Slip and Skid Control of a Wheeled Mobile Robot

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Slip and Skid Control of a Wheeled Mobile Robot

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In

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Slip and Skid Control of Wheeled Mobile Robot

A Thesis Presented to

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A Post Graduate Thesis submitted to the Department of Electrical Engineering as partial fulfilment of the requirement for the award of Degree of MS in Electrical Engineering.

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Declaration

I Khuram Naveed **CIIT/FA11-REE-020/ISB** hereby declare that I have produced the work presented in this thesis, during the scheduled period of study. I also declare that I have not taken any material from any source except referred to wherever due that amount of plagiarism is within acceptable range. If a violation of HEC rules on research has occurred in this thesis, I shall be liable to punishable action under the plagiarism rules of the HEC.

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DEDICATION

This thesis is dedicated to my Mother, other Family Members, who supported my education and kept me motivated in peaks and falls of my degree.

This research work is also dedicated to all my Teachers, who lead me with their strong vision; and my Friends who became a great moral support for me and helped me in every possible way.

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ABSTRACT

Slip and Skid Control of a Wheeled Mobile Robot

Recent technological advancements have made it possible to see the 'fiction' robots in reality in various spheres of our life. Most of these applications demand a robot to be mobile, thus requiring a locomotion system that can permit motion of a robot. The locomotion can be based on legs (humanoid), tracks (tank-like) or wheels (car-like). Wheels devise efficient locomotion strategy and thus wheels are the locomotion mean for most of the mobile robots keeping in view their inherent advantages. Contrary to their merits, the major disadvantage of the wheel is its tendency to slip especially on the slippery surfaces.

This thesis is aimed at presenting an efficient slippage control mechanism for a Wheeled Mobile Robot (WMR) operating on various slippery surfaces. The algorithm has been tested on custom platform that is specifically designed and developed for this research work. This platform is centered on a car-like wheeled structure equipped with actuation subsystem and various sensory mechanisms as per task requirements. Actuated with two DC motors (a DC servo motor and a simple DC motor), the platform steers in Ackermann style. The sensory system mainly consists of speed and angle sensors. For tele-operating the developed WMR, a remote control mechanism has to be designed. A telemetry system displaying the required information (speed, angle and position of robot) in real time has been realised. Moreover, a camera based motion monitoring system has been developed. Once platform has been developed and tested for its functionality, the proposed algorithm for slippage control of WMR has been validated on a slippery surface. The candidate slippery surface in the present research is a stone covered uneven and slippery terrain. Data collected from the platform through telemetry system has been used to evaluate the performance of the slip control algorithm implementation. Results show that the proposed controller minimizes the slip up to 7% of the initial slip induced in the wheel while its motion.

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LIST OF ABBREVIATIONS

ADC	Analog to Digital Conversion
BT	Bluetooth
GPS	Global Positioning System
ICR	Instantaneous Center of Rotation
IC	Integrated Circuits
I/O	Input/Output
MCU	Microcontroller Unit
RPM	Revolutions per Minute
UART	Universal Asynchronous Receiver Transmitter
UAV	Unmanned Aerial Vehicle
USB	Universal Serial Bus
WMR	Wheeled Mobile Robot

Chapter 1

Introduction

1.1 Robotics

Robots are programmable, self-controlled electromechanical machine to perform human like tasks. Robots are inherently much faster and accurate compared to human. They are efficient because unlike human robots never tire, they don't get bored of repetitive work, they are impossible to distract from the task at hand and they can be handful in conditions which are not conducive or may even be dangerous for a man to work. Because of these advantages of robots over human, they have taken over the danger some, delicate and mundane tasks from man. Due to their high processing speeds and non-tiredness, robots have increased the rate of productivity in industry. The main difference between other machines and robots is that they are intelligent and work on their own also they are sensitive to their environment as well [1].

In antiquity, word robot was just a fiction up till twentieth century when it became a reality. Since then robots have greatly influenced human life and changed the structure of society. Robots were used as a mean of entertaining Royals in the beginning but latter they were used in industry as labour. First real use of robotics into industry was introduced by George Devol who developed and installed a manipulator into his factory which could lift, die, cut pieces of metal and stack them for human workers [2].

Subsequently robotics has affected different streams of industry very positively. Robotic arms and manipulators have become integral part of industrial applications just because they can work with greater speed, accuracy and they don't get bored of monotonous tasks like picking and placing. They help increase the productivity because they are not tire of working which allowed extra shifts at nights as well. Industrial manufacturing has observed greatest success in the field of robotics. Robotic manipulators make a 2 billion dollar industry used for making portable computer and phones by placing surface mounted components with superhuman accuracy, spot welding and painting etc. Instead of all this success these manipulators suffer from a fundamental problem which is their inability to move. A fixed manipulator has a limited range of motion or workspace that depends on where it is bolted down while a moveable manipulator would best fulfil the job by moving wherever it is needed [3].

Use of automated harvesters, automated robots for planting and extracting crops has seriously profited agriculture. Similarly waste disposal organizations uses robotics for dirtier jobs. Another industry where automated robotics has benefitted the most is medical industry. Robotic manipulators are used for Tele-operations, sophisticated surgeries and rehabilitation of handicapped [4]. Military is using robots not only for surveillance and transportation but also for attacking the enemy. In addition to this it has not only facilitated our daily life as an aider or helper. With all these services robots have also allowed human to look beyond its limitation i.e. exploring space, depth of land and sea [5]-[7].

1.2 Mobile Robots

While the role of technology in our lives is increasing, robotic applications facilitating our daily life are also increasing. Most of these applications demand a robot to be mobile, thus requiring a locomotion system that can permit motion of a robot. Robots having the ability to move are called mobile robots. There are further classifications in Mobile Robots as to how a robot moves or what the means of its motion are? Given below are some types of mobile robots based on their locomotion strategies.

Locomotion is the mechanism used by a robot for transporting itself from one place to other. Robots use different type of locomotion strategies for its motion, the most famous ones are walking robots (Humanoid robots), flying robots (UAVs), swimming robots (Submarine), snake robots, skid steered robots (Tank like robots) and wheeled robots (Car like Robots etc.).

Figure 1.1 shows the types of robots in hierarchical view.

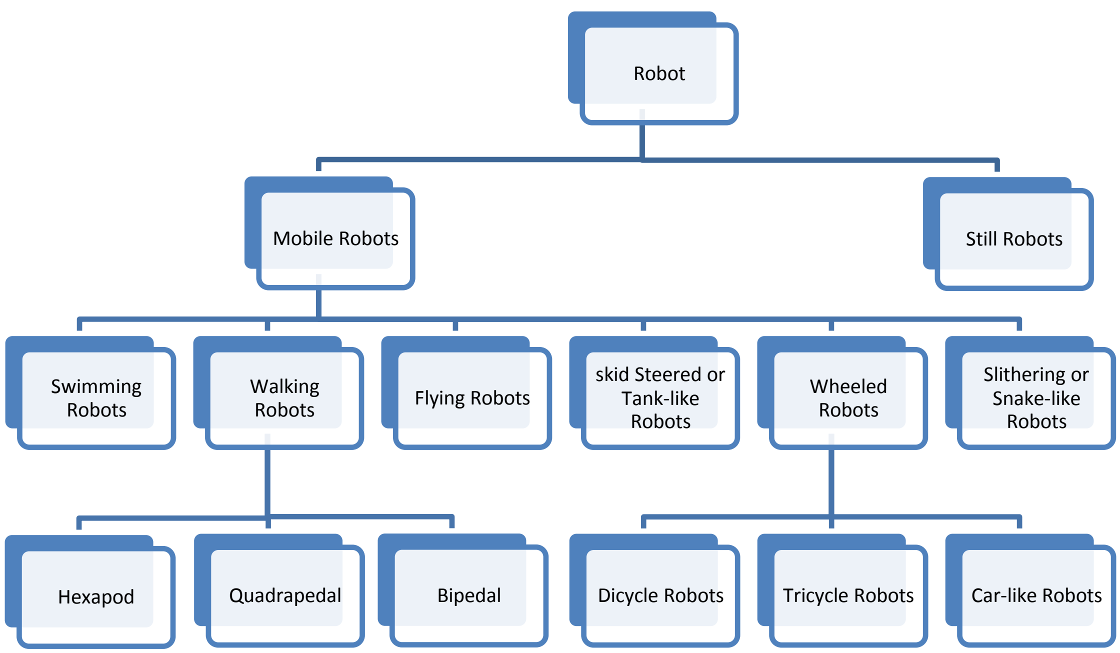


Figure1.1: Types of robots

1.2.1 Walking Robots

Walking robots use legs for their locomotion. The biggest plus of this locomotion technique is that it provides a robot with the capability to move on uneven terrains where most of the other strategies fail. On the contrary it is very difficult to implement practically as it is very hard to keep the structure of robot upright and stable not only while walking but also while standing. In addition to this they are cumbersome and slow. They are further categorized as how many legs are used for locomotion.

a) Bipedal (b) Quadrupedal b) Hexapod

Figure 1.2: Walking robots [26-28]

Bipedal robots are like human and use two legs for their locomotion but their biggest issue is instability while moving. In order to fix this problem of instability, number of legs is increased to four in quadrupedal robots (just like Animals) but still they are very slow. Similarly robots with 6 legs namely Hexapods are also developed for different scenarios. Such robots move like insects having more than four legs and provide even more stability but have control issues. Figure 1.2 presents a realization of aforementioned robots.

1.2.2 Flying Robots

These robots possess the ability to fly to move from one place to other such as unmanned aerial vehicle. Such robots are mostly used by military as spy for surveillance. An example of it is a drone (shown in Figure 1.3) used for surveillance and attack as well.

Figure 1.3: Flying Robots [29]

1.2.3 Skid Steered Robots

Skid steered robots or tank like robots (shown in Figure 1.4) use tracks for locomotion, where all the wheels on one side are aligned through tracks on longitudinal axis. In order the robot to turn in this strategy tracks need to skid and hence this strategy is called skid steered. This strategy is useful in off-the road robotics on uneven or sandy terrain for land-mine detection, planetary explorations, rescue mission and wars [8].

Figure 1.4: A tank-like Robot [30]

1.2.4 Swimming Robots

Robots having the ability to move in or under water are termed as swimming robots. Marine robots can move under water, used for sea exploration, surveillance and wars as shown in Figure 1.5.

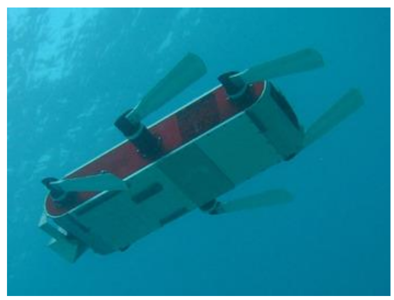


Figure 1.5: Submarine moving under water [31]

1.2.5 Snake Like Robots

Such robots use slithering mechanism for their motion just like snakes. Snake like robots possess multiple degree of freedom (hyper redundant). They are made up of multiple joints with linkages and move through internal shape changes. They are capable of moving on uneven grounds and slopes. However their diverse mechanism allows them to move through channels, pipes, poles and trees [9].

a) Slithering motion b) Obstacle avoidance c) Tree climbing

Figure 1.6: Snake Like robots [32-34]

1.2.6 Wheeled Robots

These robots use wheels for their locomotion such as autonomous cars, autonomous wheel chairs etc. Mostly the combinations of two, three and four wheels are used to provide locomotion as shown in Figure 1.7. Two wheeled robots are called dicycle; they are tough to balance because in order to keep the structure upright they need to keep moving. Normally the third wheel is added as a support to resolve the stability issue. In this case back wheels are used for driving as well as steering called differential drive mechanism. Another drive mechanism in three wheel strategy is tricycle where front wheel is not just a support wheel but also it is used for steering while back wheels are used for driving[10].

a) Dicycle robot b) Tricycle robot c) Car-like robot

Figure 1.7: Wheeled Mobile Robots [35]

Four wheels govern ideal structure not only in terms of stability but also in terms of control. In this strategy front two wheels are used for steering and back wheels are used for driving such robots are called car-like robot. Robots using wheels for their motion are generally termed as Wheeled Mobile Robots (WMR). WMRs will be discussed in detail ahead in next chapter.

1.3 Motivation for Wheeled Robots

Wheels are the most famous and useful way for robot motion because they possess following inherent advantages over other locomotion strategies [11].

- Simple structure
- Easy to build
- Faster than any other locomotion strategy
- Consume least energy for motion
- Minimum control effort
- Stability

These inherent qualities have made WMRs an important candidate for industrial as well military applications. On the contrary WMRs have some inherent disadvantages as well.

- Slipping
- Inability to move on uneven, rocky or declining surface

In this thesis we intend to minimize slip and make its motion smooth on slippery and uneven terrain.

1.4 Problem Statement

Wheel slip and skid is a vital problem in WMRs which enforces some stern constraints on their motion in order to avoid destruction and injuries. Slip depends largely on the type of terrain. Essentially, probability of slip increases as the grip with the surface of the terrain decreases. In our daily life, every now and then we come across such surfaces where it becomes almost impossible for a WMR to continue its motion because of the slip and skid due to the slick nature of the terrain. Thus the importance of realizing slip and skid control mechanism increases when terrain is slick or slippery. Such mechanism, keeping in view dire consequences reduces or if possible removes the wheel non-linearity. This work intends to address this critical operational problem of WMRs and help them to smooth their motion in unfavourable circumstances.

Chapter 2

Wheeled Mobile Robots

2.1 Introduction

As discussed earlier wheels devise an efficient mechanism for robot locomotion because they consume least energy for their motion. They are easier to move and possess the ability to move faster than all other locomotion strategies. More importantly they require minimal control effort compared to other locomotion strategies simply because of less stability issues and simple mechanism [11]. Even with all these inherent paybacks WMRs cannot travel through uneven, rocky and declining surfaces. This is the reason why they are not used for off-the-road activities. But the inherent backdrop with wheels as a mean of locomotion is their tendency to slip specially on slippery surfaces [12]. We will discuss this backdrop of WMRs in detail ahead in this chapter as the aim of this thesis is to tackle the problem of slipping in the scenarios facilitating slip.

