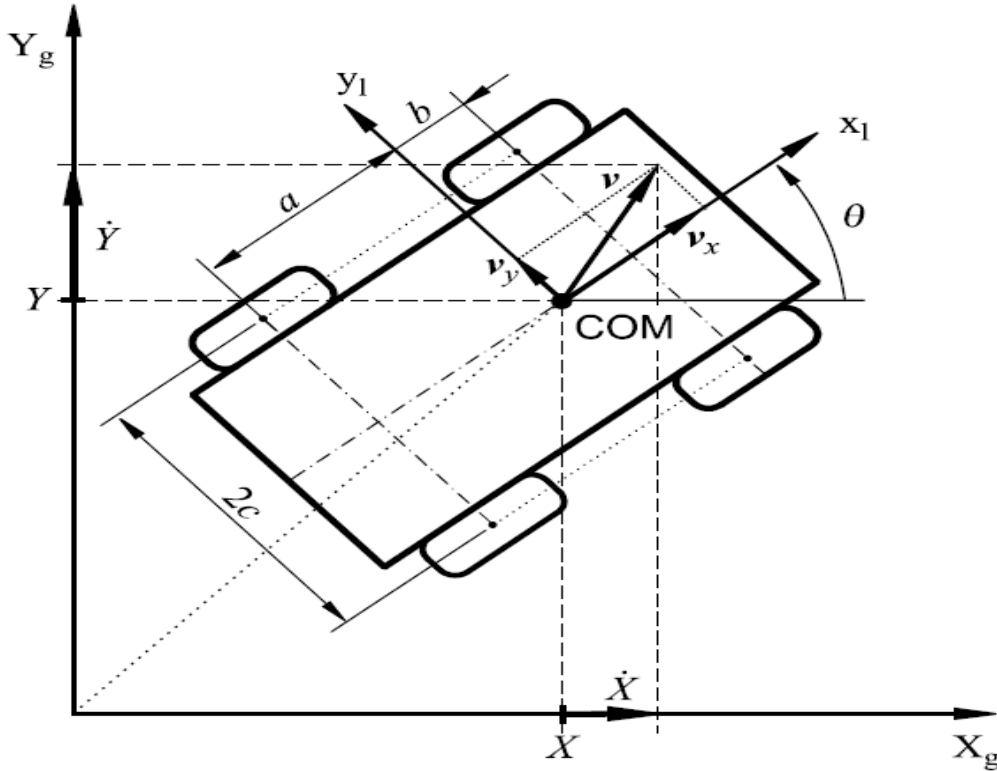


Figure 3.1: Free body diagram of WMR in a plane surface[15].

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = [A] \begin{bmatrix} v_x \\ v_y \end{bmatrix} \quad (3.1)$$

Where,

$A = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$: is known as the orthogonal rotation matrix.

v_x : is the longitudinal velocity of the vehicle.

v_y : is the lateral velocity of the vehicle.

And a , b and c are the positive kinematic parameters of the vehicle. Also, since the vehicle is enduring a planar movement there will be no velocity component in the vertical direction. It is also assumed that the global frame is fixed relatively to the local frame the WMR is placed in, there for it can be concluded that ($\dot{\theta} = \omega$).

Where ω : the angular velocity about the Z-axis.

Moreover, for simplicity it was also assumed that there is no thickness on the wheels, which leads us to conclude that the wheels are only having a contact with the plane's surface at point P_i for each wheel represented in the Fig(3.2).

Keeping in mind that each wheel is moving with an angular velocity W_i which can be considered as a control input for the WMR system, therefore, each wheel has a velocity of $(V_{xi}=\Gamma_i*W_i)$, where V_{xi} is the longitudinal component of each wheel.

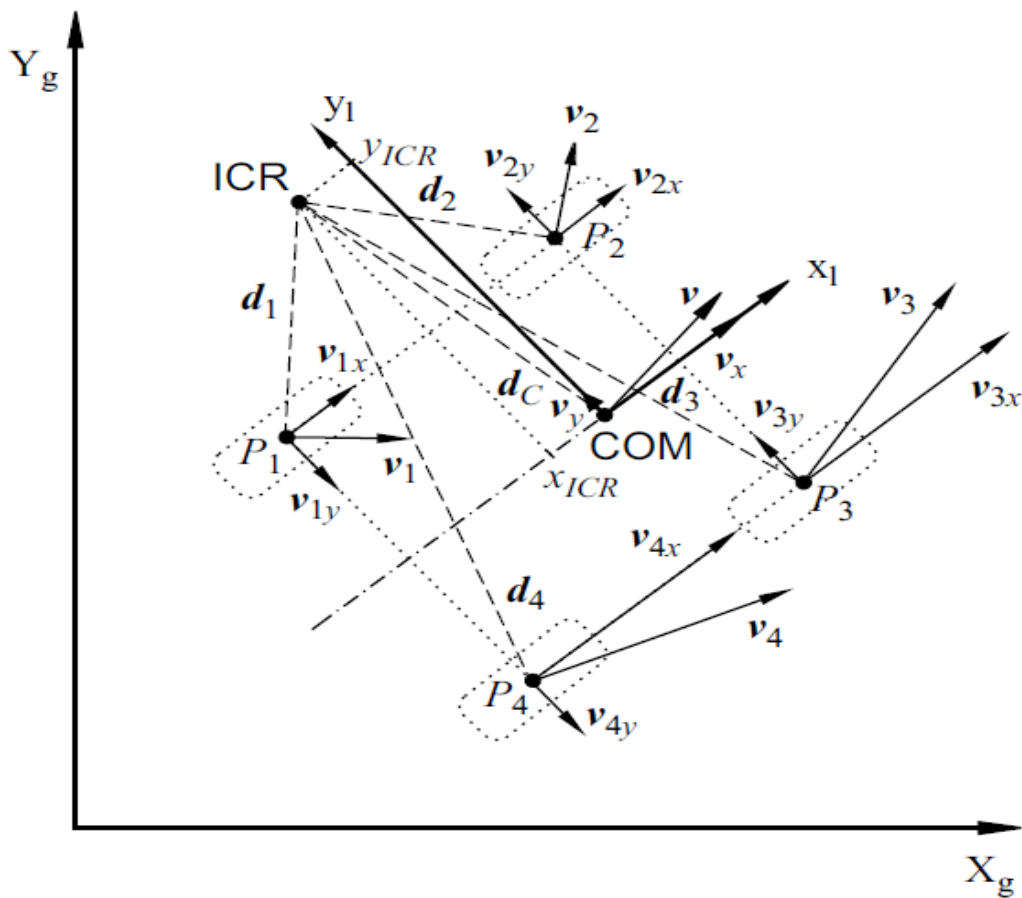


Figure 3.2: Kinematic Model of Four Wheeled Mobile Robot.

In order for the vehicle to move in a straight line, the velocities of the left wheels and the right wheels must be the same, while keeping in mind that the lateral velocity is equal to zero ($V_y=0$).

When the vehicle enters a curved path or a corner in the road, the velocity will have two components in the direction of motion, (V_x) in the longitudinal direction and (V_y) in the lateral direction, which means that there is also a tangential acceleration and lateral acceleration

respectively for the vehicle on the corner of (a_x, a_y) , in order for the vehicle to rotate around the curved path, the velocity of the outer wheels must be greater than the velocity of the inner ones and the opposite as well depending on the direction of the corner.

To develop a kinematic model, it is necessary to take into consideration all wheels together, the movement of the vehicle in a curved path is described with the relationship between the wheel velocities and the velocity of the robot the following matrix is denoted:-

$$\begin{bmatrix} V_L \\ V_R \\ V_F \\ V_B \end{bmatrix} = \begin{bmatrix} 1 & -C \\ 1 & C \\ 0 & -X_{ICR} + b \\ 0 & -X_{ICR} - a \end{bmatrix} \begin{bmatrix} V_X \\ \omega \end{bmatrix} \quad (3.2)$$

Where:-

- V_L : longitudinal coordinate of the left wheel velocity.
- V_R : longitudinal coordinate of the Right wheel velocity.
- V_F : lateral coordinate of the Front wheel velocity.
- V_B : lateral coordinate of the Rear wheel velocity.

As it can be seen from the equation if (ω) is equal to zero, the velocity V_L will be equal to the velocity of V_R , which means that the vehicle is moving in a horizontal straight line.

To find the angular wheel velocity of the left and right wheel (ω_L, ω_R) , respectively. The following equation can be denoted as follows:-

$$\mathbf{\omega}_{\text{wheel}} = \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix} = \frac{1}{r} \begin{bmatrix} V_L \\ V_R \end{bmatrix} \quad (3.3)$$

Combining (Equ.2) and (Equ.3), the following approximated relations between the angular wheel velocities and the velocities of the robot can be developed to recognize the kinematic control input for the vehicle:-

$$\eta = \begin{bmatrix} v_x \\ \omega \end{bmatrix} = r \begin{bmatrix} \frac{\omega_L + \omega_R}{2} \\ \frac{-\omega_L + \omega_R}{2c} \end{bmatrix} \quad (3.4)$$

Where, η is a new control input introduced at the kinematic level, where now (ω_L, ω_R) can be treated as the control kinematic input signal as well as velocities u and ω . To find the values of V_L, V_R, V_F and V_B as shown in Equ.2

3.2.2 Dynamic Modeling

Dynamics is the study of the motion of a mechanical system taking into account the various forces that affect its motion, unlike kinematics where the forces are not taken into account. The dynamic model is essential for the analysis of the WMR motion and for the design of various motion control algorithms.

The basic need of dynamic modelling in the project is mainly to understand the Comprehensive changes forces make and produce on the system, and recognize the systematical changes it reflects on the system's performance, nature and what possible limits the system has in its performance to maintain its stability and robustness, and by that knowing the validity limit of the inputs and what allowable domain the control has.

And as it was already mentioned before, the assumption that the vehicle is moving in planar surfaces mainly arises two main categories when talking about dynamic modelling in vehicle dynamics, one is longitudinal forces and the other is lateral forces, which will be studied and analyzed critically.

In order for a vehicle to translate in a planar surface, it must have a generation source of forces in order to let it move forward, in the case of this project, the source is an electrical DC motor that gives torque and angular velocity which can be considered as an input on the wheel, and as it is known.

$$\tau_i = F_{xi} * r_i$$

Where:-

τ_i : torque excreted on each wheel.

F_{xi} : longitudinal force produced on each wheel.

r_i : radius of each wheel.

When the vehicle is moving a straight horizontal direction, the only type of forces acting on it would be the longitudinal force coming from the motor, it would be the only force driving the vehicle as long as it's not entering any curved path, when such a case happens a new force will be generated called lateral force in the (y) direction.