2.2 Classifications of WMRs

Robots are divided into classes based on their structural and behavioural characteristics. On the basis of its structure WMRs are divided into four major categories classes. The structural properties include number of wheels their mobility, steerability and instantaneous center of rotation. Before going ahead it is important to understand these structural properties.

2.2.1 Degree of Mobility and Steerability

Mobility is measured from the Instantaneous center of Rotation (ICR). ICR is the cross point of all the axis of wheels as shown below in the figure 2.1. Degree of mobility is the number of ICRs of the robot while the degree of steerability is the number of steerable wheels in a robot [11].

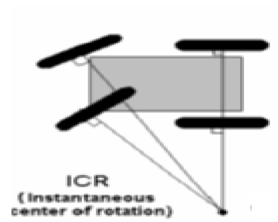


Figure 2.1: Car-Like Robot ICR [11]

2.3 Types of Wheels

Wheels are mainly of two types; special wheels omnidirectional motion and standard wheels for conventional non-holonomic motion [11]. Both are discussed in below.

2.3.1 Special or Omnidirectional Wheels

As the name suggests these wheels are different from the traditional wheels they are capable of moving in all directions. These wheels are used to make holonomic mobile robots. A holonomic mobile robot has the ability to move in any desired direction without taking a turn. Normally Swedish and spherical wheels are used for this purpose.

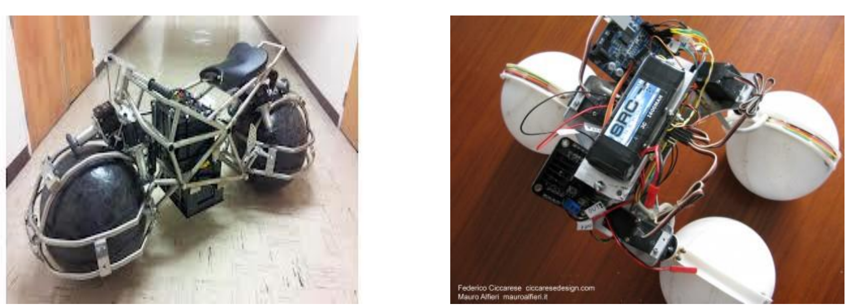
2.3.1.1 Swedish Wheels

Swedish wheels are specially developed for omni directional motion, they have the ability to provide longitudinal as well as lateral motion at a time. The beauty of this wheel is that it is not a single wheel there many wheels in one all moving in different directions. As shown in the Figure 2.4 below there is a big core wheel which executes longitudinal motion while there are many small wheels as the end of this core wheel which move in lateral direction. While the core wheel moves forward the smaller wheels or rollers move perpendicular to its motion allowing the wheel to move in all directions.

Figure 2.2: Swedish Wheels[36]

2.3.1.2 Spherical Wheels

These wheels are made of spheres which are actuated using motors to move in any specific direction. Actuators make rolling contact with the sphere to direct and derive it. These types of wheels provide smooth omni directional motion. Figure 2.5 below shows an omni directional motor cycle using these wheels. But they are not widely use because of their inability to overcome irregular ground conditions and high payload due to the contact point.



a) Spherical wheeled dicycle

b) Spherical wheeled tricycle

Figure 2.3: Spherical wheeled robots [37-38]

2.3.2 Standard Wheels

Standard wheel is the conventional wheel used in vehicles. Robots using these types of wheels are called nonholonomic mobile robots. Standard wheels satisfy the condition of nonholonomy as they cannot provide omni directional motion mainly because violating no slip and pure rolling conditions [13]. These wheels are simple in mechanical design and operation. There are further classifications in this type of wheels depending on following points.

- Longitudinal and lateral offsets of wheel (‘*d*’&’*b*’)
- Mechanical design allows steering or not?
- Steering or deriving actuation mechanism

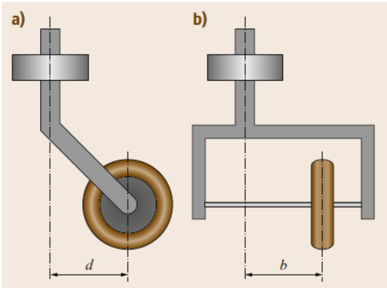


Figure 2.4: Mechanical views of a wheel [11]

Longitudinal offset *d* is the distance between the center of wheel and the point of contact with chassis of robot. This offset plays an important role in the kinematics of WMR(Figure 2.6). It is zero for conventional wheel but for an off-centered orientable wheel it is nonzero.

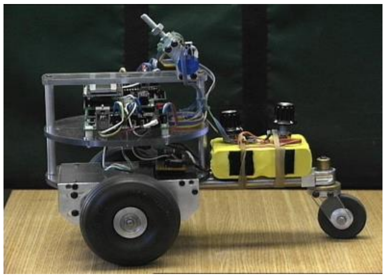


Figure 2.5: A tricycle robot with a caster wheel for steering [39]

Similarly the lateral offset *b* is also taken as zero normally except in special cases where it is kept on purpose to satisfy the condition of pure rolling. An off-centered orientable wheel with nonzero *b* or *d* is called a caster wheel. Such caster wheels are normally used in developing a tricycle shown in Figure 2.7. The front wheel is a caster wheel having a nonzero offset *d* and the back wheels are conventional standard wheels with zero *b* and *d.*

Secondly, wheel's mechanical design is very import aspect while selecting a wheel. Its mechanical design tells u whether the wheel is steerable or fixed. In the figure back wheels are fixed while front wheel is steerable. Next point of concern is how to steer a wheel; actively or passively. Active steering is done through a dedicated actuator while passive steering takes place when a wheel undergoes a turn under the effect of some other wheels turn [11].

Depending on its above mentioned conditions a standard wheel has four types (Figure 2.8).

i. Passively steered caster wheel with fixed steering axis &*offset* $d = 0$
ii. Actively steered caster wheel with *offset* $d = 0$
iii. Passively steered caster wheel with fixed steering axis &*offset* $d > 0$
iv. Actively steered caster wheel with *offset* $d > 0$

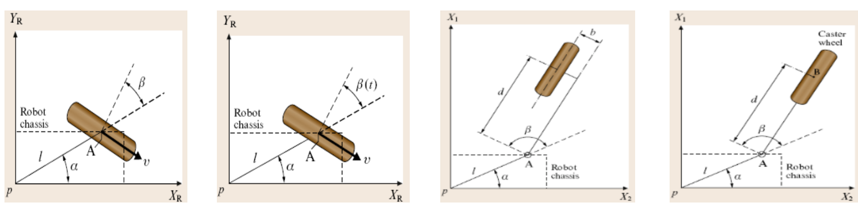


Figure 2.6: Different types of wheels based on steerability and offset *b & d*[11]

2.4 Robot Classes

WMRs are classified on the basis of their mobility and steerability. A robot having the *m* degree of mobility and *s* degree of steerability has a type ***(m,s)***.

- Type (3,0)

  These WMRs have zero fixed and zero steerable wheels which they have either free caster wheels or Swedish wheels which can move in all directions. They are termed as omnimobile robots.

- Type (2,0)

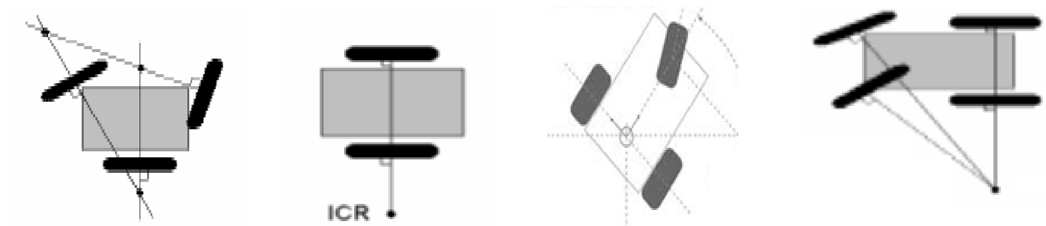
  These WMRs have at least one fixed wheel but no steerable wheels. All the fixed wheel share common axle to make their axis one. An example may be a wheel chair.

- Type (2,1)

These robots have no fixed wheel and at least one steering wheel. A try cycle is the example of such robots.

- Type (1,1)

These robots have one or more fixed wheels on single axle while and one or many steering wheels on single common axis as well. Another important condition is that the steering and fixed wheels must not share same common axle. A car-like robot is an example of this type [12]. Figure 2.9 gives an overview of robot classes.

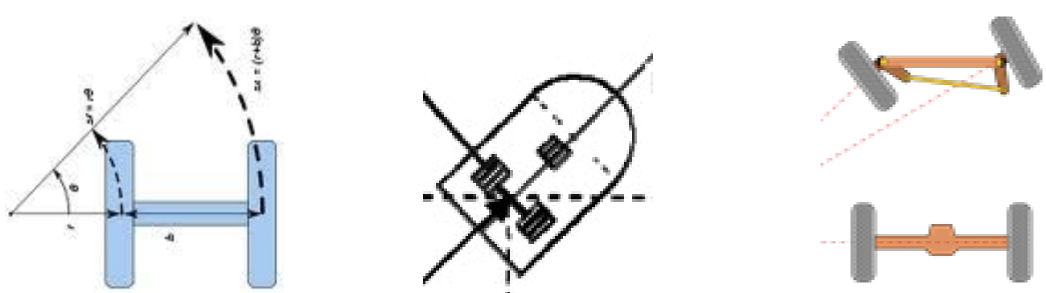


a) Type(3,0) b) Type(2,0) c) Type(2,1) d) Type(1,1)

Figure 2.9: Classes of WMRs based on their mobility and steerability [11]

2.5 Driving Strategies for WMRs

WMRs are driven using many different strategies depending on their class. These strategies differ in the way they force a turn on a robot. Two wheeled mobile robots are driven usually with differential derive strategy in this strategy both the wheels are driven using separate motors and while taking a turn one wheel is slowed or stop while the other one rotate around it. These robots are very famous in educational activities. Differential drive is also used to drive three wheeled mobile robots where the third wheel is acting just as a supportwheel to remove the stability issues. Another strategy for three wheeler



a) Differential Drive b) Tricycle Drive c) Ackerman Drive

Figure 2.10: Different driving strategies for WMRs [11]

robot is where front wheel does steering and back wheels do driving, normally tricycles use this strategy. Ackerman derive mechanism is somewhat similar where both the front wheels are used for steering using a servomotor while back wheels derive it. Figure 2.10 gives an overview of these strategies. Car like robots are driven using this strategy [11].

2.6 Slip and Its Types

Phenomenon of wheel slip occurs when the grip between wheel and the surface decreases while it is in motion. The reasons behind it may be sudden application of breaks, over speeding, sharp turn or a slippery surface. Slip may cause deadly and dangerous accidents especially on slippery terrain which facilitates slip and will never allow smooth motion of a robot.

Depending on its direction, slip has two types; longitudinal and lateral slippage. Longitudinal slippage is also referred to as slippage while lateral slip is also called skidding. Both of these are discussed separately below.

2.6.1 Longitudinal Slip or Slippage

Longitudinal slip happens when the speed of motion of the vehicle does not remain equal to wheel's linear velocity [13]. We call it longitudinal slippage because it is parallel to the direction of motion of robot. It is referred simply *slippage* in common understanding thus in this thesis we will use slippage for longitudinal slippage. One of the main reasons of this type of slip is tire deformation, where the speed of tire decreases due to its deformation but inertia of vehicle wants the vehicle to move on an increased speed hence forcing it wheels to slip.

2.6.2 Lateral Slippage or Skid

This type of slip is perpendicular to the direction of motion of wheel hence called lateral slippage or simply *skid*. While negotiating a sharp turn a cornering force acts on the wheel of the robot displacing it away from its plane. This movement of wheel away from its plane is called skid.

2.7 State of the Art of Slip Control for WMRs

Researchers around the world have done considerable work on modelling of wheel slip & skid in WMRs. Wang and Low presented a WMR model in the presence of wheel skidding and slippage from the perspective of control design [13]. In mid-nineties, Balakrishna and Ghosal [14] modelled slip in a WMR considering it to be non-holonomic assuming that wheel undergoes no pure-rolling in practical circumstances. Both of these scientists were also involved in presenting a GPS based skidding and slippage control for a car-like robot. The robot incorporated Real-Time Kinematic (RTK)-GPS and other sensors to measure the WMR's posture, velocities and perturbations due to wheel skidding and slipping for control compensation [15]. Just recently, Ozoemena*et al.* [16] modelled and analysed a five wheeled robot with slip on an uneven terrain.

Scientific community reports significant research on slip & skid control for WMRs. Kececi and Tao [17] addressed the problem of stability and tracking of a vehicle during slippage of its wheels without braking using an adaptive vehicle skid control. In 2010, Amodeo*et al.* [18] developed a sliding mode traction controller to control the wheel slip during skid braking and spin acceleration of a WMR. S. J. Yoo [19] proposed an adaptive tracking control of a WMR encountering with unknown skidding and slipping. A path tracking control of a WMR considering slippage and unknown dynamics was implemented by W. Dong [20]. In recent times, Magallan*et al.* proposed a sliding-mode observer to estimate the wheel slip and vehicle velocity under unknown road conditions by measuring only the wheel speed [21]. Afterwards Tian and Sarkar have presented a study of multi-robot formation control subject to slip [22]. Lately in 2013, Ćirović and Aleksendrić have been involved in presenting a couple of research works involving an adaptive fuzzy logic for slip control [23] and neural network based longitudinal slip control [24].

Considering all of the aforementioned research works, it is evident that slip and skid control has been very hot topic among roboticians. The present thesis is an effort to extend this research by focusing slip and skid control on slippery terrains.