The following in (Fig3.3) explains the set of forces acting on a single wheel in the WMR model:-

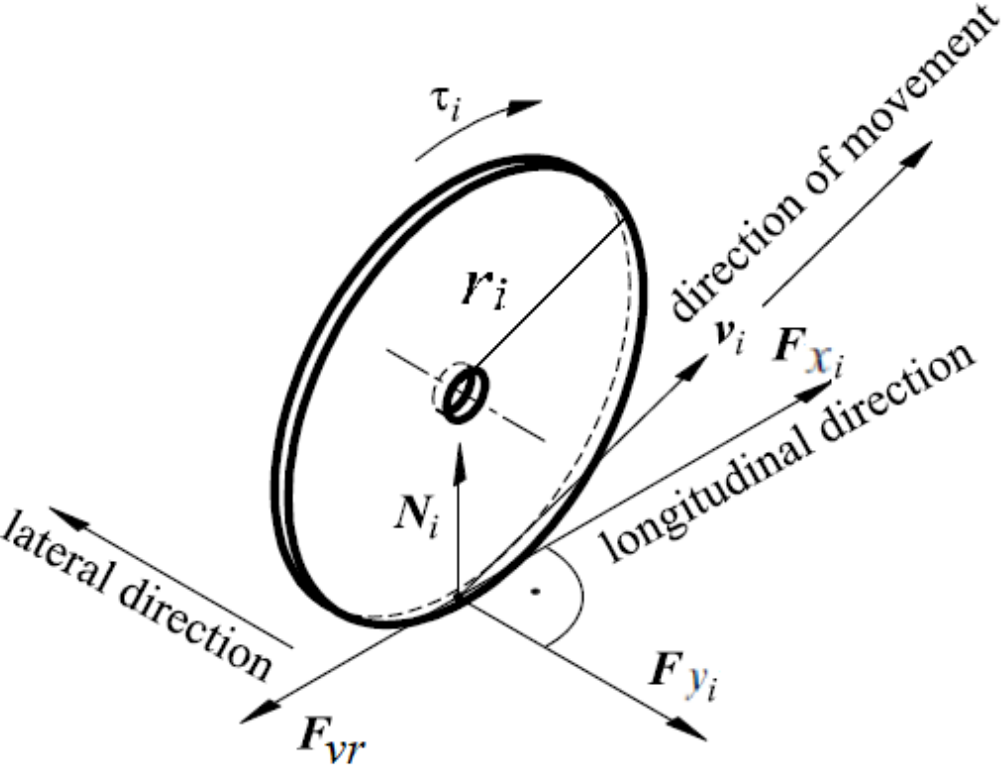


Figure 3.3: Forces acting on one wheel.

Where:-

- F_{vr} : vehicle resistance force for each wheel.
- F_{yi} : lateral force produced on each wheel.
- N_i : normal force acting on each wheel.

The following (Fig3.4) describes the forces acting on the WMR model:-

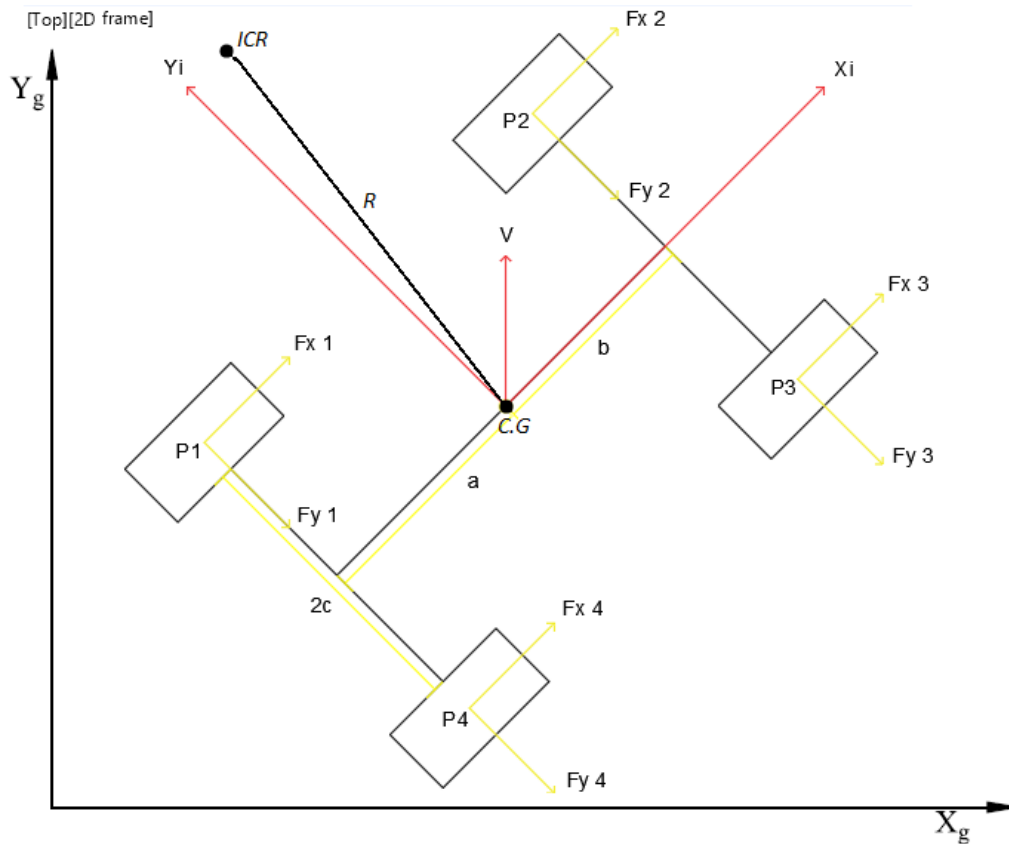


Figure 3.4: Dynamic Model of Four Wheeled Mobile Robot in a curved path.

By applying newton's second law on the system $\sum F = m a$

Firstly, in the (x) direction: -

$$\begin{aligned} \sum F_x &= m a_x \\ F_{xi} - F_{vr} &= m a_x \\ (F_{xf} + F_{xr}) - (R_a - R_r - F_d) &= m a_x \end{aligned}$$

Where:-

- F_{xf} : is the attractive force acting on the front wheels.
- F_{xr} : is the attractive force acting on the rear wheels.
- R_a : Aerodynamic force which resists the motion of the vehicle.
- R_r : Rolling resistance which resists the wheels motion.
- F_d : Trailer force.

And while the WMR system in this project has specific constrains, the vehicle doesn't have a trailer attached to it in the back, the trailer force will be neglected as well, so the equation becomes:-

$$(F_{xf} + F_{xr}) - R_a - R_r = m a_x$$

$$R_r = f_r * W$$

$$R_a = \frac{1}{2} * \rho * C_D * V^2 * A_f$$

$$v^2 = \sqrt{v_x^2 + v_y^2}$$

Where:-

ρ : Density of air.

C_D : Drag coefficient.

A_f : Front area of vehicle.

V : is the total velocity of the vehicle from the C.G.

f_r : Friction factor in the touching point between the wheel and plane surface.

W : is the weight of the vehicle.

And known that the maximum longitudinal force the vehicle can produce is $F_x(\mathbf{max}) = \mu.W$

And knowing that the vehicle has forward and rear drive the equation becomes,

$$(F\mathbf{max})_f = \mu. W_f$$

$$(F\mathbf{max})_r = \mu. W_r$$

Secondly, in the (y) direction: -

$$\sum F_y = m a_y$$

$$F_{yf} + F_{yr} = m a_y$$

Where: -

F_{yf} : is the lateral force acting on the front wheels.

F_{yr} : is the lateral force acting on the rear wheels.

$$a_y = \frac{v^2}{R},$$

R : distance between the ICR and the CG of the vehicle.

w_f : the reaction force at the front axle.

w_r : the reaction force at the rear axle.

Assuming that the wheels model is a linear tire model as the curve is shown in (Fig3.5),

$$(F_{yf} = C_{\alpha f} * \alpha_f), (F_{yr} = C_{\alpha r} * \alpha_r)$$

Where: -

$C_{\alpha f}$: cornering stiffness of the front wheel.

α_f : slip angle of the front wheel.

$C_{\alpha r}$: cornering stiffness of the rear wheel.

α_r : slip angle of the rear wheel.

So the equation becomes: -

$$(C_{\alpha f} * \alpha_f) + (C_{\alpha r} * \alpha_r) = m \frac{v^2}{R}$$

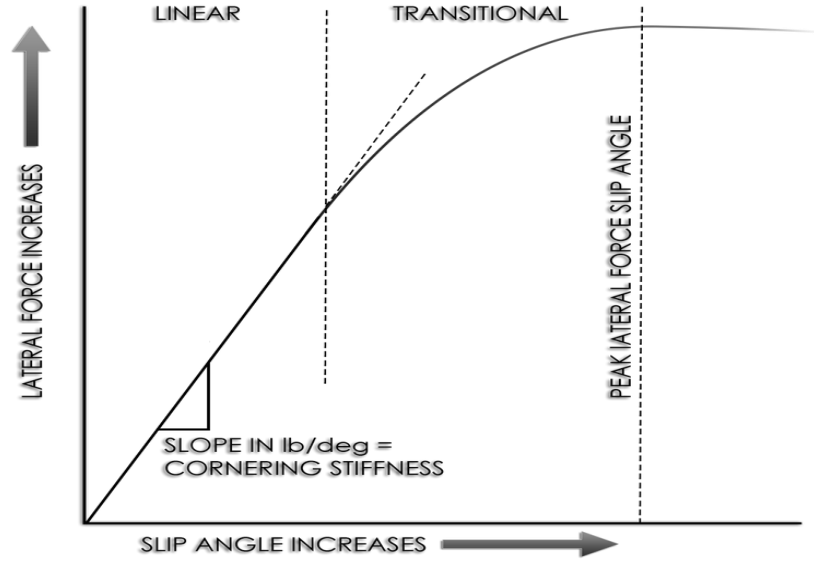


Figure 3.5: Relationship between the lateral force curve and slip angle.[16]

Now by using conservation of linear momentum (\vec{G}) law:-

$$\vec{G} = m \vec{v}$$

$$\vec{F} = \dot{\vec{G}} \equiv \mathbf{F} = \frac{d\mathbf{G}}{dt}$$

$$\vec{v} = [u \quad v \quad w]^T$$

$$\dot{\vec{G}} = m \dot{u} \hat{i} + m \dot{v} \hat{j} + m \dot{w} \hat{k} + m u \dot{\hat{i}} + m v \dot{\hat{j}} + m w \dot{\hat{k}}$$

$$\vec{F} = \dot{\vec{G}} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} m\dot{u} - m\omega v \\ m\dot{v} + m\omega u \\ m\dot{w} \end{bmatrix}$$

The final unmentioned phenomena needed to be considered in the dynamic modelling is the moment (\vec{M}) arising when the vehicle enters a curved path during its operation, which will be derived using the angular momentum (\vec{H}) laws as follows:-

$$\vec{H} = \vec{I} \vec{\omega}$$

Where (\vec{I}): is the moment of inertia.

$$\vec{I} = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix}$$

$$\vec{\omega} = [0 \quad 0 \quad r]$$

Where r = the angular velocity about the Z-axis, which is the rate of change of the angle of vehicle with respect to time.

$$\vec{M} = [M_x \quad M_y \quad M_z]^T$$

$$\vec{M} = \vec{H}$$

$$\vec{M} = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ I_{zz}\dot{r} \end{bmatrix}$$

So the only type of moment needed to be taken under consideration is the moment around the Z-axis which is equal to $(M_z = I_{zz} \dot{r})$.

The modelling algorithms illustrated in this chapter, is believed to be enough to describe the motion of the WMR needed to be represented at the end of this project, though if any further needed information it will be studied and developed to meet any futural requirments.

Chapter 4

Control Architecture

4.1 Control Architecture and calculation

4.1.1 Front Wheel Drive

4.1.2 Rear Wheel Drive

4.1.3 Four Wheel Drive

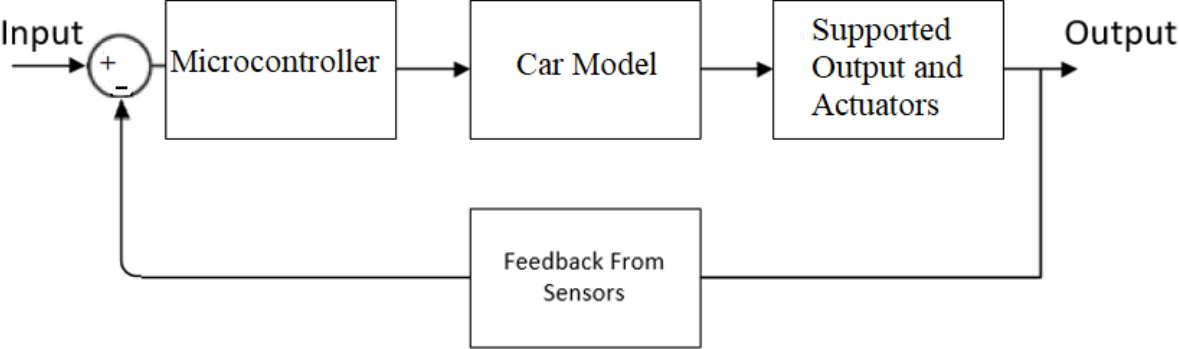
4.2 Software Design

4.2.1 Flowchart

4.3 Control Procedure

Control Architecture and Calculation

This chapter will discuss the control design of the WMR in order to obtain the possible optimal desired outputs in high precision and accuracy. On the other hand, the software design will be clarified using flowchart and an explanation of the WMR control procedure.



(Figure 4.1): Control Block Diagram of the Control Procedure

4.1 Control Architecture

Depending on the motions study in chapter 3, the vehicle has three operating modes; forward wheel drive, rear wheel drive and four wheel drive.

In order to achieve high accuracy in positioning the moving head, a controller is needed for each independent motion. So, to make the steady state error go to zero, proportional-integral(PID) controller is needed, and to improve transient response, proportional-derivative(PD) controller is needed; therefore, a proportional-integral-derivative(PID) controller will be used for each independent motion in the motor control to improve either steady state response and transient response.

In the next demonstrated control of WMR the vehicle has three modes to be operated in, depending on the known modes of vehicle dynamics, so the operation of the vehicle follows the next main steps:

4.1.1 Front Wheel Drive

Firstly, front wheel drive in a straight path, in the case of selection the WMR will only operate the front motors which are Motor2 and Motor3 with the same angular velocity, meanwhile the rest of the motors will be disconnected and only operating as followers by a clutch mechanism that will be added to the system.

So the driving output for the vehicle will depend on the performance reflected by this case, so the given inputs for those two motors must not overcome the allowable range of the input, in terms of angular velocity and torque.

Therefore depending on the next equations the vehicle will not be allowed to exceed the maximum value of acceleration, which will be a variable input coming from the sensors, because if it does slipping phenomena will occur. The next equation will show the procedure depended on for making the judgment:-

$$(F_{max})_f = \mu \cdot W_f \tag{4.1}$$

$$(F_{max})_f = m \cdot \mathbf{a}_x$$

$$\mathbf{a}_x = \frac{(F_{max})_f}{m}$$

However, if the path changes and the vehicle starts to endure a lateral force in a curved path, and a new component of acceleration is added. To maintain the stability and prevent the vehicle from skidding, the motors are controlled in order to limit the motors from exceeding the maximum value of the lateral acceleration.

Where the following shows the theoretical procedure of calculation for the static case:-

$$W_f = w \cdot \frac{a}{l}$$

$$W_f = 8.33 \text{ N}$$

Now to know the value of acceleration for each surface, substituting the values of μ_k from table (2.1) into Equ (4.1) gives:-

- 1) For grass : $a_x = 1.764 \frac{m}{s^2}$
- 2) For wood : $a_x = 2.59 \frac{m}{s^2}$
- 3) For sand paper : $a_x = 3.283 \frac{m}{s^2}$

As for the dynamic calculations, it's illustrated as follows:-

$$W_f = \frac{w*a}{l} - \frac{a_x*h}{g*l} \quad , \text{ Where:-}$$

h: the height of the center of gravity for the vehicle from the ground, which in the case of this project it's equal to 9cm.

But in the kinematic case when the vehicle runs on the track, a part of the load of it is shifted from the front axle to the rear axle, which is known as **Load Shift**, so it's needed to calculate the values of the new w_f' for each surface becomes as follow:-

- 1) For grass : $w_f' = 8.24 \text{ N}$
- 2) For wood : $w_f' = 7.96 \text{ N}$
- 3) For sand paper : $w_f' = 7.73 \text{ N}$

And knowing that the change in w_f will cause a change in the value of a_x according to Equ(4.1), so the value of a_x' becomes:-

$$F_X = m * a_x' = \mu * w_f'$$

- 1) For grass : $a_x' = 1.736 \frac{m}{s^2}$
- 2) For wood : $a_x' = 2.46 \frac{m}{s^2}$
- 3) For sand paper : $a_x' = 3.034 \frac{m}{s^2}$

Now the following graph illustrates the relationship between the acceleration (a_x') and the coefficient of friction (μ_k) for the front drive as it follows:-

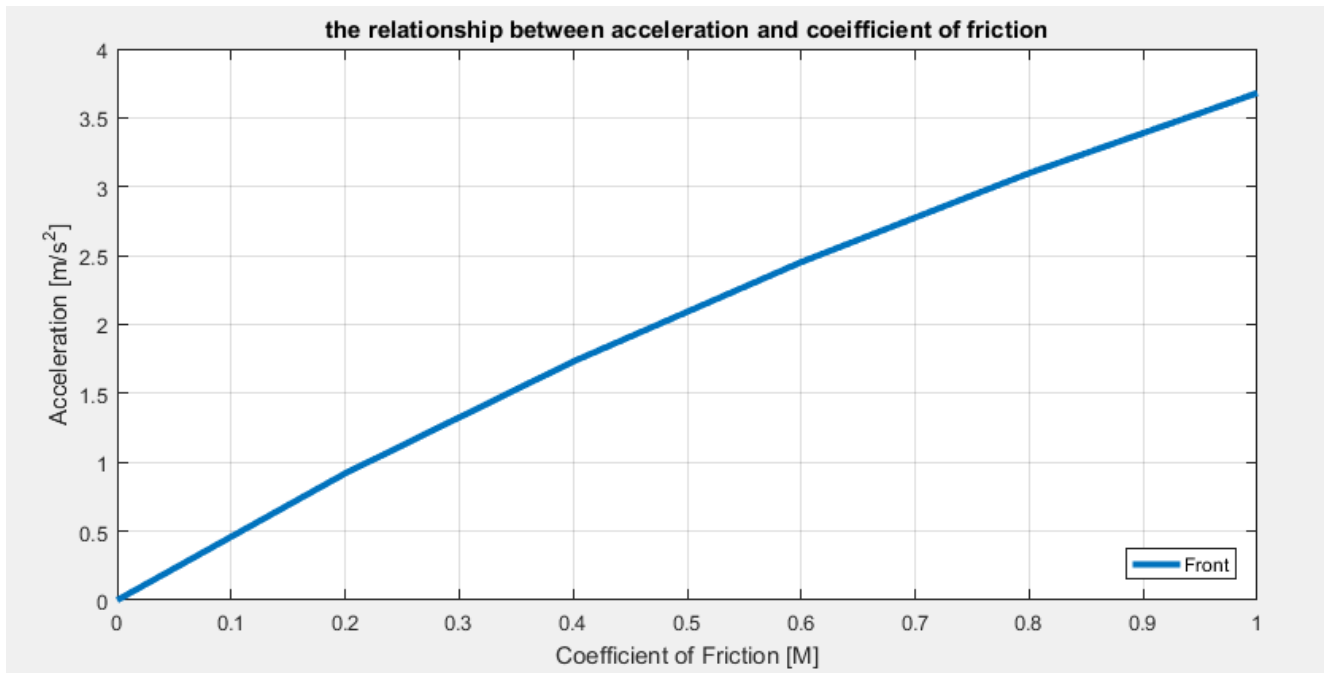


Figure (4.2): The relationship between the acceleration (a_x') and the coefficient of friction (μ_k)

It can be clearly seen that the relationship is linear, so now it's needed to compare between it and the rear drive mood as it follow in sec(4.1.2)

4.1.2 Rear Wheel Drive

Secondly, rear wheel drive in a straight path will take the same working algorithm of a front wheel drive, but only with the reflection of motors 1 and 4 respectively.

Same as before motors 2 and 3 will be clutched and left as followers, the leading performance of the vehicle will be the rear wheel drive in such a case.

$$(F_{max})_r = \mu \cdot w_r \quad (4.2)$$

$$(F_{max})_r = m \cdot a_x$$

$$a_x = \frac{(F_{max})_r}{m}$$

However when the vehicle endures a curved path such as mentioned in case number one the vehicle will endure a lateral force, therefore the system will be controlled in order to prevent the system from reaching its maximum allowable limit, and by so prevent it from skidding.

Where the following shows the theoretical procedure of calculation for the static case:-

$$W_r = w \cdot \frac{b}{l}$$

$$w_r = 8.33 \text{ N}$$

Now to know the value of the acceleration for each surface, substituting the values of μ_k from table (2.1) into Equ (4.2) gives :-

1) For grass : $a_x = 1.764 \frac{m}{s^2}$

2) For wood : $a_x = 2.59 \frac{m}{s^2}$

3) For sand paper : $a_x = 3.283 \frac{m}{s^2}$

It can be seen that the values of a_x in the static case remained the same, which reinforces the understanding that this happened because ($w_r = w_f$), meanwhile it will change for sure in the dynamic case as it is shown next.

Dynamic calculations:-

$$W_r = \frac{w*b}{l} + \frac{a_x*h}{g*l}$$

Also as before when the vehicle runs on the track a **Load Shift** will occur, so it's needed to calculate the values of the new w_r' for each surface as before, therefore the values become as follow:-

- 1) For grass : $w_r' = 8.87$ N
- 2) For wood : $w_r' = 8.89$ N
- 3) For sand paper : $w_r' = 8.92$ N

And knowing that the change in w_f will cause a change in the value of a_x according to Equ(4.1), so the value of a_x'' becomes:-

$$F_X = m * a_x'' = \mu * w_r'$$

- 1) For grass : $a_x'' = 1.87 \frac{m}{s^2}$
- 2) For wood : $a_x'' = 2.77 \frac{m}{s^2}$
- 3) For sand paper : $a_x'' = 3.5 \frac{m}{s^2}$

Looking at the values of both a_x'' and w_r' , it can be clearly seen those values are higher than the values of w_f' and a_x' in the dynamic case, which can be explained because the load shift which originally shifted some of the weight of the vehicle backwards and by so shifter the center of gravity as well, so the rear part of the vehicle will have to accelerate faster than the front one to take over this.