Chapter 3

Slip Modelling and Control

Longitudinal slip or simply slippage happens when linear velocity of a wheel does not remain equal to vehicle velocity. For longitudinal slip problems normally the straight line desired trajectory is used. Thus the driving wheel is modelled for the simulation without any steering action. The motion control of WMRs in the past was constrained about the assumptions that it fulfils the non-slipping and non-skidding criteria. The performance of these control algorithms was never satisfactory in practical situations, thus it is very important to obtain the slip model of the wheel and then compensate it [25].

3.1 Wheel Modelling with slippage

We know that when a wheel interacts with ground, the traction force overcomes all the resistive forces making move on the ground. The fig. below shows the resistive forces acting on a wheel while its motion.

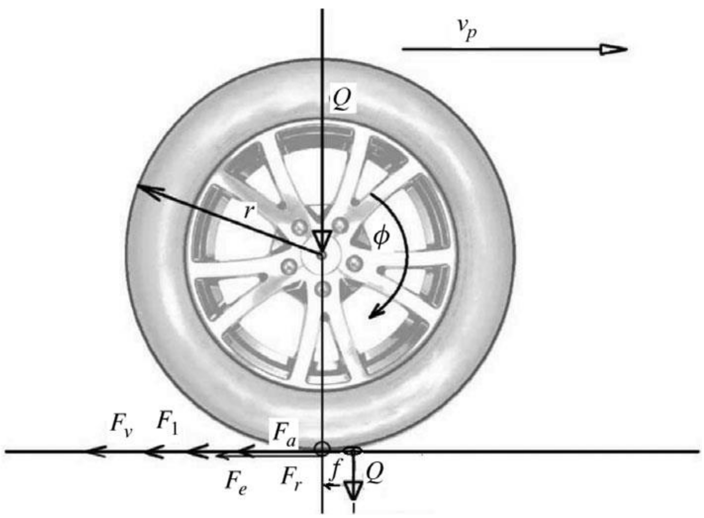


Figure 3.1: Resistive forces on wheel

In the first step we consider the forces and torques acting on the wheel to develop its slip model.

$$F_t = F_l + F_y + F_r + F_a + F_e \qquad (3.1.1)$$

Where F_t is Wheel traction force, F_I is wheel inertia force and $F_v$is vehicle inertia force, F_r is rolling resistance force and F_a is the cohesion force between road and tire while F_e represents all the other resistive forces. These forces are defined by following equations.

$$F_v = m\dot{v}_p \qquad (3.1.1a)$$

Where *m* is the mass of robot while v_p is the linear velocity of the robot.

If *r* is the radius of the wheel, Q is the force acting on the wheel shaft than rolling resistance force is given by,

$$F_r = \frac{fQ}{r} \tag{3.1.1b}$$

Here *f/r* is rolling resistance coefficient without any dimensions. Similarly another unit less constant is wheel ground cohesion coefficient μ_0 which is used for the computation of cohesion force.

$$F_a = \mu_o Q \tag{3.1.1c}$$

Now substituting the value of these forces from 3.1.1(a,b,c) in 3.1.1 to get the following result,

$$F_t = F_l + m\dot{v_p} + f_o Qr + \mu_o Q + F_e \tag{3.1.2}$$

The actuating torque M_t can be calculated from the wheel traction force F_t by considering the fact that torques of resistive forces is balanced by the actuating torque.

$$M_t = J\ddot{\emptyset} + m\dot{v_p}r + f_o Q_r + \mu_o Qp + M_e \tag{3.1.3}$$

Where $F_v r = m\dot{v_p}r$is the wheel moment inertia overcoming the vehicle inertia. Rolling resistance is compensated by the $F_r r = f_o Q_r$ and the torque suppressing cohesion force is given as $F_a r = \mu_o Qp$ where p is the normalized radius of the wheel ground extract and plays as the acting arm for F_r for the torque due to cohesion without depending on the wheel radius and $M_e$is the torque due to external factors.

3.1.1 No Slippage Condition

The motion of the mobile robot will be slippage free if its velocity (v_p) is equal to the linear velocity of its wheels $v_c = \dot{\emptyset}r$ (where $\dot{\emptyset}$ is the angular velocity of wheel).

$$v_c = v_p$$

$$v_p = \dot{\emptyset}r \tag{3.1.4}$$

When slip occurs the actuating torque M_t must be equal to $\mu_c Qr$. Where μ_c is virtual slip coefficient, thus placing $M_t = \mu_c Qr$in eq. (3.1.3) we get:

$$J\ddot{\emptyset} + m\dot{v_p}r + f_0 Qr + \mu_o Qp + M_e = \mu_c Qr \tag{3.1.5}$$

$$\ddot{\emptyset} \leq \frac{\mu_c Qr - f_0 Qr - \mu_0 Qp - M_e}{J + mr^2} \tag{3.1.6}$$

3.2 Slip Ratio and Friction Coefficient

The difference between the linear velocity of the wheel and vehicle velocity has a proportional relation with longitudinal slip. Slip ratio signifying the wheel ground motion is represented as:

$$\lambda = \frac{v_c - v_p}{\max(v_c, v_p)} \tag{3.2.1}$$

The ground conditions and wheel ground relative motion are main factors defining the μ_x and μ_y i.e. Longitudinal and lateral friction coefficients. These factors are very important in vehicle dynamics. Figure 3.1 shows a graph between frictional coefficient and slip ratio λ. Here the in the curve μ_x (λ), μ_x increases with the increase in slip ratio till it reaches its peak value μ_{xp} at slip ratio λ_p. If the slip ratio keeps on increasing further, there is a sudden decline in μ_x causing the wheel to spin with instability on the ground. On the contrary, in the $\mu_y(\lambda)$ curve, μ_y decreases with the increase in λ or with the increase in speed.

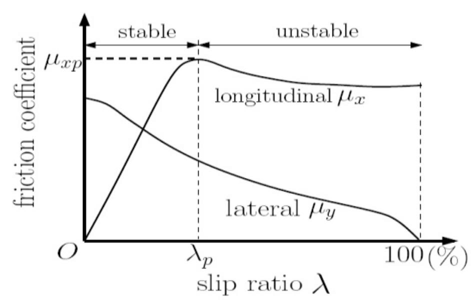


Figure 3.2: Friction coefficients

As the straight line desired trajectory is applied for longitudinal slip, therefore no steering action is required and only μ_x relation is involved in the calculation of slip ratio in simulation. Now assumingly the slip declines exponentially.

$$\lambda(t) = \lambda(o)exp(-at) \tag{3.2.2}$$

Where,

t = time measured from start of slip reduction.

a = constant chosen to keep the wheel velocity and acceleration in acceptable range.

3.3 Critical Slip Coefficient

The proposed virtual slip coefficient model depends on slip ratio exponentially [25].

$$\mu_c s = \mu_c \exp(-\frac{\lambda^2}{b}) \tag{3.3.1}$$

For simplification in eq. (3.1.6) neglecting the external Moment M_e and The moment resulting from cohesion during slip reduction we get,

$$\ddot{\phi} = \frac{\mu_c Qr}{J + mr^2} \tag{3.3.2}$$

Now using eq. (3.3.1) & eq. (3.3.2), we get

$$J\ddot{\phi} + m\dot{v}_p r = \mu_c \exp(-\frac{\lambda^2}{b})\, Qr \tag{3.3.3}$$

As slip ratio is a function of time so the velocity v_p is given by the $v_p = \dot{\phi}r(1 - \lambda(t))$. Now putting this in eq. (3.3.3), following relation is obtained for wheel slip model.

$$J\ddot{\phi} + mr^2(\ddot{\phi}\big(1 - \lambda(t)\big) - \dot{\phi}\dot{\lambda}(t)) = \mu_c \exp(-\frac{\lambda^2}{b})Qr \tag{3.3.4}$$

3.4 Devising a Control Law for Longitudinal Slip

We propose a divided model based controller [3], control signals is represented by:

$$T_c = \alpha T_l + \beta \tag{3.4.1}$$

Where T_c is the control torque and T_l is the linear part of the controller expressed as $T_l = \ddot{\emptyset} + k_v\dot{\emptyset} + k_p\emptyset$. While β is the model based part of our controller. From eq. (3.3.4) the control algorithm in our case becomes.

$$T_c = J + mr^2(1 - \lambda_M)]\big[\ddot{\phi} + k_v\dot{e} + k_p e\big] - \dot{\phi}\dot{\lambda}_M mr^2 \tag{3.4.2}$$

Where *e(t)* is the difference between reference value and the real value taken from an encoder.

$$e(t) = \emptyset_d(t) - \emptyset(t)$$

$\lambda_m$is obtained from slip model given by the eq (3.2.2). Real torque of the wheel is expressed as,

$$T_r = J + mr^2(1 - \lambda_R)]\ddot{\phi} - \dot{\phi}\dot{\lambda}_R mr^2 \tag{3.4.3}$$

Now for stable control of the wheel the difference between the compensation torque and the real torque should become zero i.e. $T_c = T_r$. Now by equating both the torques and some manipulations we get,

$$\ddot{e} + k_v\dot{e} - \frac{mr^2 j_M}{1+mr^2(1-J_M)}\dot{e} + \frac{k_p}{1+mr^2(1-J_M)}e = \tag{3.4.4}$$

$$\frac{1}{1+mr^2(1-J_M)}[(\lambda_M-\lambda_R)\ddot{\phi}+\ mr^2(\dot{\lambda}_M-\dot{\lambda}_R)\dot{\phi}]$$

Eq. (3.4.4) above equation can be interpreted into as a block diagram as given below in figure 3.3.

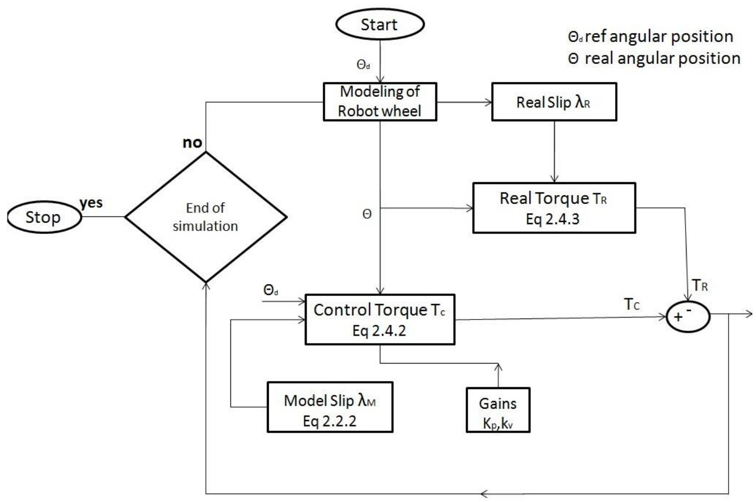


Figure 3.3: Difference between the real torque and modeling torque

Our designed control algorithm shown by eq. (3.4.4) and the figure- is implemented by us for slip control of our robot. the implementation and the results are discussed in the next chapter.

3.5 Tuning Of K_p and K_v

The tuning process for this control algorithm include following steps to find the value of k_p and k_v. First k_p is fixed at zero and the value of k_v is increased till oscillations start at output and then k_v is decreased till the oscillations almost disappear, this is taken as k_v. Then at a preset value of k_p we start increasing k_p till a small overshoot occurs as output response. This represents the value of k_p. We calculated the controller tuned parameters to be k_p =1 and k_v =0.9 with step input as shown by the following graph

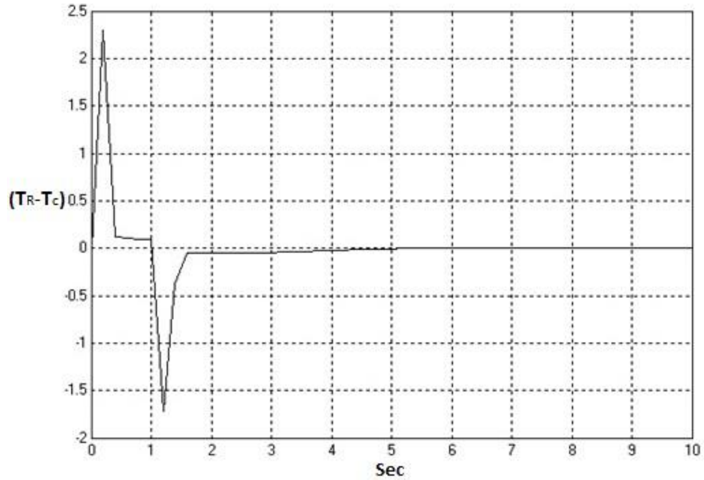


Figure 3.4: Graph between real torque and actual torque

Chapter 4

WMR Dynamic Skid Model

4.1 Introduction

Lateral slip skidding of wheeled mobile robots is a well-known fact while it moves on low traction or uneven terrain, it will most likely cause skid or slip at the contact points of wheel and ground. So it’s impossible to smear the same methods used for kinematic study of wheeled mobile robots while moving on high traction or even terrain to wheeled mobile robots moving on low traction or uneven track. The two foremost glitches with skidding of WMR on low traction or uneven tracks are:

a) Most autonomous WMRs use data from on-board sensors to localize or estimate change in their positions during course-plotting and due to slip or skid leads to increase in localization error.
b) Skidding leads to large wastage of power.

In this section, we projected the model of lateral friction for wheel mobile robots. The suggested lateral friction model displays the features of side friction faced by WMRs while rotating along a round track. We suggested skid check condition during rotatory motion of wheeled mobile robot along a circle on the behalf of the suggested side friction model. This suggested skid check state expresses the prospect of slipping of wheeled mobile robots on round tracks. To avoid skidding Logic based controller was also proposed, which was usually encountered by wheeled mobile robots while moving along an orbicular track. Simulation on this has also been done which demonstrates how WMR can avoid skidding while moving along an orbicular track.

4.2 Model Development

Prior to this, A variety of wheeled mobile robot designs are proposed for uneven terrain. But in our design we have kept things simple by using most commonly used wheeled mobile robot architecture i.e. car like robot. Which contains two front steering wheels and two rear wheels which are fixed as displayed in Figure 4.1.

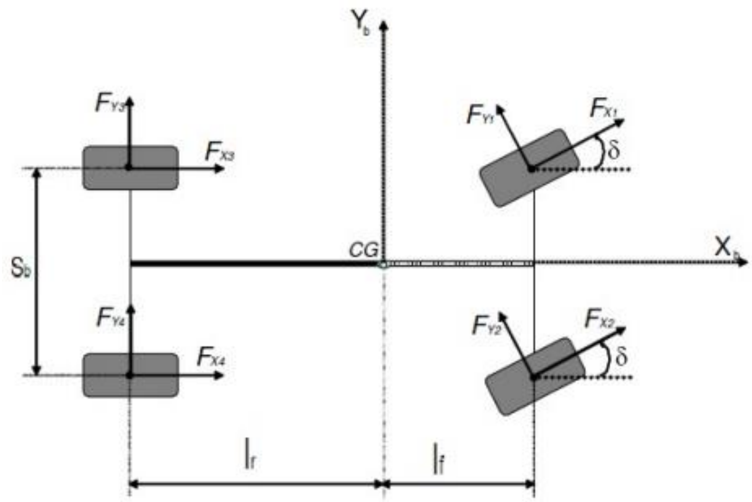


Figure 4.1: Car like Robot

It is a simplified depiction of a nonlinear robot model that considers the road/tire forces. The vibrant movement of the robot is demonstrated by equations 4.2.1 that exemplify correspondingly the longitudinal and lateral translational motion and the rotational movement of yaw:

$$\mathrm{m}V_x = \sum_{i=1}^{4} F_{xi} + m\Theta V_y$$

$$\mathrm{m}V_y = \sum_{i=1}^{4} F_{yi} - m\Theta V_x$$

$$I_z\Theta = \sum_{i=1}^{4} M_{zi}$$

It can be re-written as:

$$V_x = \frac{1}{m}\sum_{i=1}^{4} F_{xi} + m\Theta V_y$$

$$V_y = \frac{1}{m}\sum_{i=1}^{4} F_{yi} - m\Theta V_x$$

$$\Theta = \frac{1}{I_z}\sum_{i=1}^{4} M_{zi} \qquad (4.2.1)$$

Where

$$\sum_{i=1}^{4} F_{xi} = (F_{x1} + F_{x2})\cos(\delta) - \left(F_{y1} + F_{y2}\right)\sin(\delta) + F_{x3} + F_{x4}$$

$$\sum_{i=1}^{4} F_{yi} = (F_{x1} + F_{x2})\sin(\delta) + \left(F_{y1} + F_{y2}\right)\cos(\delta) + F_{y3} + F_{y4}$$

$$\sum_{i=1}^{4} M_{zi} = I_f(kF_{x1} + F_{x2})\sin(\delta)\, L\cos(\delta) + \frac{S_b}{2}(F_{x2} - F_{x1})\sin(\delta) + \frac{S_b}{2}(F_{y4} - F_{y3}) - \frac{S_b}{2}(F_{y2} - F_{y1})\sin(\delta) - I_r(F_{y3} + F_{y4})$$

The Dug-off model is opted for this study for two foremost reasons: it requires less number of parameters to assess the tire/road forces, and the formulation residues close to the linear formulation. The forces are given by:

$$F_{x_i} = C_{xx}\frac{\lambda_i}{1-\lambda_i}K_i$$

$$F_{y_i} = C_{yy}\frac{tana_i}{1-\lambda_i}K_i \tag{4.2.2}$$

With

$$\mathrm{K}_i = \begin{cases} 2\ \sigma_i - 1, & \sigma_i \le 0 \\ 1, & \sigma_i \ge 0 \end{cases} \tag{4.2.3}$$

$$\sigma_i = \frac{1-\lambda_i\mu_i F_{n_i}}{\sqrt[2]{C_{xx}^2{\lambda_i}^2 + C_{yy}^2 tan^2\alpha_i}} \tag{4.2.4}$$

$$\begin{cases} \alpha_i = \delta_i - \arctan\left(\frac{V_{pyi}}{V_{pxi}}\right) \\ \lambda_i = \frac{R\omega_i - V_{pxi}}{1-\lambda_i} \end{cases} \tag{4.2.5}$$

$$
\begin{cases}
F_{n1} = \dfrac{l_r mg}{2(l_f + l_r)} - \dfrac{hma_x}{2(l_f + l_r)} - \dfrac{l_r hma_y}{(l_f + l_r)S_b} \\
F_{n2} = \dfrac{l_r mg}{2(l_f + l_r)} - \dfrac{hma_x}{2(l_f + l_r)} + \dfrac{l_r hma_y}{(l_f + l_r)S_b} \\
F_{n3} = \dfrac{l_r mg}{2(l_f + l_r)} + \dfrac{hma_x}{2(l_f + l_r)} - \dfrac{l_r hma_y}{(l_f + l_r)S_b} \\
F_{n4} = \dfrac{l_r mg}{2(l_f + l_r)} + \dfrac{hma_x}{2(l_f + l_r)} + \dfrac{l_r hma_y}{(l_f + l_r)S_b}
\end{cases} \tag{4.2.6}
$$

$a_x$and$a_y$are respectively longitudinal and lateral vehicle acceleration.

4.2.1 Velocities at the Tire and Road Contact Point

We can find linear velocities of any element of frame attached with rotating vehicle. We know the linear velocities $V_{rel}$and yaw rate ω of every element of frame that is attached with rotating vehicle. It is defined as:

$$V = V_{rel} + \omega \times \mathrm{r} \tag{4.2.7}$$

Where V_{rel} is the velocity of the particle relative to the rotating coordinate system and r is position vector. So from equation 4.2.7 we can find the longitudinal and lateral vehicle velocities at the tire/road contact point V_{pi} for each tire. It can be written as:

$$V_{pi} = \begin{bmatrix} V_p xi \\ V_p i \end{bmatrix} \tag{4.2.8}$$

Where i=1 to 4 signifies the number of tires of wheeled mobile robot. These velocities are specified using the following reference change.

$$V_{pi} = V_g + \Omega + P_i \tag{4.2.9}$$

Where V_g is the velocity vector of the vehicle at the center of gravity of the vehicle, ω is the rotational velocity vector which is limited in this circumstance to the yaw motion along the z-axis of a robot that looks like a car as shown in Figure 4.2.1,$P_i$represents the vector location of each wheel with reference to the center of gravity. On the Basis of the above equation we derived the model in the form:

$$\Omega = [0\ 0\ \theta]^T, P_i = [l_{xi} l_{yi}\ 0]^T \tag{4.2.10}$$

$$V_g = \begin{bmatrix} V_x \\ V_y \\ 0 \end{bmatrix}, \Omega \times P_i = \begin{bmatrix} -\theta l_{yi} \\ l_{xi} \\ 0 \end{bmatrix} \quad (4.2.11)$$

$$\mathrm{P1} = \begin{bmatrix} l_f \\ \frac{S_b}{2} \\ 0 \end{bmatrix}, \mathrm{P2} = \begin{bmatrix} l_f \\ -\frac{S_b}{2} \\ 0 \end{bmatrix}, \mathrm{P3} = \begin{bmatrix} -l_r \\ \frac{S_b}{2} \\ 0 \end{bmatrix}, \mathrm{P4} = \begin{bmatrix} -l_r \\ -\frac{S_b}{2} \\ 0 \end{bmatrix} \quad (4.2.12)$$

$$\begin{bmatrix} V_{px1} \\ V_{py1} \end{bmatrix} = \begin{bmatrix} V_x - \theta \frac{S_b}{2} \\ V_y + \theta l_f \end{bmatrix}, \begin{bmatrix} V_{px2} \\ V_{py2} \end{bmatrix} = \begin{bmatrix} V_x + \theta \frac{S_b}{2} \\ V_y + \theta l_f \end{bmatrix}$$

$$\begin{bmatrix} V_{px3} \\ V_{py3} \end{bmatrix} = \begin{bmatrix} V_x - \theta \frac{S_b}{2} \\ V_y - \theta l_f \end{bmatrix}, \begin{bmatrix} V_{px4} \\ V_{py4} \end{bmatrix} = \begin{bmatrix} V_x + \theta \frac{S_b}{2} \\ V_y - \theta l_f \end{bmatrix} \quad (4.2.13)$$

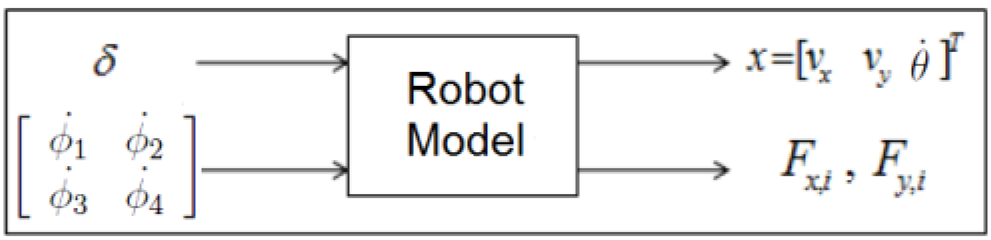


Figure 4.2: Car like Robot Dynamics

4.3 Lateral or Side Friction

To deal with sliding or skidding, friction is an important factor. During WMR motion along a circular curve, side friction that tires exert on ground plays an important role, which is always limited. Lateral force limits the centripetal force. So we can calculate the limit of centrifugal force as it will be equal to centripetal force.

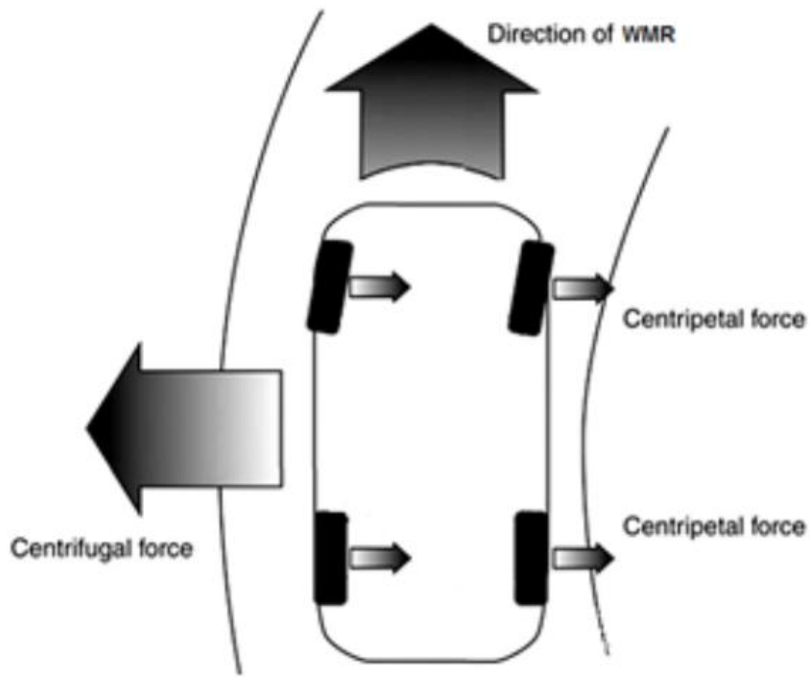


Figure 4.3: Balancing forces while turning

4.3.1 Demand of side friction in a circular horizontal curve

The friction required by a mobile robot to maintain its trajectory while moving along horizontal curve is known as Friction demand. It depends on various factors like radius of horizontal curve R and linear velocity of WMR V. the relationship among them is defined as

$$f_t = \frac{V^2}{R_g} \quad (4.3.1)$$

Where g is the gravity constant. Above equation is a point-mass model. R is always known in existing horizontal curves, so taken as constant.

4.3.2 Supply of Friction in a Circular Horizontal Curve

Tire-ground interaction and WMR velocity affects the friction supply. A model named as Pennsylvania model is given to show the characteristics of side friction while sliding. It is given by equation.

$$F(S) = F_0 e^{\frac{-S}{S_0}} \quad (4.3.2)$$

Where F(S) is the friction coefficient of the wheel in contact with road. F_0 is the static skid number and S_0 is a constant value having units of velocity. The model proves that the friction decreases at exponential rate, as velocity increases. Figure 4.3.2 shows the change in supply and demand of friction, both in same graph.

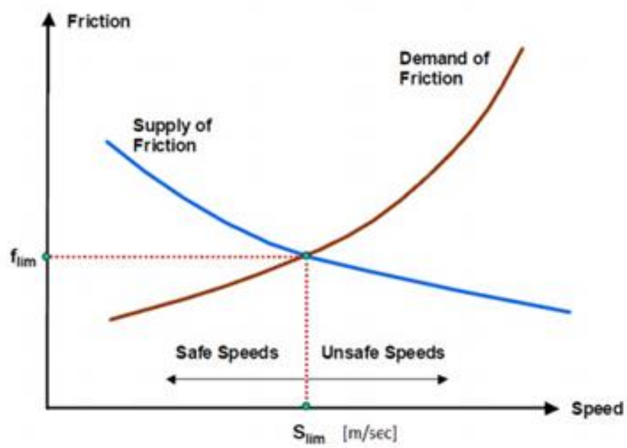


Figure 4.4: Relationship between supply and demand of friction in circular path

Dynamic stability of a vehicle for a given radius and friction is ensured by Speed limit (S_{lim}), in figure. Equilibrium point is at the intersection of both the curves. The available friction will be not enough to compensate demanded friction if the operating speeds are more than the speed limit. This causes the vehicle to be at the risk of losing its dynamic stability, which generates an unsafe condition in adverse conditions. To obtain the minimum radius of curvature, the design procedures assume a predefined and constant value of maximum friction. So adopting a clearly high radius than the minimum reduces the risk on friction demand.