So the following graph illustrates the relationship between the acceleration (a_x'') and the coefficient of friction (μ_k) for the rear drive as it follows:-

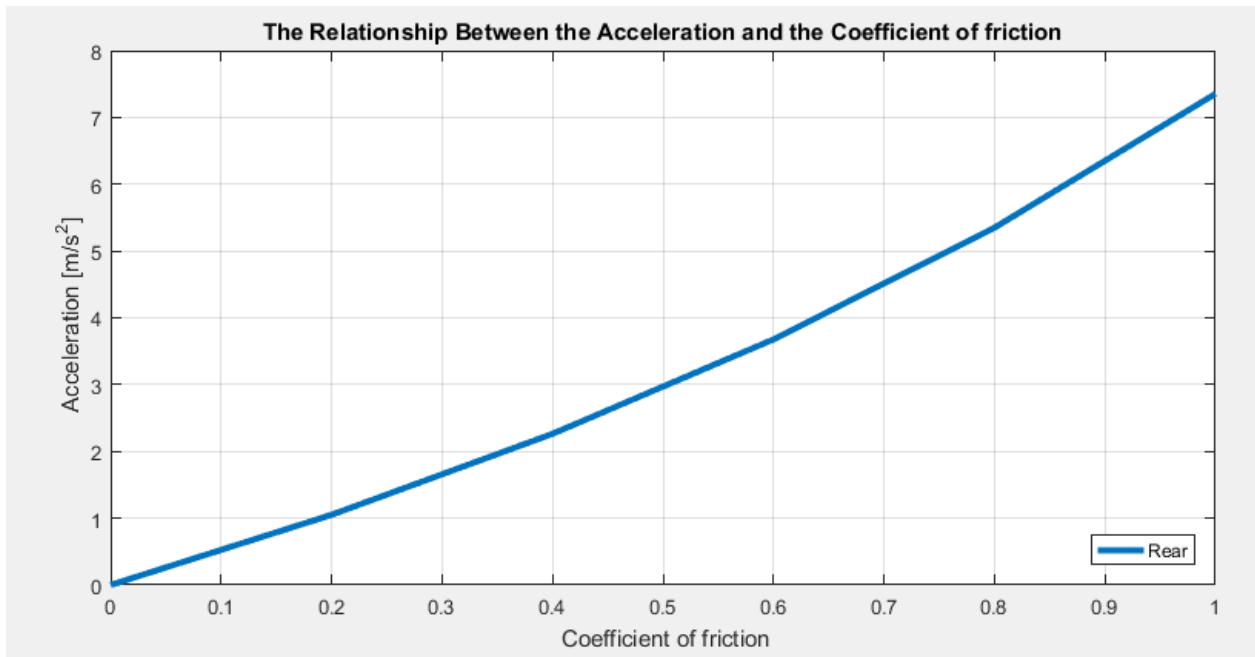


Figure (4.3): The relationship between the acceleration (a_x'') and the coefficient of friction (μ_k)

4.1.3 Four Wheel Drive

When the vehicle is set to be in the case of four wheel drive, the four motors will be activated at the same time.

Using Newton's second law, it can be concluded that:-

$$\sum F_x = m a_x$$

$$F_{\max f} + F_{\max r} = m a_x'''$$

$$(\mu \cdot w_f) + (\mu \cdot w_r) = m a_x'''$$

$$a_x''' = \frac{(\mu \cdot w_f) + (\mu \cdot w_r)}{m} = \frac{\mu \cdot w}{m}$$

The following shows the theoretical procedure of calculation is:-

- 1) For grass : $a_x''' = 3.6 \frac{m}{s^2}$
- 2) For wood : $a_x''' = 5.3 \frac{m}{s^2}$
- 3) For sand paper : $a_x''' = 6.7 \frac{m}{s^2}$

And the following graph illustrates the relationship between the acceleration (a_x''') and the coefficient of friction (μ_k) for the four drive as it follows:-

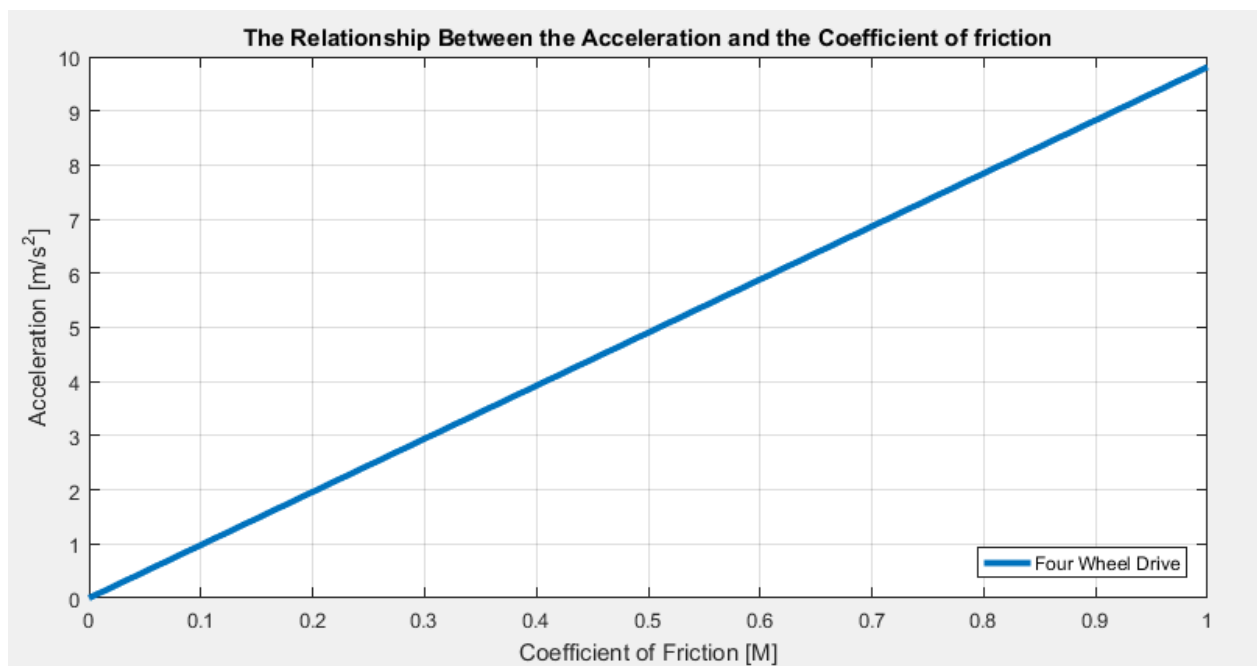


Figure (4.4): The relationship between the acceleration (a_x''') and the coefficient of friction (μ_k)

From the graph above, it can be seen that the acceleration increased more than the rear drive, knowing that the rear drive acceleration is bigger than the front one, thanks to this increase in the 4 wheel drive mode, it gives us a better range to increase the speed of the motors without reaching the skidding limit.

4.2 Software Design

In order to write the procedure code correctly, the operation should be well studied through drawing the flowchart and understanding its details, then a section is needed to be designed for the coding process and its language and logic.

4.2.1 Flowchart

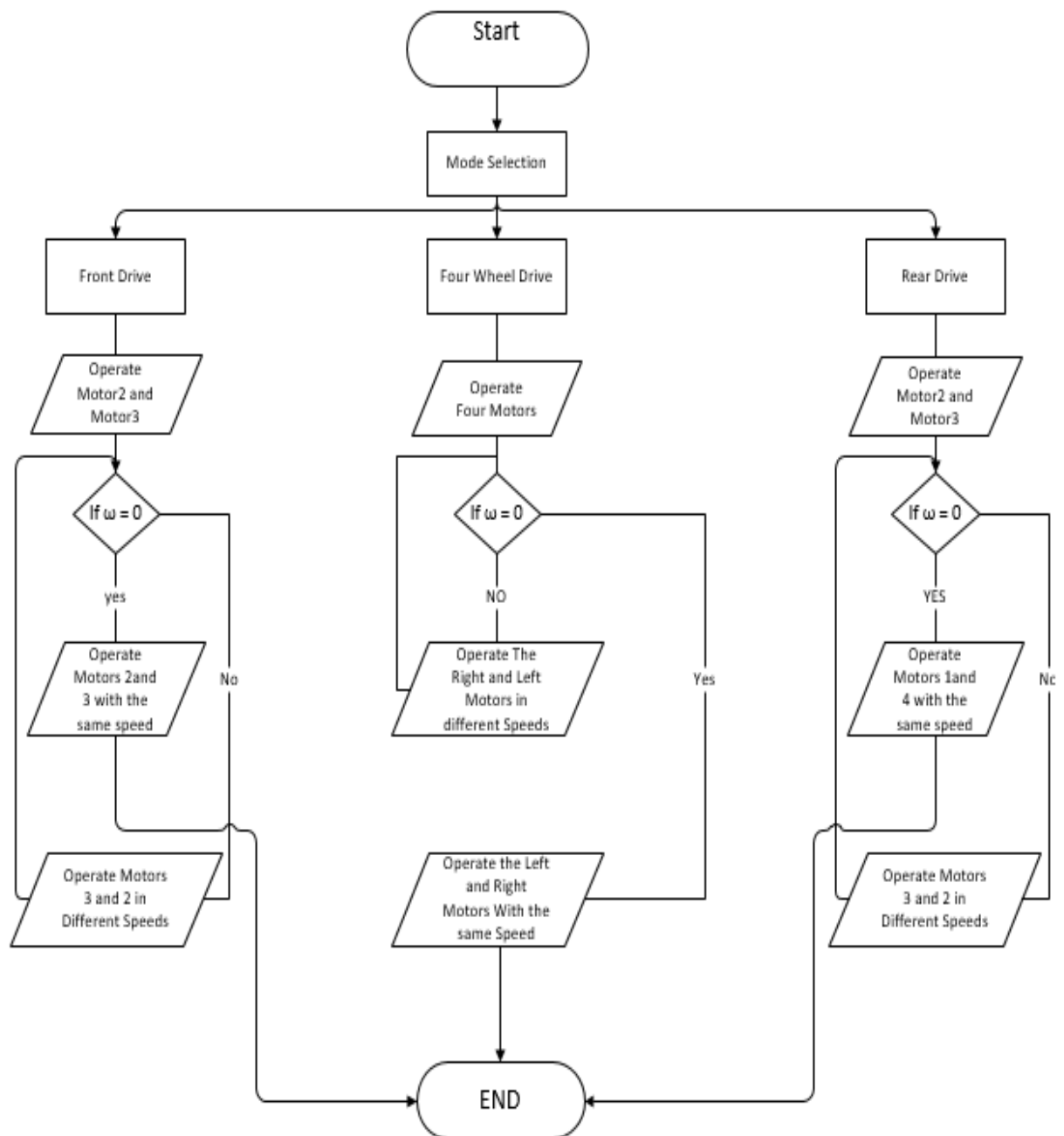


Figure 4.2: Control Flow Chart of the Project

As shown in (Fig.4.2) for Vehicle Procedure Operation, the mode selection is the first thing needed to be done before running the vehicle, then follows the appropriate output for the motors and what in order to know how to be performing through the process and what maximum limits the vehicle has in this mode.