4.4 Proposed Side Friction Model in a Circular Horizontal Curve

The Pennsylvania model proposed earlier was for high speed vehicles whereas WMRs are slow and light weighted. So we suggest another model which depends on tire-surface interaction and speed. Given purposed model is defined by equation:

$$\mu(v) = \mu_s\, e^{\frac{-V}{V_0}} \qquad (4.4.1)$$

Where $\mu_s$is coefficient of friction between surface of track and WMR tires.

4.5 Forces Act on WMRs while Turning

The forces acting on a turning or moving along a rotating path WMRs are composite. Assuming the wheeled mobile robot as a point mass that is moving along a round curve then there are two main forces acting on it, e.g. frictional forces and centripetal force. When these two forces are stabled, as a result WMR can follow preferred circular route without sliding. But when frictional forces acting on wheel-ground contact points become less then required centrifugal force or curve resistance then WMR suffers skidding. While rotating the center of gravity of wheeled mobile robot is exposed to centrifugal force. As center of gravity is near the front wheels and if the WMR is heavier towards front wheels as shown in figure 4.5.1, so evidently the front wheels will share most of the centrifugal force. Therefore they have to generate larger slip angle thus larger frictional force needed to overcome the centrifugal force.

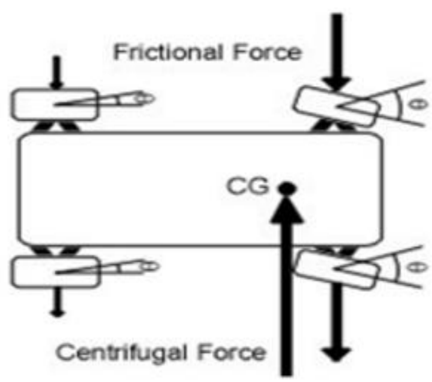


Figure 4.5: Center of gravity of WMR heavier from front

On the contrary, rear-heavy WMR has larger slip angle at the rear. Similarly, a neutral balanced WMR can be found having same slip angle for both front and rear wheels while skidding as shown in figure 4.5.2.

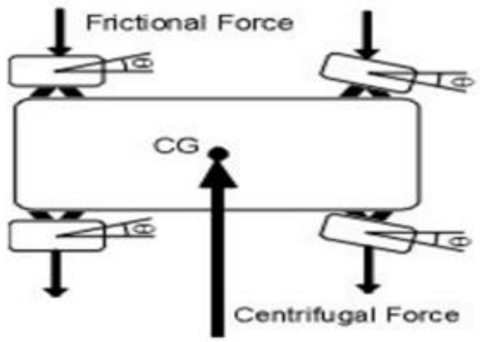


Figure 4.6: Neutral balanced WMR

4.5.1 Curve Resistance or centrifugal force

When a wheeled mobile is being moved along a circle, it behaves like it is facing some centrifugal force and that force is forcing it outside of the circle. Whereas the centrifugal force is dependent on the mass of the wheeled mobile robot and the speed of the wheeled mobile robot and also on the radius of the circle. It is known that centrifugal force is always equal to the centripetal force. And is shown in the figure (4.5.3).

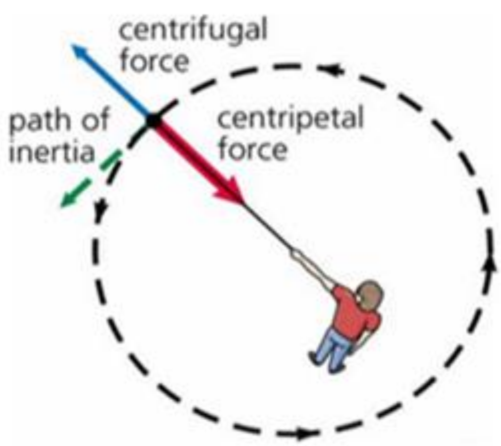


Figure 4.7: Balancing of centripetal and centrifugal forces

When a WMR rotates or take a turn, the outer forces act on both front and rear wheels. The force required for the wheeled mobile robot to hold the horizontal curve while moving is known as the 'curve resistance'. And it (curve resistance Rc) depends upon the speed of the robot and the radius of the horizontal curve of the circle.

$$R_c = \frac{V^2}{R} m \tag{4.5.1}$$

Where

R_c - curve resistance (N)

v – Vehicle speed (m/sec)

m – Gross vehicle mass (kg)

g – Acceleration due to gravity (9.8m/sec2)

R – Radius of curvature (m)

4.5.2 Frictional Forces:

Wheeled mobile robot’s lateral friction is proportional to the type of terrain and it’s mass. Normally the two materials that are involved to describe the behavior of the terrain have the friction coefficient assigned to them. Lateral friction mathematical model that is also our proposed side is being used here, which is also mentioned in the equation (4.4.1), to define the lateral or sum of frictional forces on WMR while moving on rounded path. So this sum of all frictional forces can be written as:-

$$Frictional\ forces\ = \mu e^{\frac{-V}{-V_0}} \sum_{i=1}^{4} \left(F_{Y_i}\right) \tag{4.5.2}$$

Where $\sum_{i=1}^{4} \left(F_{Y_i}\right)$ is the sum of the lateral forces acting on wheeled mobile robot’s wheels from equation 4.2.1.

4.6 Dynamic Stability:

The combined effect of the magnitude of the lateral forces that are parallel to the terrain and the transverse friction, generate the force towards the center which describe the round path. Therefore, it is known that sum of all frictional forces equals to curve resistance or centrifugal forces matches to curve resistance or centrifugal force that our WMR is dynamically stable.

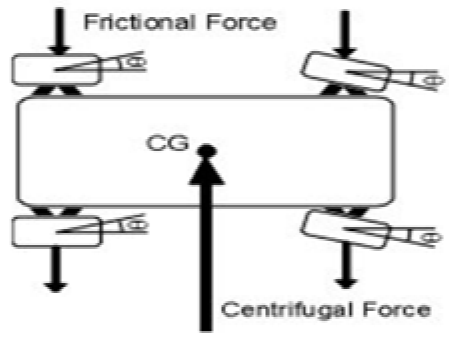


Figure 4.8: Acting forces while turning

$$\text{Sum of frictional forces} = \text{curve resistance}$$

4.6.1 Skidding Condition

When forces acting on WMR i.e. lateral Forces moving along the circle are smaller than the forces that are result of demand curve resistance, and when the available friction also becomes smaller than the required friction, as a result the vehicle would tend to run off the curve and would follow a tangential route and will most likely skid. From equation 4.5.1 and 4.2.1:

$$\mu_s e^{\frac{-V}{-V_0}} \sum_{i=1}^{4} \left(F_{Y_i}\right) \leq \frac{V^2}{R} m \tag{4.6.1}$$

In the above mentioned equation as the wheeled mobile robot is moving along a circular track, the WMR will most likely will go in skid mode or run off the horizontal curve and following a tangential route when all the lateral forces that are acting on WMR are less than the demand curve resistance. While moving on Horizontal curve, when the speed of WMR increases the production of side friction decreases. As a result the lateral force that is acting on the wheel-ground contact points of WMR also decreases. Due to lag in centrifugal force or supply curve resistance, WMR undergoes into skidding mode. From equation 4.6.1 it's clear to us that demand curve resistance can easily be reduced by reducing the velocity of wheeled mobile robot and also by increasing the radius of the circular horizontal curve.

At the end, 4.6.1 gives us condition for proposing logic based controller for WMR while moving a curve that is horizontal to the circle.

Chapter 5

Custom Platform for Slip & Skid Control Implementation

5.1 Introduction

A custom platform is developed to implement the slip control algorithms in order to validate its performance. This platform is centered on a wheeled mobile robot along with some peripheral subsystems to make its motion slippage free. Peripheral subsystems are incorporated in the platform in order to record different aspects of WMR motion. In this chapter the formation and operation of this platform is discussed in detail. The platform consists of the following,

i) Car-like robot (WMR)
ii) Remote control mechanism for WMR
iii) Telemetry System
iv) WMR motion monitoring system
v) Slippery surfaces

A car-like robot with feedback mechanism and a remote control mechanism has been developed. Telemetry system is set up to communicate several features of robot's motion to PC on laptop computer in real time. These aspects will help to measure the performance of the controller implemented in the WMR. Similarly another system to measure the control algorithm performance is motion monitoring system. This system is based on a camera and a video processing algorithm to extracts the trajectory of motion of WMR. In addition to all this few slippery surfaces are custom developed to perform experimentation.

5.2 Car-Like Robot Development

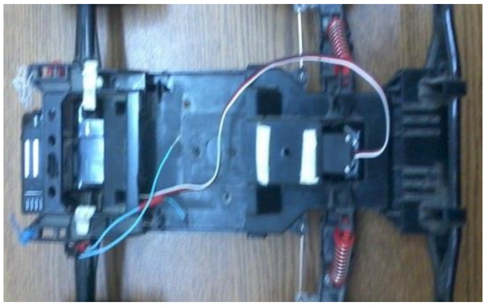
A car like robot consists of four wheels and two actuators, one actuator is responsible for driving and other is liable for steering. This type of robot uses Ackerman drive strategy where front two wheels are used for steering and back wheels are used for driving the robot.

The custom developed car like robot comprises of

- Simple mechanical structure
- Four rubber wheels
- A simple DC motor for driving
- Futaba S3003 DC servomotor for steering
- HS-30A rotary incremental encoders for speed
- Custom developed angle (Potentiometer + ADC + Calibration Algorithm)

5.2.1 Mechanical Structure

A built-in structure has been used for the development of this custom WMR simply because of its light weight, small size and efficient design. Appropriate amendments have been made according to requirements while installing actuators, encoders and gears in this structure. The Figure 5.1 presents different views of the mechanical structure of the car-like robot body.


a) Front view of mechanical structure of robot

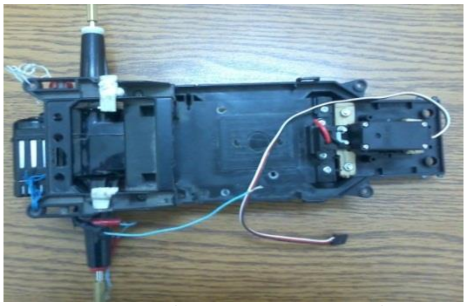
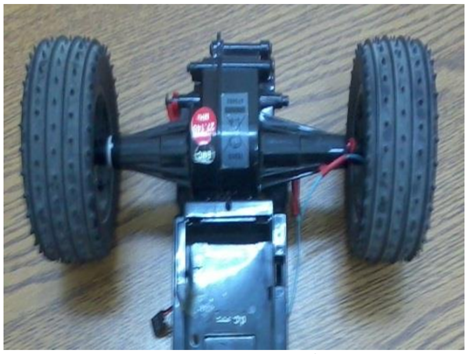

b) Back view of mechanical structure of WMR

Figure 5.1: Mechanical Structure of robot

5.2.2 Rubber Wheels

Wheels are the most important part of any WMR as they specify how much actuation and actuators are needed for its motion. In the first chapter the types of wheels have already been discussed, in this platform standard wheels have been used. All the wheels are conventional standard type wheels. Front wheels are centered orientable wheels and back wheels are centered fixed wheels. Back wheels are passive fixed wheels while front wheels are actively steerable as shown in Figure 5.2


a) Driving wheels of our robot

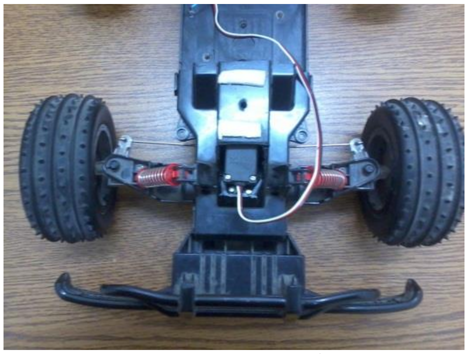

b) Steering Wheels of our robot

Figure 5.2: Wheels used for car-like robot

5.3 Drive Mechanism of the WMR

This mechanism is based on the back wheels driven through a DC motor with the help of a geared system which has been installed in by the manufacturer already. A motion encoder has been used to measure the current RPM of the robot to aid the drive mechanism in feedback.

5.3.1 DC Motor

Despite the above mentioned advantages of the built-in structure its main disadvantage is that you are left with very little choice or freedom. While selecting a DC motor for the custom robot a few constraints were kept in mind. Small size is one of the constraints imposed by the structure thus a motor which could fit in the drum at the back of the structure shown in the Figure 5.3 with enough capability to drive the robot with a decent speed was selected. It possesses following characteristics

- 9 – 12 volts
- 5000+ RPM at no load
- Less than 300 RPM at load

a) DC motor b) Drum for fixing DC Motor

Figure 5.3: DC motor installation

Before finalizing this motor sufficient amount of experiments were conducted to insure that motor contains enough capability to derive the robot as per requirement.

5.3.2 HS30 Rotary Incremental Motion Encoders

HS30A are smart encoders used for encoding rotational motion, they can not only encode the revolutions of a DC motor but they are equally good for encoding the angle of a servomotor. HS30A is shown in Figure 5.4. We have used them for both steering angle and driving speed. It possess following features.

- Two channel TTL compatible output
- 500 pulses per revolution
- Voltage required is 5V
- Intelligent design and mounting

Figure 5.4: HS-30A rotary incremental encoder motion encoder

Two channels output the same pulses but with a phase difference of 50% of the width of the pulse as shown in Figure 5.5. The purpose of two channels is to determine the direction of rotation of the motor shaft, it depends on which channels is leading or lagging.

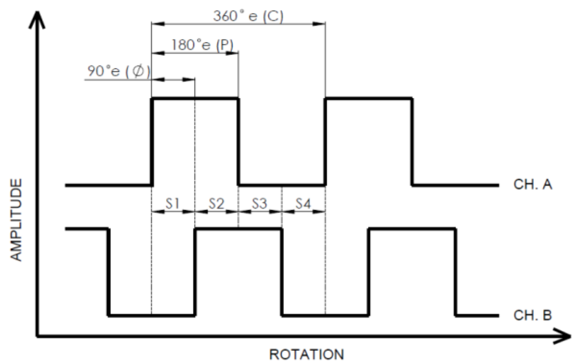


Figure 5.5: HS-30A channel output pulses

It is made up of an IR transmitter/receiver module, a disk with transparent spots. The transparent disk is attached with the motor shaft and the IR Tx/Rx module is attached with the disk in a way that the disk is positioned to rotate between the Tx and Rx of the module. While the disk is moving and transparent spot comes between the IR transmitter and receiver allowing the light to pass. The receiver receives the light and generates a pulse, this pulse is recorded by the microcontroller. The Figure 5.6 below shows the work flow of these motion encoders.

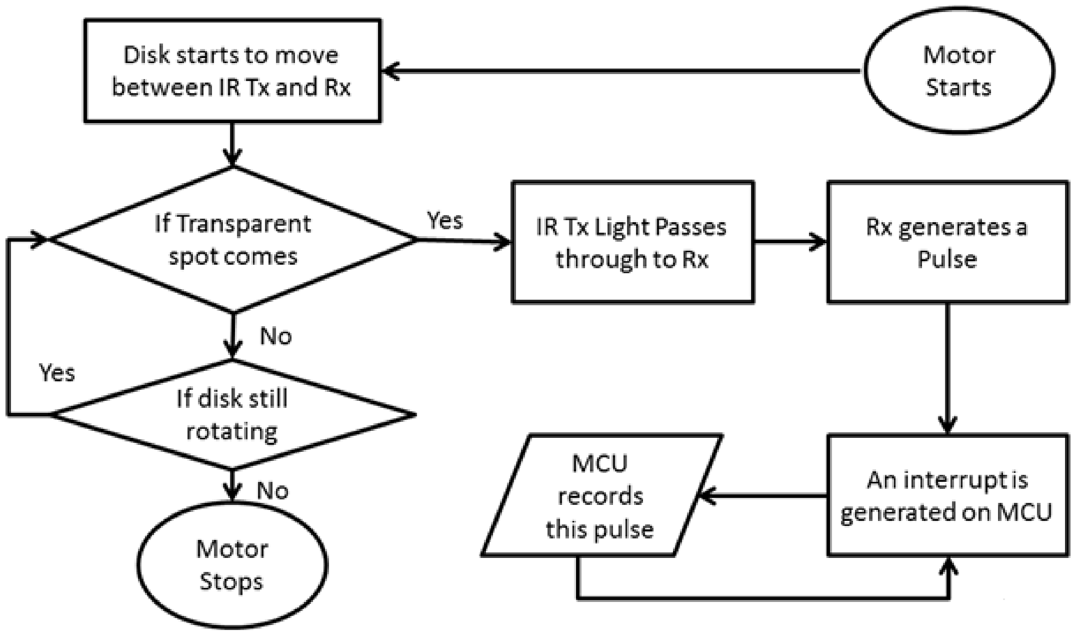


Figure 5.6: Flow chart of the working of motion encoder

As these encoders provide 500 PPR so they can also be used for determining the angular position. Dividing 500 pulses of a revolution on 360, approximately 1.4 pulses per degree are obtained. Thus we tried to use it as angle sensor as well but few problems of restrained us from it.

5.3.3 Encoder Installation on WMR

We had to find out a motor with an aditional shaft at its tail so that the disk of the encoder could be attached with the motor. Figure 5.7 shows the process of installation.

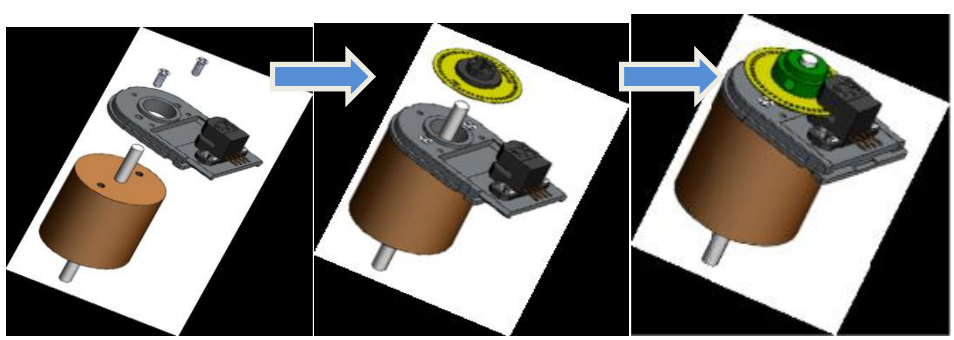


Figure 5.7: Procedure of mounting encoder on DC motor

After the integration mentioned in the figure above the motor was fixed in the car-like robot structure as shown below in Figure 5.8.

Figure 5.8: Mounted encoder on DC motor

5.3.4 Drive Methodology

Flow chart in Figure 5.9 shows the drive methodology.

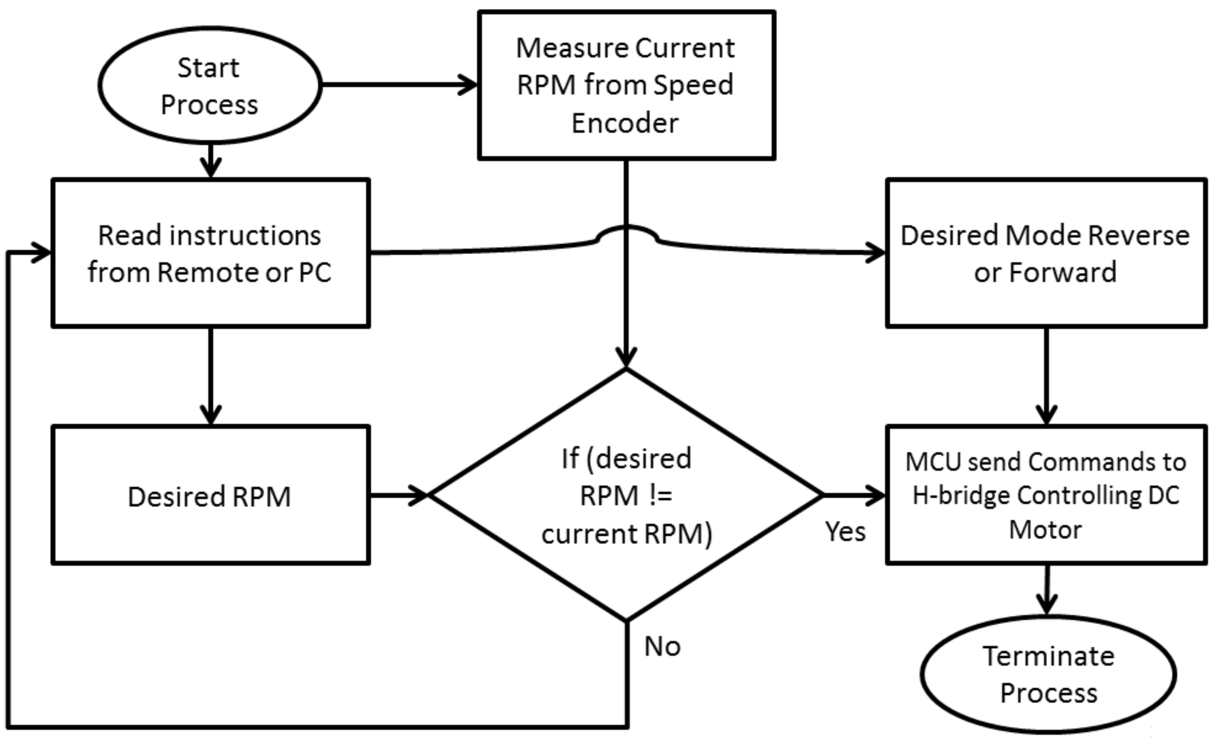


Figure 5.9: Flow chart of the drive mechanism of WMR

5.4 Steering Mechanism

Steering is done through a servomotor by using a rotary to linear mechanism for steering the front wheels. The custom developed robot can be steered up to 25 degrees at both sides making its total span 50 degrees. For feedback we have used potentiometer with an analog to digital converter and an algorithm mapping ADC values to servo shaft angle.

5.4.1 Servomotor

A servomotor contains a DC motor and a servomechanism (feedback) implemented for it, called DC servomotor. The servomechanism enables the motor to move at a specific angle very precisely. Figure 5.10 is a block diagram showing the servomechanism for a servomotor.

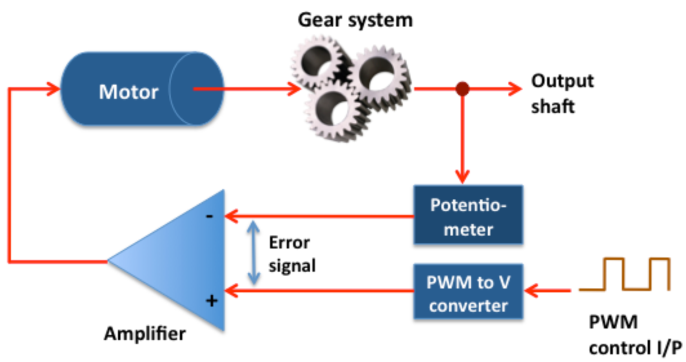


Figure 5.10: Servomotor working principle [40]

A PWM signal dictates the reference position while a feedback mechanism is implemented to obtain the current position of the rotor as a voltage signal using a potentiometer or a motion encoder. In the next stage an error signal is obtained by subtracting both the signals and the obtained signal is fed to the DC motor. Which reacts appropriately to the signal provided and once the error signal becomes zero (reference position is achieved) the motor stops. Which means the PWM signal acts as a control signal here thus in order to change the position of the rotor PWM signal needs to be changed.

5.4.2 Futaba S3003 Servomotor

For steering mechanism we have used Futaba S3003 servomotor, which is a powerful tool for educational projects. It possesses following capabilities.

- Works at 4.8-6V
- Move from 0 to 180 degrees
- Stall torque 4.1 kg.cm

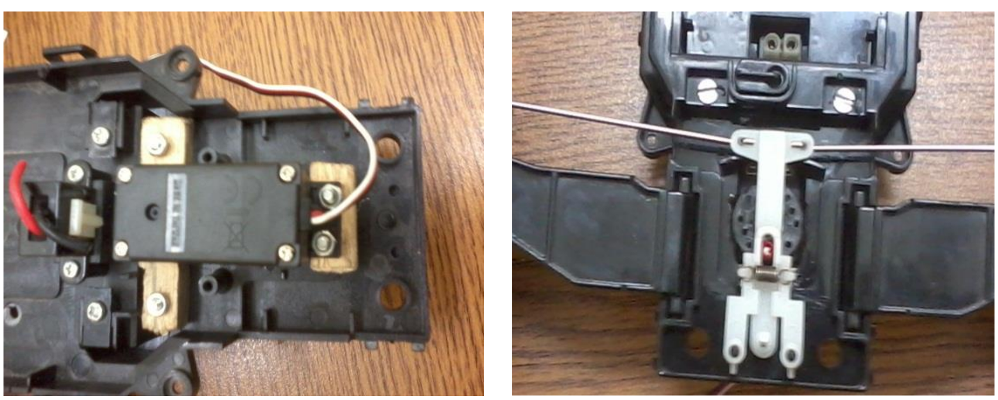
Figure 5.11: Futaba S3003 Servomotor

As shown in the Figure 5.11 it has a three pin J-type connector with following pin configuration.

- Red colour pin is used for power supply
- Black is a ground
- White pin is used to send the control signal (PWM pulse) to the servomotor

Unlike DC motor, a servomotor works at a control signal of a specific frequency. Our Futaba S3003 works on frequencies between 50Hz to 100Hz.

In order to install this motor on or robot, unnecessary part of the robot structure was cut and wood pieces of required width and height were specially crafted and used to place it on the robot as shown in the figure below. Afterwards a rotary to linear mechanism was developed for steering the wheels as shown in the Figure 5.12.



a) Installation of servomotor on the WMR

b) Rotary to linear mechanism for steering WMR

Figure 5.12: Installation of steering mechanism in the WMR

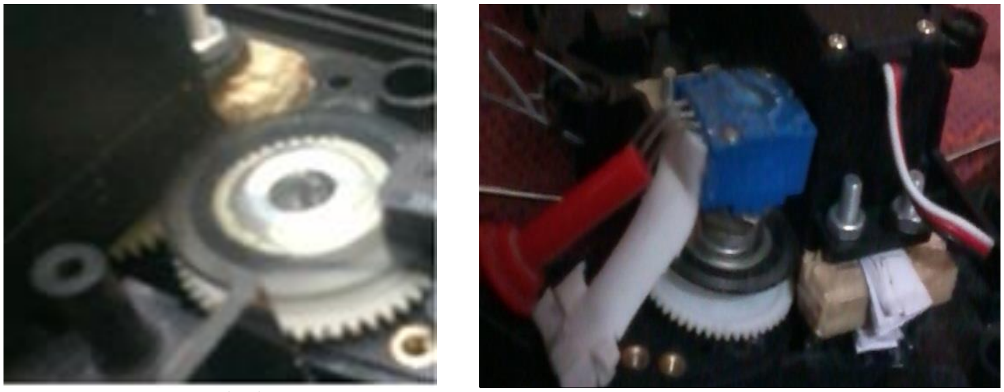
5.4.3 Potentiometer as an angle sensor

The Figure 5.13 shows the potentiometer we used as an angle sensor. It has three terminals, the outer and bottom terminals can be used as power supply and ground. While middle terminal acts as a variable terminal. It is connected to the rotor of the potentiometer. As the rotor moves the value of the resistance or voltage changes. This characteristic makes it a position sensor as voltage signal is changing with the change in its shaft position. If this is somehow attached to servo shaft then it will move along servo shaft producing a change in voltage drop. The distance moved can be found by digitizing the changed voltage and then calibrating it with the rotation of servomotor shaft.