Next comes the statement of (if $\omega=0$) which mainly is depending on the reading of the yaw rate sensor in it's detection, in order for the microcontroller to understand that there is a curvature in the path of the vehicle, then adjust the rotation with the appropriate value relative to the sensor continuous feedback. Therefore, if a curvature is detected the control will differ from its straight path algorithm, and as a result, the adjustments will be done in the control algorithm integrating the output with the modelling and control procedure done in the project and correct the error happening by the time, with a continuous feedback and adjustment for the behavior of the WMR during it's operation.

4.3 Control Procedure

As for the control of the WMR in this project using the Arduino Mega Microcontroller, the following figure will show the needed procedure for controlling the system:-

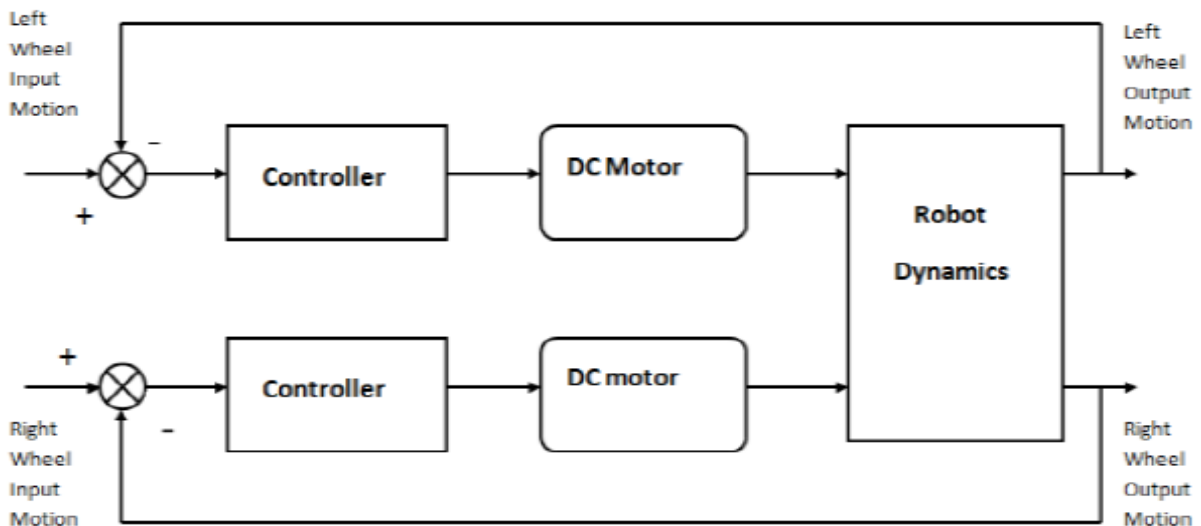


Figure 4.3: Control System Block Diagram[17].

The Code shows how the Microcontroller's work and what operation it does using the C language for it's compiler as added in the appendix A

With the following figure illustrating the overall connection of the WMR and the working principle:-

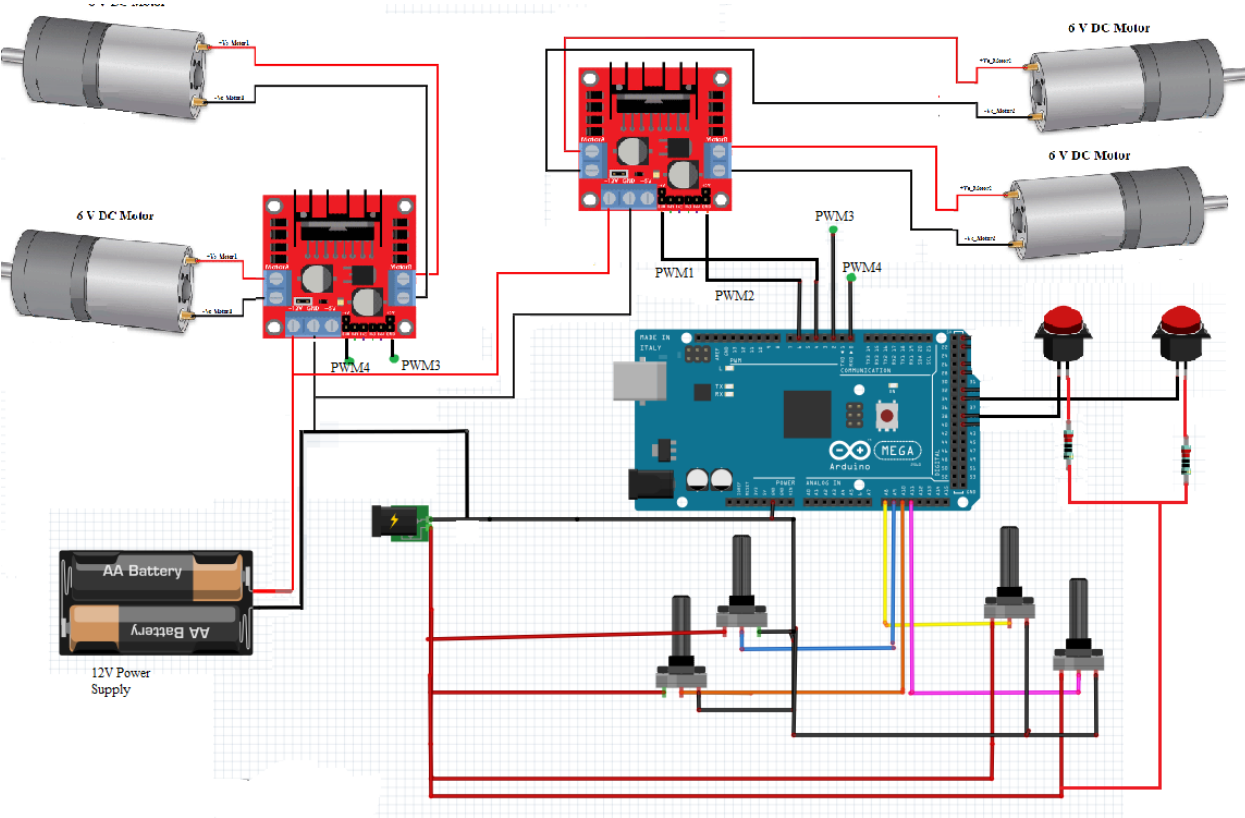


Figure 4.4: Overall Connection for the WMR.

The Four DC motors shown are connected to the Arduino Microcontroller, each Two motors are connected to a driver, the Front wheels are connected to the First driver, while the rear wheels were connected to the Second one, Also in the graph it is shown that there are Two main push buttons to clarify the Operational Mode needed for the Vehicle, were the first push button choses whether to operate in front drive or rear drive, and the second push button operates the Four wheel drive mode.

Moreover, four potentiometers were added to give a manual control for the wheels speeds, each numbered for the motor connected to, to enable the user to see what possible difference it makes and what result is given depending on the manual change made.

Chapter 5: Experiential Work

5.1 Front Drive Mode

5.2 Rear Drive Mode

5.3 Four Wheel Drive Mode

The experiments were done to test the various designed surfaces for the vehicle to operate on the track and the results were taken and graphed as it will be shown in this chapter.

5.1 Front Drive Mode

The following graphs illustrate the response of the motors at a speed of 100RPM in a straight line test for the Three designed surfaces:-

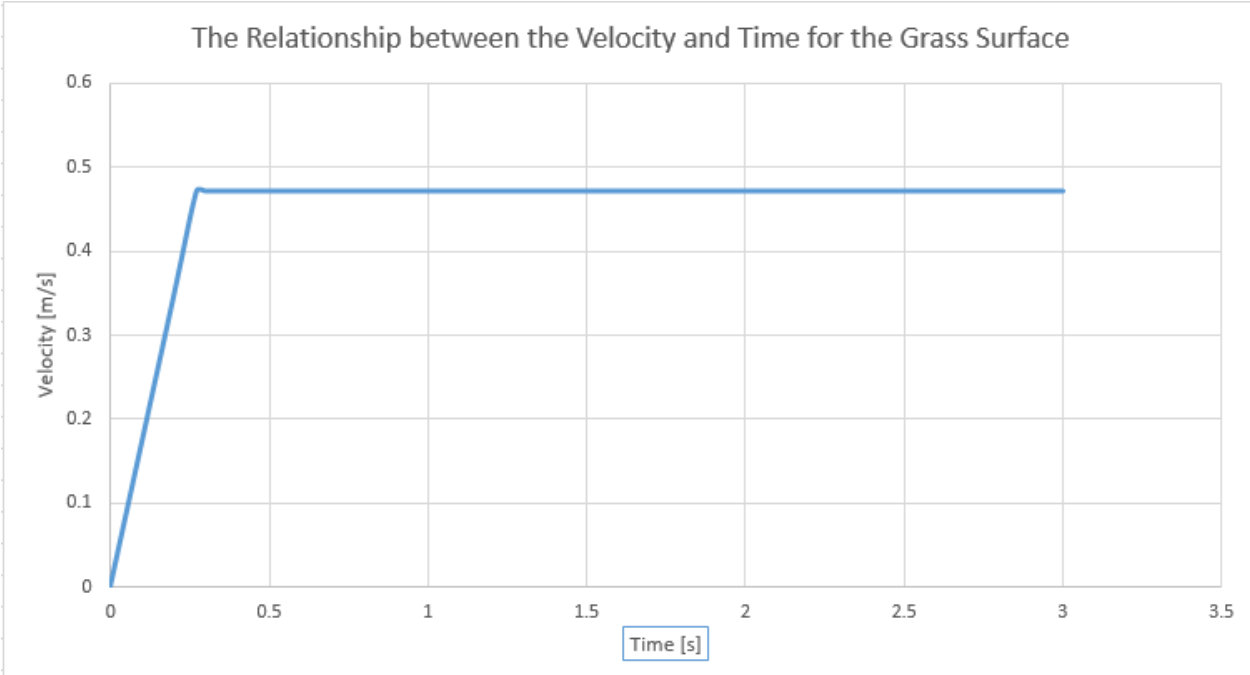


Figure 5.1: The response of the vehicle in front drive mode for the Grass surface.