Figure 5.13: Potentiometer

5.4.4 Installing the Potentiometer on the WMR

As shown in figure below, a gearing system has been developed to install a potentiometer as an angle sensor. One gear is fixed with servomotor shaft, which is attached with another gear containing the potentiometer on it, while the servo moves the gearing system forces the shaft of the potentiometer to rotate as well and hence the voltage drop across the variable resistance terminal is varied. This variable resistance terminal of the potentiometer is connected with ADC which gives digital out to the program.



a) Gearing system for feedback angle   b) Potentiometer attached with servo using gears

Figure 5.14: Installation of Potentiometer on WMR

5.4.5 Calibration

Next step for using potentiometer as an angle sensor is to calibrate the output of the ADC with the angle of servomotor shaft for the control unit to determine how much angle it has moved. Figure 5.15 shows how I did this caibration.

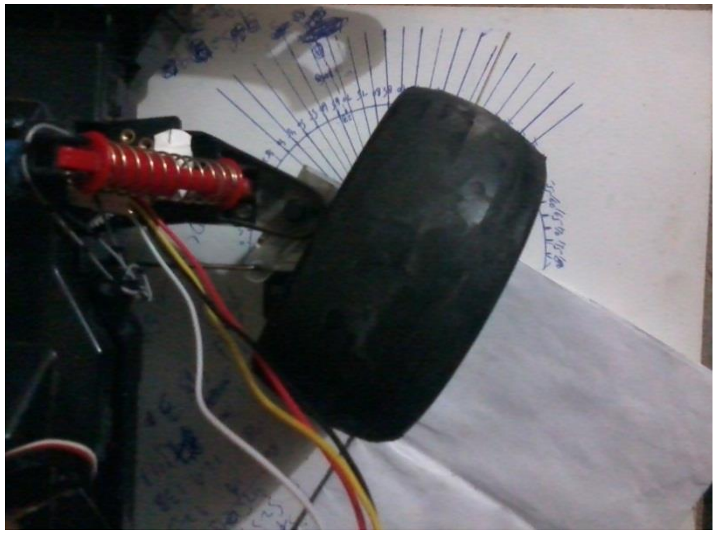


Figure 5.15: Calibration of angle sensor with wheels

A half circle was drawn through geometrical D and angles were montioned on it. Afterwards one of the steering wheels was placed on the center of the half circle and and it was steered using different PWM values, at the other end the ADC values were recorded for every angle. After completing this process it was observed an aproximate 2.3 ADC value represents one degree movement of servo shaft. Here I am using internal built in ADC of ATMEGA16 microcontroller.

Angle	ADC Value
0	150
4	164
8	174
11	183
18	191
22	200

Table 5.1: Calibrating steering angle with potentiometer output

Figure 5.16 shows the tabular results displaying in graphical form, afterwards the curve fitting tool in Matlab was used to fit it using linear interpolant method and slop of the curve was obtained.

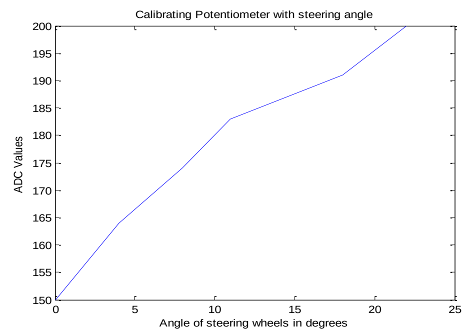


Figure 5.16: Plot of the calibration table

5.4.6 Steering Methodology

Flow chart is given in Figure 5.17 for expressing the steering mehodology.

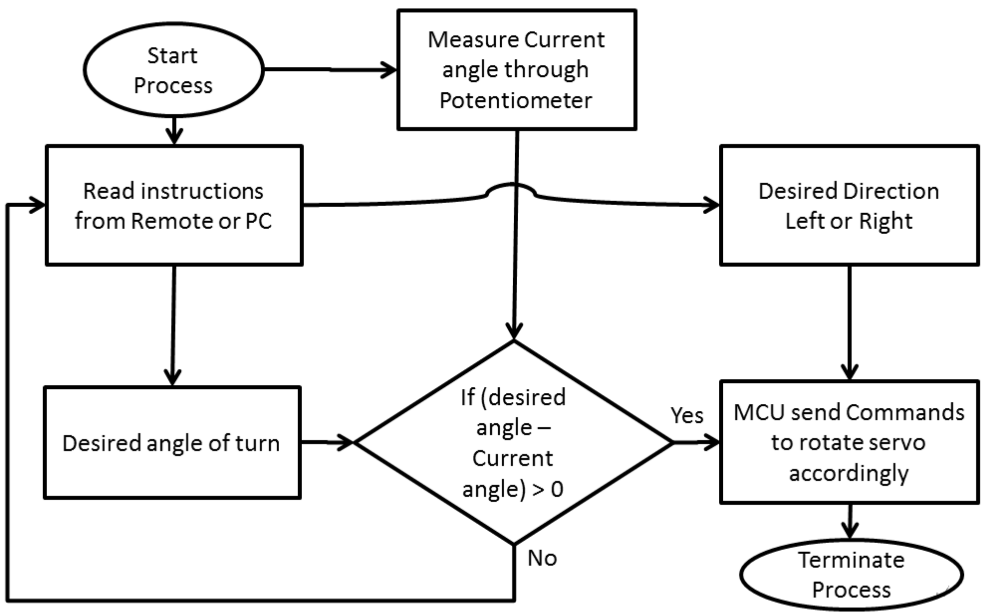


Figure 5.17: Flow chart of steering mechanism

While Figure 5.18 shows the PCB developed to govern the driving and staring mechanism of the robort.

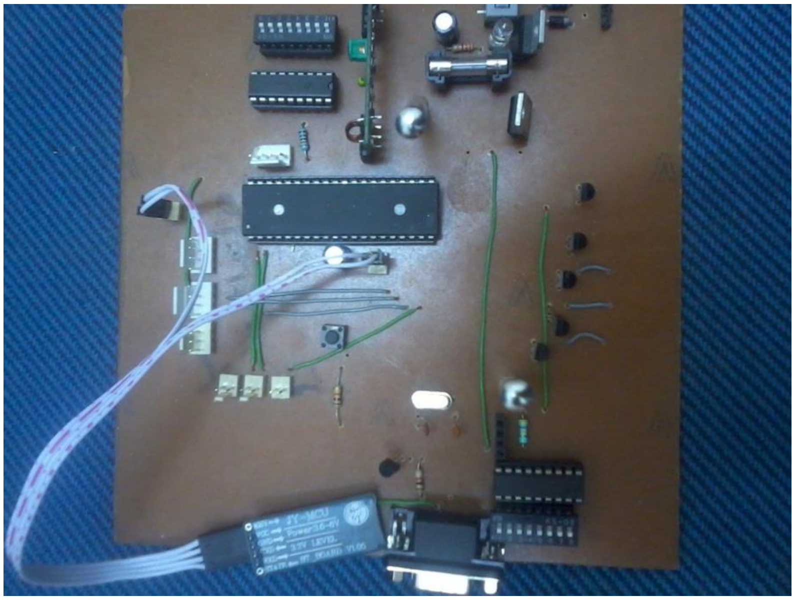


Figure 5.18: Robot Deriving and Steering Circuit

5.5 Remote Control Mechanism

For controlling the behaviour of the robot from a distance we have devised a remote control strategy for our robot. Typical remotes are simply used for increasing/decreasing or moving robot right left with only four to five buttons. Unlike typical remotes our remote control mechanism is rather more precise and task specific. This custom developed remote transmits reference values for speed and angle. We cannot only send reference values to our robot before starting simulation but we can also change its reference during the simulation with the help of this remote control mechanism.

Like every remote control mechanism we have used a transmitter receiver pair for communication with robot. We have used RLP/TLP434A, shown in Figure 5.19, RF transmitter receiver pair and HT12E/D transmission encoder/decoder.

5.5.1 RLP/TLP 434A Transmitter/Receiver

This transceiver is used because they are cheap, easily available, vast range of communication and easy to use. Below are few of their characteristics

- Pros
  - They can with cheap antennas
  - Work at a frequency of 434 MHz
  - Range 100+ feet approximately
  - Transmitter can work at 5-12v (more the voltage more is the range)
  - Receiver works at 5v
- Cons
  - Too much noise and distortion because of its frequency band of 434MHz

Figure 5.19: RLP/TLP 434A

In order to remove this noise from these transmitters motion encoder HT12E/D are used.

5.5.2 HT12E/D Transmission Encoder/ Decoders

These encoders convert parallel stream of data into serial stream of pulses, It's a 18 pin IC with

- 8 address bits
- 4 I/O bits
- Encoder works at 5-12v
- While decoder works at 5v

When data is received at their I/O pins, they attach an 8 bit address with this four bit data and convert it into serial pulses and sends it to the transmitter. Transmitter then throws it to the receiver. Once receiver receives this it sends this data to HT12D decoder which twice matches the address bits and then it sends the data to it I/O port.

Figure 5.20: Remote control Implementation

The figure above shows the remote circuit we have developed containing a keypad with microcontroller and RLP/TLP transmitter/receiver pair.

5.5.3 Working Principle

The block diagram explains the working principle of our remote control mechanism

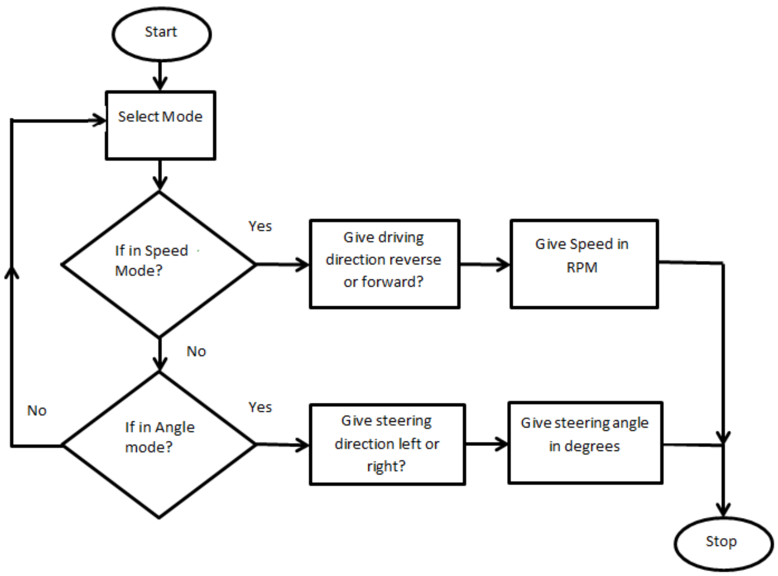


Figure 5.21: Block diagram explaining remote control flow

5.6 Telemetry System

A telemetry system for data logging during real time simulation has been developed, for communicating the sensor values from robot to PC we have used Bluetooth module serial module. Block diagram below explains our telemetry system

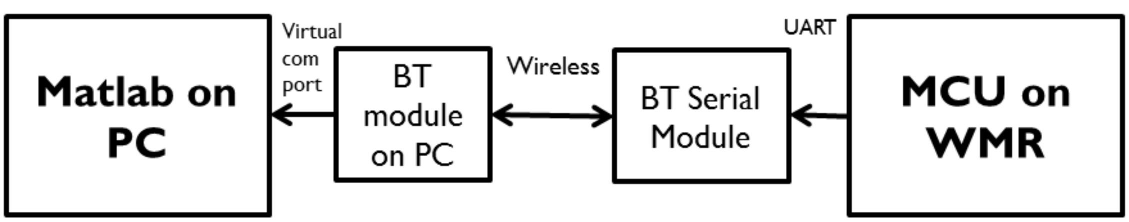


Figure 5.22: Block diagram of telemetry system

5.6.1 Bluetooth Serial Module JY-MCU BT Board

As the name suggests it is used for serial communication between MCUs and PC. It is Ineffaceable with MCU using UART and it is interfaced with PC using Bluetooth in laptop or PC. However it does not connect with PC using PC Bluetooth in conventional way, it creates an artificial COM port and then it uses this port for communication with remote Bluetooth module.

Figure 5.23: Bluetooth module

This Bluetooth module has four pins

1. Vcc
2. DND
3. Tx
4. Rx

It is very easy to use and interface, Simply provide it with 5v positive voltage & ground and connect the its Tx pin to Rx pin of UART in MCU and Rx pin to the Tx pin of the MCU.

We have connected the virtual COM port with hyper terminal from where this Bluetooth module is accessed through. Once the data starts to come Hyperlink Terminal receives and stores the data in a .txt file. Matlab then reads this file and plots the results of the robot.