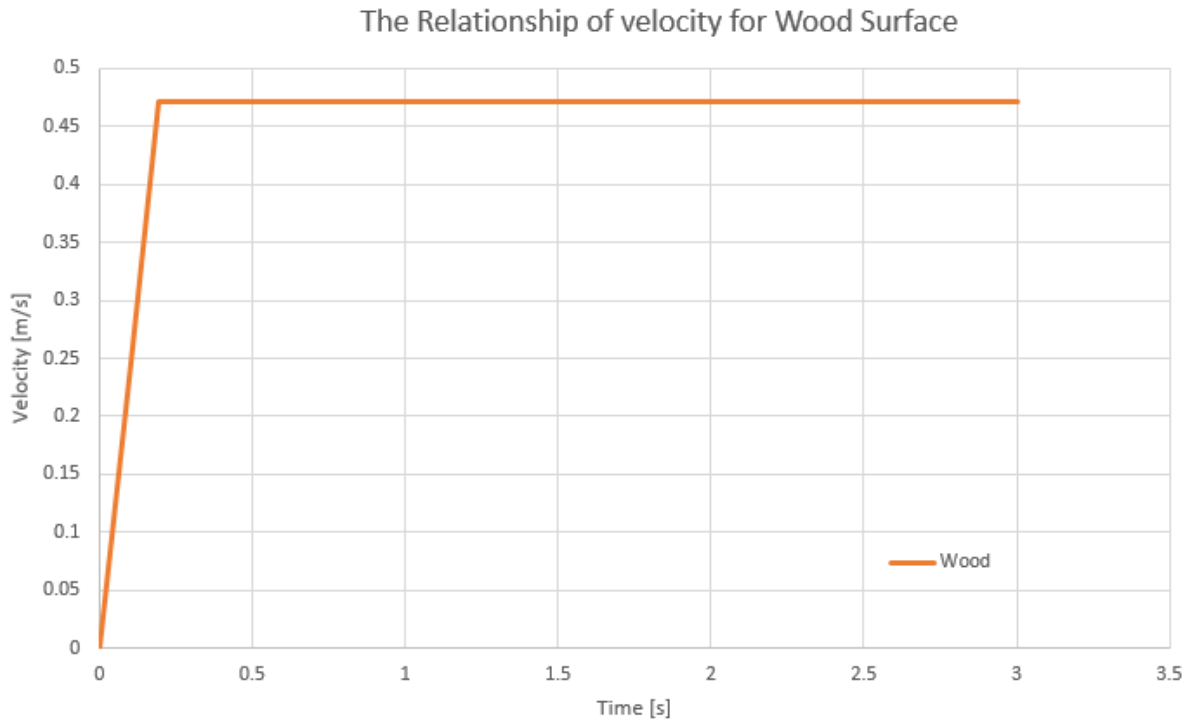


Figure 5.2: The response of the vehicle in front drive mode for the wood surface.

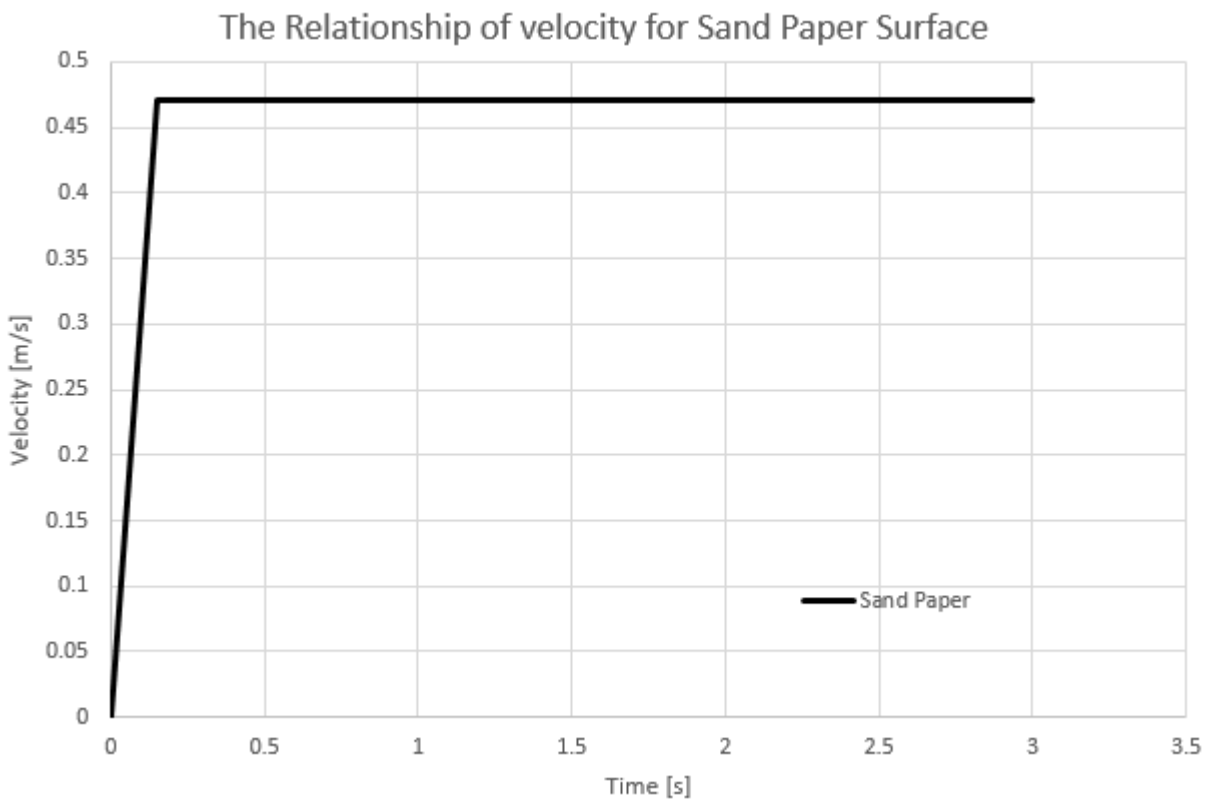


Figure 5.3: The response of the vehicle in front drive mode for the Sand Paper surface.

5.2 Rear Drive Mode

The following graphs illustrate the response of the motors at a speed of 100RPM in a straight line test for the Three designed surfaces:-

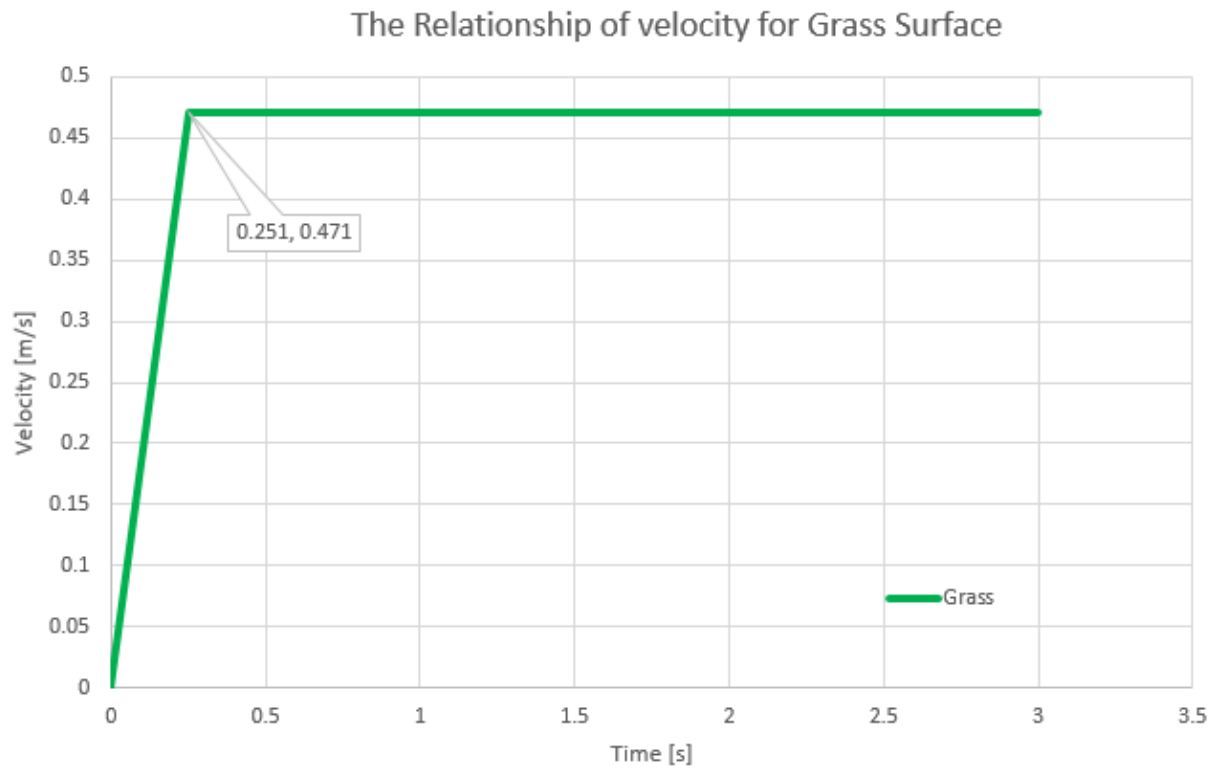


Figure 5.4: The response of the vehicle in Rear drive mode for the Grass surface.

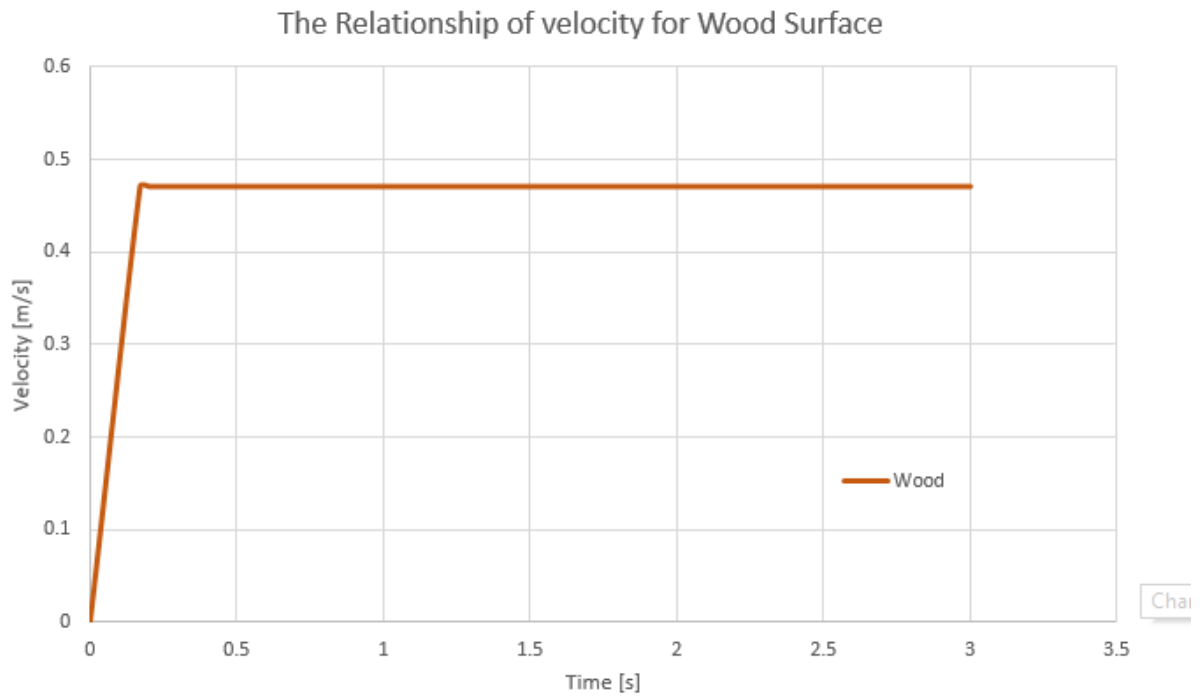


Figure 5.5: The response of the vehicle in Rear drive mode for the Wood surface.

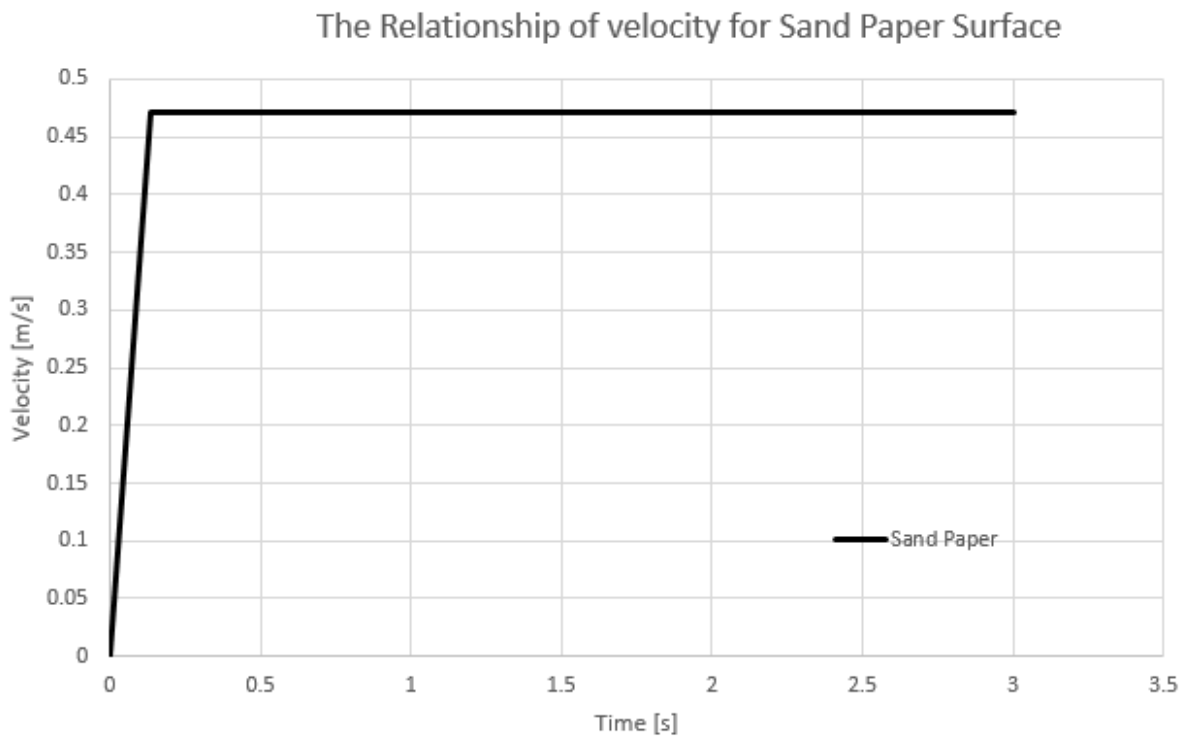


Figure 5.6: The response of the vehicle in Rear drive mode for the Sand Paper surface.

5.3 Four Wheel Drive Mode

The following graphs illustrate the response of the motors at a speed of 100RPM in a straight line test for the Three designed surfaces:-

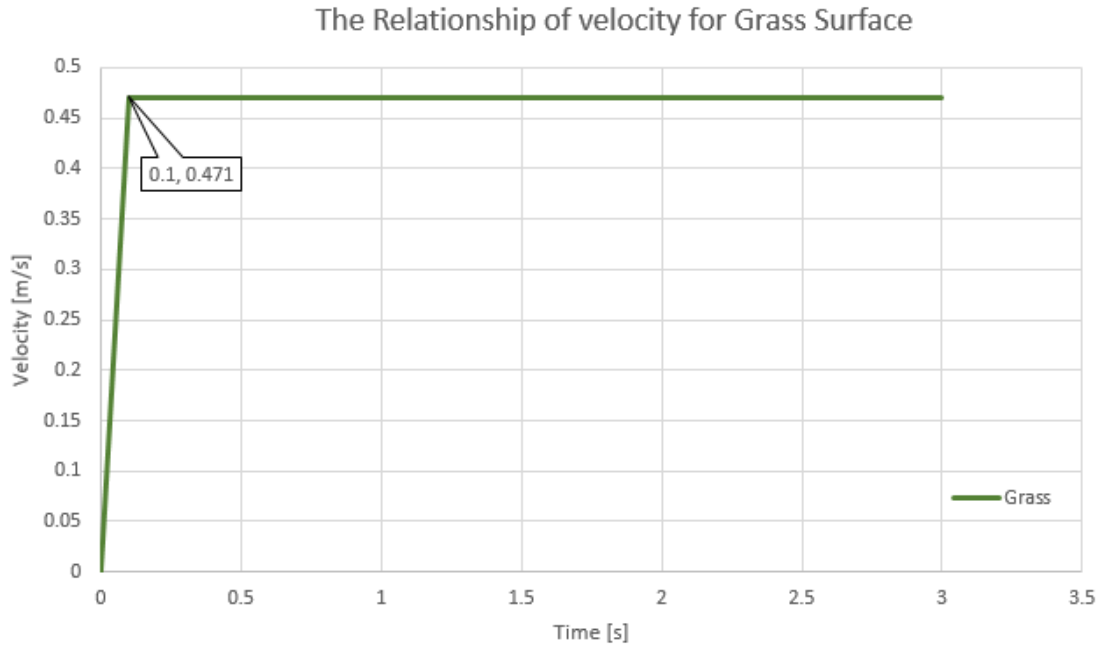


Figure 5.7: The response of the vehicle in Four wheel drive mode for the Grass surface.

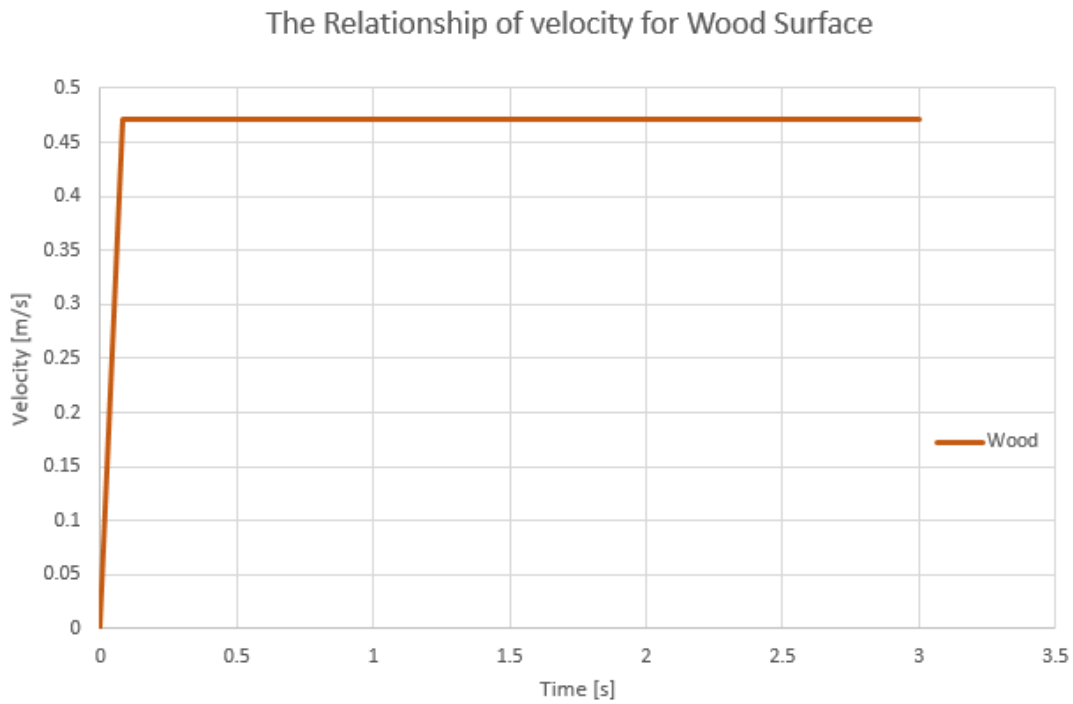


Figure 5.8: The response of the vehicle in Four wheel drive mode for the Wood surface.

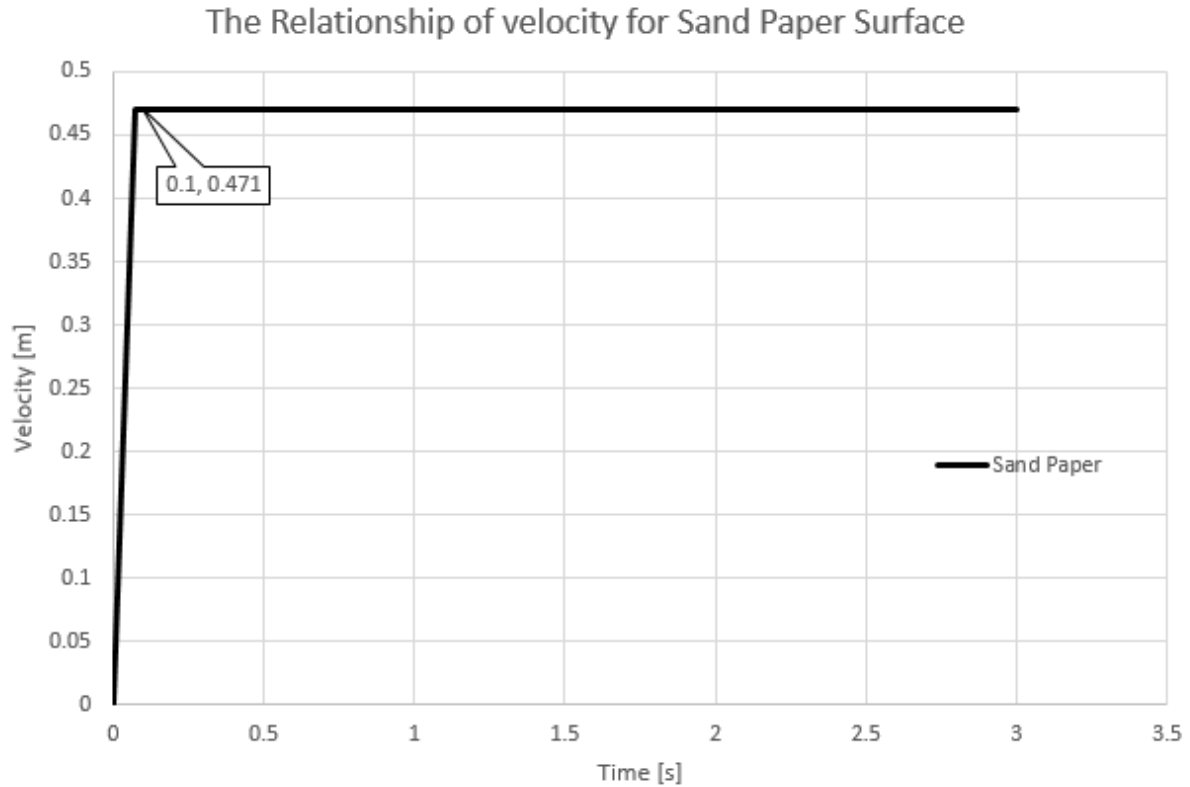


Figure 5.9: The response of the vehicle in Four wheel drive mode for the Sand Paper surface.