5.7 Motion Monitoring System

A motion monitoring system consisting of a camera and an image processing module has been developed for extracting the trajectory of the robot while it is in motion. We have used a Logitech camera, it is connected to laptop using USB ports. Block diagram in Figure 4.24 expresses the working of this system

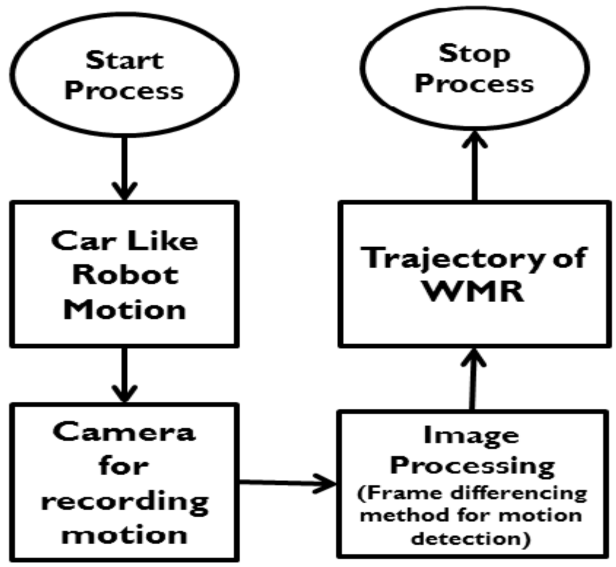


Figure 5.24: Motion monitoring system

5.7.1 Frame Differencing Method

Frame differencing is a simple and easy to implement algorithm, the idea is to take the difference of current frame and the previous frame if there are any non-zero values then that is the location where some thing has moved. Thus the moving object has been detected now take the mean of the co-ordinates where the motion was detected. Afterwards the co-ordinates of this mean point is mapped to another image where you plan to draw the trajectories as shown in Figure 5.25.

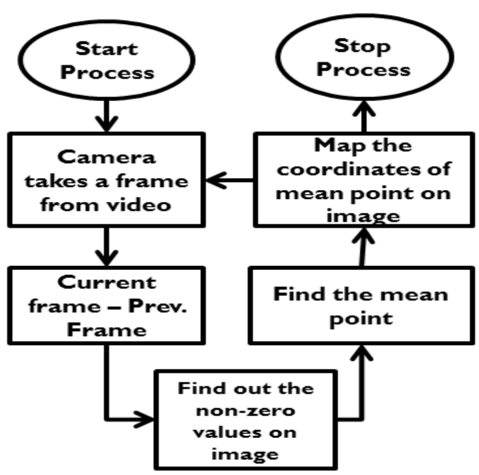


Figure 5.25: Frame differing algorithm

Chapter 6

Results and discussion

This chapter presents the results obtained after implementing the longitudinal slip control algorithm given in (3.4.4) on the custom developed car-like robot. The control algorithm discussed in Chapter 3 has been converted into a difference equation using backward difference rule. A sampling time 0.01s for the discretization process has been chosen. At the end of each iteration, the driving speed and steering angle has been transmitted to control station for data logging through Bluetooth serial UART module. Hyper Terminal in the laptop, received these values through virtual COM port and stored the acquired values into a text (.txt) file. This file has been then read in Matlab to plot and analyse the slip control results.

6.1 Challenges and Considerations

Before discussing the results obtained it is worth to mention the challenges encountered because of hardware which we have coped up with through reasonable assumptions.

1. As discussed in chapter 3 slip will happen only if the velocity of robot is not equal to linear velocity of the wheel. We have implemented the feedback mechanism for finding the revolutions per minute (RPM) of the wheel so robot velocity will be the reference value of the control algorithm. Thus as long as the wheels linear velocity is lagging the reference velocity (considered as robot velocity) it is assumed the slippage is present and need to be compensated.
2. For longitudinal slip control, normally straight trajectories are used (refer to Chapter 3) here in these results we have assumed that for straight line trajectory $\emptyset$ = 90 degree and if it deviates from its trajectory towards left then the deviated angle δ will be added reference angle i.e. $\emptyset = 90 + \delta$ and the deviation towards right will be subtracted from reference to determine its current angle i.e. $\emptyset = 90 - \delta$. Thus the reference value of the angle is 90 degree.
3. Similarly we take a reference value of 1 *m/s* for our robot velocity. Now in order to convert this into rpm we found the radius of our robots wheels, which happened to be 4.6cm and the circumference of this wheel become 28.9cm. Which means our robot move 29cm when its wheels cover one revolution. Thus after some calculation we get to know that robot should move at around 207 rpm.

6.2 Selection of terrain for experiment

The test bed for our designed control algorithm and the hardware platform was chosen to be a terrain covered by crushed stones as shown in Fig 5.1. This terrain was chosen because it only is slippery but also it is uneven too, which will check the capabilities of our control algorithm in real meaning.

Figure 6.1: Chosen terrain for the slip control experiments

6.3 Setting up the hardware

The car-like robot with its connections is illustrated in Figure 5.2.

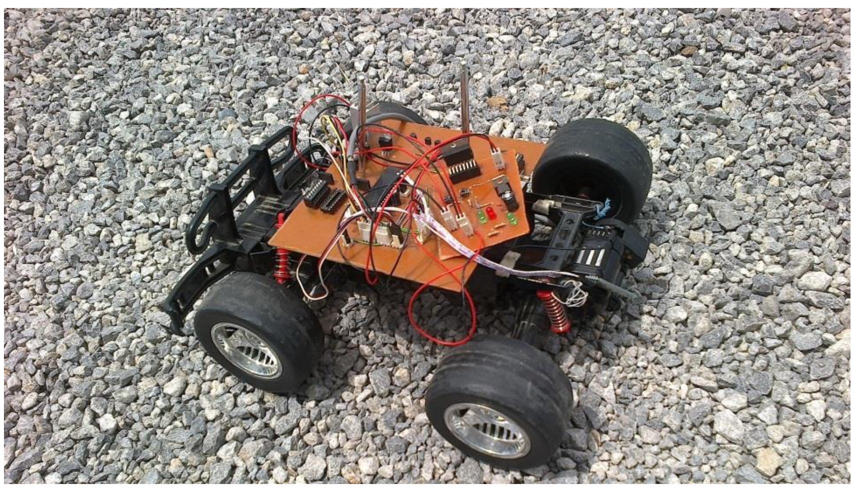


Figure 6.2: Car-like Robot on an uneven and slippery terrain

Afterwards the Telemetry system was run by setting up the connection between Hyper Terminal on laptop and WMR through Bluetooth module for data logging. Similarly the motion monitoring system was also connected and run by interfacing the camera with Matlab. After all this we let the robot run over this terrain as shown in Figure 5.3.The telemetry system was also running on the same laptop.

Figure 6.3: While taking results on a terrain covered by crushed terrain

6.4 Results and their interpretation

Preliminary results collected from hardware platform include WMR speed, steering angle and the real slip. Figure 5.4 shows that slip decreases rapidly up till almost 3 second afterwards robot operates on optimal slip value which stays almost nearly constant till the end of the simulation.

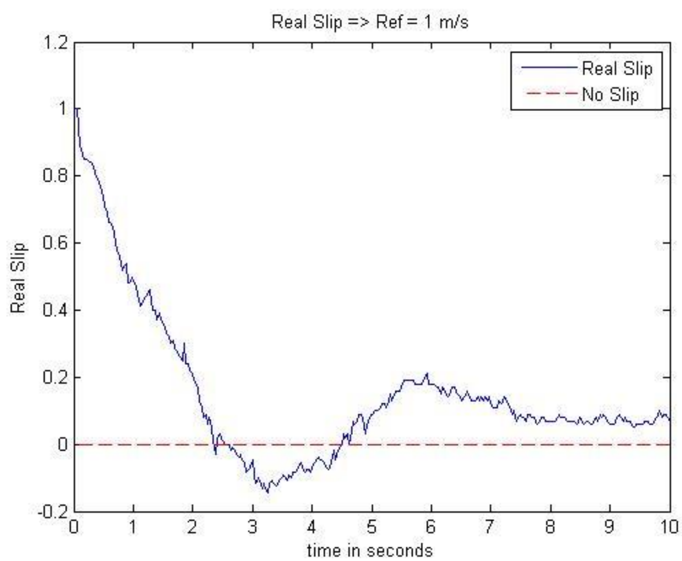


Figure 6.4: Graph of the real slip encountered by the WMR

Speed profile of the WMR is illustrated in Figure 5.5 showing that it takes 5 seconds to reach its steady state value which is because of the induced slip from the uneven and slippery nature of the terrain, however there is still steady state error of less the 0.1.

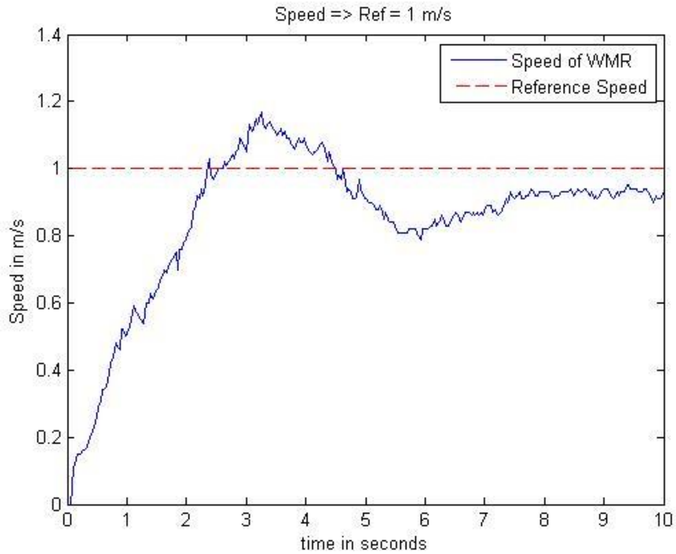


Figure 6.5: Speed of the WMR on crushed stoned terrain

Figure 5.6 presents the steering angle plot which was originally set to be 90 degrees (straight trajectory) and it can be seen that after almost 1.7 seconds WMR sets itself on the desired direction and afterwards it maintains that angle throughout its motion. A zoomed view of the robot's steering angle is shown in figure 5.7.

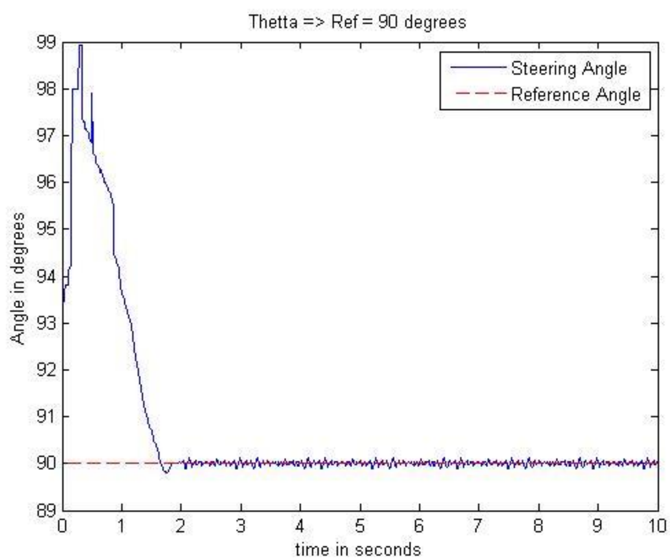


Figure 6.6: Steering Angle of the WMR on crushed stoned terrain

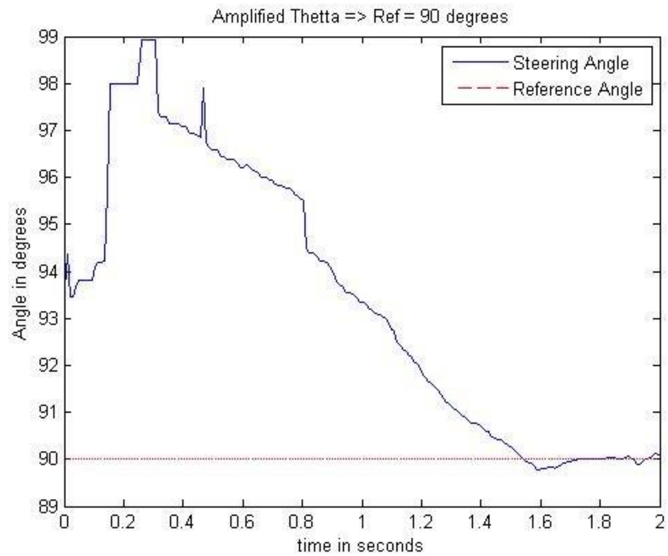


Figure 6.7: Steering Angle of the WMR on crushed stoned terrain

Chapter 7

Conclusion

WMRs are being used extensively in many applications including transportation, surveillance, entertainment, military operations and mining etc. WMRssuffer from a basic issue of slippage especially on slippery and uneven terrains. Most of the research on the control of WMRs up till now assumes that wheel undergo no slippage. Thus the performance of such control algorithms on actual roads is poor as the slip is most likely to happen in practical scenarios. On the contrary for an uneven and slippery terrain these control strategies will fail completely. In order for the slip to be controlled it needs to be modeled first, hence in this thesis we have developed a slip model for a wheel of the WMR and we designed a control algorithm to compensate the induced slip for this model. Later this control algorithm was implemented on a custom developed car-like robot. The results of the simulation we conducted on the stone covered uneven and slippery terrain appear to be satisfactory. However these results can be further improved by further tuning of the controller parameters.

This work unveils a lot of unanswered questions for researchers and it has opened a new gate for research in robotics. AWMR's ability to move on a set trajectory successfully on slippery and uneven terrain will massively increase the magnitude of their applications tomorrow. It is a great sight to imagine that a WMR is moving on surfaces like a wet course, a sand path, an ice terrain and an oily terrain by self-controlling and compensating the slip induced by the unevenness and its slippery nature of surface to insure smooth run. In this work slip control mechanism is developed for a car-like robot but developing a similar control mechanism for other wheeled structures i.e. one wheeled, two wheeled and three wheeled robots is another research problems. The scope of this work was only limited to longitudinal slip modeling and control but lateral slip or skid modeling and control is another problem to be tackled.

This work can also be useful for many real world applications as a starting point. As the difference between a car-like robot and a four wheeled vehicle is just that earlier is self-driven and controlled while latter is driven and controlled by man. While the slip model for a wheeled Mobile Robotics already developed in this work it can also be used for drive simulation in future. Similarly many other applications for a vehicle can be developed from this work.

In future we intend to implement a similar mechanism for aforementioned slippery surfaces as well. A comparative analysis for these surfaces in terms of slip ratio may also be done. Similarly a study for change in slip ratio with increase and decrease of speed of robot is also planned for future work using this platform.

Chapter 8

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