So as it can be seen in the previous graphs, the experimental work for the vehicle in the straight line experiment was done for the three operational modes, in three different surfaces of friction, and as it can be seen from the graphs, the theoretical values are very similar to the experimental ones, mostly because we are using an electrical motors with an efficiency of 99% comparing to the internal combustion engines used in the normal vehicles.

Also, we can see that the graphs illustrates a higher slope in the rear drive mode more than it is in the front drive mode, and more than both of them in the Four drive mode, even if it is a small difference between of them, due to the very small value of error as it is noticed and mentioned before.

Also as it is concluded from the experimental results, it can be seen than in the front drive mode that the values of acceleration were less than it in the rear drive mode, due to the load shift happening at the moment the vehicle starts moving, and also the values are less than the four wheel drive mode in both cases. The curves in chapter Five illustrate the relationship between the velocity and time in each mode, with different coefficient of friction. The slope of the line represents the acceleration of each mode, the more the slope increases the more does the acceleration and vice versa.

Conclusion

The project was successfully implemented and controlled well with an experimental procedure for it on the track which had a few barriers in the process of experimenting it, one of those obstacles was that the vehicle itself is a skid steering vehicle, and its dimensions and the control procedure were not as strong as possible, to make it pass the curved path in the optimal way as desired, but it was successful in the straight line path and documented as it can be seen in the experimentation chapter.

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Appendix A

Code:-

```
int setpoint1; //for motor1
int setpoint2; //for motor2
int setpoint3; //for motor3
int setpoint4; //for motor4
int balckwhite,x=0,y=0;
int PWM1; // for motor1
int DC1; // for motor1
int PWM2;// for motor2
int DC2;// for motor2
int PWM3;// for motor3
int DC3;// for motor3
int PWM4; // for motor4
int DC4; // for motor4
int button=0;
int button1=0;
int reardrive=0;
int frontdrive=0;
int fourwheeldrive=0;
int systemoff=0;
int mode=0;

void setup() {
pinMode(4,OUTPUT); // pwm for motor1
pinMode(50,OUTPUT); // dir1 for motor1
pinMode(52,OUTPUT); // dir2 for motor1
```

```

pinMode(5,OUTPUT); // pwm for motor2
pinMode(48,OUTPUT); // dir1 for motor2
pinMode(46,OUTPUT); // dir2 for motor2
pinMode(2,OUTPUT); // pwm for motor3
pinMode(24,OUTPUT); // dir1 for motor3
pinMode(22,OUTPUT); // dir2 for motor3
pinMode(3,OUTPUT); // pwm for motor4
pinMode(28,OUTPUT); // dir1 for motor4
pinMode(26,OUTPUT); // dir2 for motor4
pinMode(A1,INPUT); // Duty cycle for motor1
pinMode(A2,INPUT); // Duty cycle for motor2
pinMode(A3,INPUT); // Duty cycle for motor3
pinMode(A4,INPUT); // Duty cycle for motor4
pinMode(8, INPUT_PULLUP); // buttonPin "front and rear drive"
digitalWrite(8,HIGH);
pinMode(9, INPUT_PULLUP); // button1Pin "four wheel drive"
digitalWrite(9,HIGH);
//TCCR0B=TCCR0B&B11111000|B00000001;
Serial.begin(9600);
}

void loop() {
  button=digitalRead(8);
  button1=digitalRead(9);

  if(button==LOW)
  {
    // x=x+1;
    frontdrive=1;
    //systemoff=0;
    reardrive=0;

  }
}

```

```

else if(button1==LOW)
{
//fourwheeldrive=1;
//y=y+1;
//systemoff=0;
reardrive=1;
frontdrive=0;

}
/*
if(x==2)
{
reardrive=1;
x=0;
systemoff=0;

}
if(y==2)
{
systemoff=1;
}
*/

balckwhite=analogRead(A0);          // for black/white sensor
////////////////////////////////////
//////////////////////////////////// pwm stettings////////////////////////////////////

setpoint1=analogRead(A1);
PWM1=map(setpoint1,0,1023,0,255);    // for motor1
DC1=map(PWM1,0,255,0,100);          // for motor1
setpoint2=analogRead(A2);           // for motor2
PWM2=map(setpoint2,0,1023,0,255);    // for motor2
DC2=map(PWM2,0,255,0,100);          // for motor2
setpoint3=analogRead(A3);           // for motor3

```

```

PWM3=map(setpoint3,0,1023,0,255); // for motor3
DC3=map(PWM3,0,255,0,100); // for motor3
setpoint4=analogRead(A4); // for motor4
PWM4=map(setpoint4,0,1023,0,255); // for motor4
DC4=map(PWM4,0,255,0,100); // for motor4
////////// running motors//////////
/*
if(mode==1) // potentiometer
{
analogWrite(4,PWM1); // for motor1
digitalWrite(52,1); // for motor1
digitalWrite(50,0); // for motor1
analogWrite(5,PWM2); // for motor2
digitalWrite(48,1); // for motor2
digitalWrite(46,0); // for motor2
analogWrite(2,PWM3); // for motor3
digitalWrite(24,1); // for motor3
digitalWrite(22,0); // for motor3
analogWrite(3,PWM4); // for motor4
digitalWrite(28,1); // for motor4
digitalWrite(26,0); // for motor4
}
*/
if(mode==2) // sensor mode
{
if(balckwhite>800) //white line
{
analogWrite(2,PWM1); // for motor1
digitalWrite(22,1); // for motor1
digitalWrite(24,0); // for motor1
analogWrite(5,255); // for motor2
digitalWrite(46,1); // for motor2
digitalWrite(48,0); // for motor2
}
}

```

```

else if(balckwhite>=5 && balckwhite<700) //black line
{

setpoint2=analogRead(A2);          // for motor2
PWM2=map(setpoint2,0,1023,0,255);  // for motor2
DC2=map(PWM2,0,255,0,100);        // for motor2
analogWrite(2,170);                // for motor1
digitalWrite(22,1);                // for motor1
digitalWrite(24,0);                // for motor1
delay(200);

digitalWrite(22,0);                // for motor1
digitalWrite(24,1);                // for motor1
delay(800);
analogWrite(5,140);                // for motor2
digitalWrite(46,1);                // for motor2
digitalWrite(48,0);                // for motor2
delay(100);
digitalWrite(46,0);                // for motor2
digitalWrite(48,1);                // for motor2
delay(800);
}
/*
else if(balckwhite>=5 && balckwhite<700) //black line
{

setpoint2=analogRead(A2);          // for motor2
PWM2=map(setpoint2,0,1023,0,255);  // for motor2
DC2=map(PWM2,0,255,0,100);        // for motor2
analogWrite(2,PWM1);               // for motor1
digitalWrite(22,1);                // for motor1
digitalWrite(24,0);                // for motor1
analogWrite(5,255);                // for motor2
digitalWrite(46,1);                // for motor2

```

```

digitalWrite(48,0);      // for motor2
delay(500);
digitalWrite(46,0);     // for motor2
digitalWrite(48,1);     // for motor2
delay(1000);
}
*/
}

if(frontdrive==1)
{

analogWrite(2,PWM1);    // for motor1
digitalWrite(22,1);    // for motor1
digitalWrite(24,0);    // for motor1
analogWrite(5,PWM2);   // for motor2
digitalWrite(46,1);    // for motor2
digitalWrite(48,0);    // for motor2
}

/*
if(balckwhite>800)     //white line
{
analogWrite(2,PWM1);   // for motor1
digitalWrite(22,1);    // for motor1
digitalWrite(24,0);    // for motor1
analogWrite(5,255);   // for motor2
digitalWrite(46,1);    // for motor2
digitalWrite(48,0);    // for motor2
}

```

```

else if(balckwhite>=5 && balckwhite<700) //black line
{

    setpoint2=analogRead(A2);          // for motor2
    PWM2=map(setpoint2,0,1023,0,255);  // for motor2
    DC2=map(PWM2,0,255,0,100);        // for motor2
    analogWrite(2,PWM1);               // for motor1
    digitalWrite(22,1);                // for motor1
    digitalWrite(24,0);                // for motor1
    analogWrite(5,255);                // for motor2
    digitalWrite(46,1);                // for motor2
    digitalWrite(48,0);                // for motor2
    delay(500);
    digitalWrite(46,0);                // for motor2
    digitalWrite(48,1);                // for motor2
    delay(1000);
}
*/

else if(reardrive==1)
{

    analogWrite(2,PWM1);               // for motor1
    digitalWrite(22,0);                // for motor1
    digitalWrite(24,1);                // for motor1
    analogWrite(5,PWM2);                // for motor2
    digitalWrite(46,0);                // for motor2
    digitalWrite(48,1);                // for motor2
}

/*

```



```

else if(fourwheeldrive==1)
{
  if(balckwhite>800)          //white line
  {
    analogWrite(5,PWM2);
    digitalWrite(48,1);
    digitalWrite(46,0);
    analogWrite(2,255);
    digitalWrite(24,1);
    digitalWrite(22,0);
    analogWrite(4,PWM1);      // for motor1
    digitalWrite(52,1);      // for motor1
    digitalWrite(50,0);      // for motor1
    analogWrite(3,255);      // for motor2
    digitalWrite(28,1);      // for motor2
    digitalWrite(26,0);      // for motor2
  }

else if(balckwhite>=5 && balckwhite<700) //black line
{

  setpoint2=analogRead(A2);  // for motor2
  PWM2=map(setpoint2,0,1023,0,255); // for motor2
  DC2=map(PWM2,0,255,0,100); // for motor2
  analogWrite(5,PWM2);      // for motor1
  digitalWrite(48,1);      // for motor1
  digitalWrite(46,0);      // for motor1
  analogWrite(2,255);      // for motor2
  digitalWrite(24,1);      // for motor2
  digitalWrite(22,0);      // for motor2
  delay(100);
  digitalWrite(24,0);      // for motor2
  digitalWrite(22,1);      // for motor2

```

```

delay(1500);
setpoint2=analogRead(A2);      // for motor2
PWM2=map(setpoint2,0,1023,0,255); // for motor2
DC2=map(PWM2,0,255,0,100);    // for motor2
analogWrite(4,PWM1);          // for motor1
digitalWrite(52,1);           // for motor1
digitalWrite(50,0);           // for motor1
analogWrite(3,255);           // for motor2
digitalWrite(28,1);           // for motor2
digitalWrite(26,0);           // for motor2
delay(100);
digitalWrite(28,0);           // for motor2
digitalWrite(26,1);           // for motor2
delay(1500);
}
}

*/
Serial.print("pwm1= ");
Serial.println(x);
}

```

Also the following are the Pictures of the Actual Built Project:-

