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# Design and Performance Analysis of All Terrain Mobile Robot

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***Abstract:*** **- This work relates to the design of a holonomic and non-holonomic mobile platform and test for the mobility parameters that affects its performance. The system is driven by the four-wheel drive mechanism where all the wheels can be steered by two centralized steering actuators. A mathematical model describing the kinematic and dynamic modelling of standard steered and non-steered wheels, which will influence the size, orientation and position of the mobile platform, are mentioned. In addition, this work relates to the study of the performance of the all-terrain mobile robot on various terrain with the different linear controller such as P, PD and PID for the control system. In particular, we compare various mobility parameters like the torque required by system, power or current consumed and robustness of the mobile robot on different terrain like ceramic, concrete and asphalt road by employing different controllers to analyze its performance. The experimental setup includes all terrain mobile robots, rotary encoders, current sensors and circuitry board that houses the mbed LPC1768, Hercules Motor Driver IC and Bluetooth for communication. This experiment is conducted for a number of trials on each terrain with each controller to understand the behavior of a robot and also measured basic factors like voltage, current, distance travelled, time taken to cover the distance. Derivatives of the basic parameter like velocity, power, torque, coefficient of friction are also calculated. Finally, the various manoeuvrability of the proposed mobile robot both in holonomic and non-holonomic configuration like straight movement, point turn on different surfaces are tested.**

***Keywords: Holonomic robots, Non-Holonomic robots, Mobile Robot, Kinematics, Linear Controller, P, PD, PID.***

## I. INTRODUCTION

Mechanical simplicity, high efficiency and performance make wheeled locomotive drive mechanism as most widely used robots. [1][2][3]Based on the type of locomotion of the robot Wheeled robots are broadly classified into two types: Holonomic and Non-holonomic wheeled robots Holonomic wheeled Robots: In these, type of robots the controllable degrees of freedom of the robot is equal to total degrees of freedom of the robot. Non-holonomic wheeled Robots: A non-holonomic robot is the one whose state depends on the path taken in order to achieve it. In these type of robots, the degrees of freedom are not equal to the total degrees of freedom i.e. they have some constraints called as wheeled constraints or the wheel constraints. The important research problem is the maneuverability, traction, stability and control. Performance testing of a newly designed product is very important step before using it for commercialization. A system can be evaluated in terms of its mechanical aspect like mass, volume and system complexity [4]. However, system complexity is not only the matter of mechanics, it also involves electronics, control used. It gives us information about the strength of the product, the power consumed by it when performing various actions and its performance under different control systems. There is no fixed method for testing the performance of a mobile robot. [5]However, it can be evaluated based on the metrics like control metrics, operational metrics, frictional requirements, maximum torque, maximum obstacle height, slip, robustness etc. which will be discussed later in this paper. Here, we have tested the robot on different surface to analyze the power consumed on each surface for different actions like point turn, forward and backward motion on the surface. In addition, the performance of the robot is compared with P, PD and PID controller to determine the optimal control algorithm. The platform used for the testing is four wheeled all terrain capable mobile robot as shown in fig.1(a) and (b)

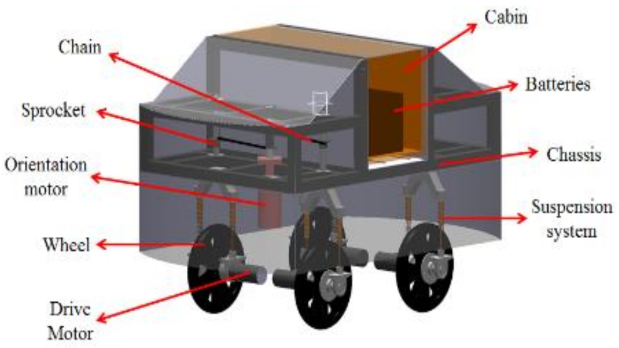


*Fig.1 (a) Complete fabricated model (b) Conceptual design*

## II. ROBOT DESIGN AND MODELLING:

### 2.1. Design approach

The basic conceptual design was inspired by the problem to establish a research platform for both holonomic and non-holonomic robots and further make these reconfigurable robots simpler and efficient. The conceptual design basically consist of the robot with 6 degrees of freedom to control, 4 for the steering of the robot and 2 for driving of the robot. Further these 6 degrees of freedom was optimized to 4 degrees of freedom to decrease the complexity both in terms of mechanical and control, in this case 2 degrees of freedom will control the orientation of the motor and 2 other for driving this decision will not only reduce the complexity but also makes the robot cost effective. The concept was first realized on Tetrix model that was then converted to a CATIA design leading to the final platform. The approach can be represented in fig.2 below.

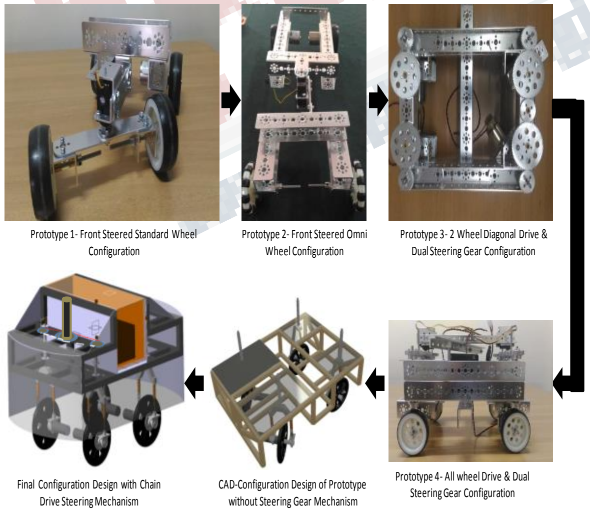


*Fig.2 Design approach from TETRIX to CARTIA model*

### *2.2 Mathematical Modelling*

### 2.2.1. **Kinematic modelling**

#### 1) Kinematics of Standard Non-steered wheel:

The fundamental kinematic equation of the non- steered standard wheels where in α is the angle made by the center of the wheel with the COM of the robot, β is the angle made by the wheel wrt the chassis of the robot, v is the velocity of the wheel in the robot coordinate, l is the distance between the COM of the robot to the center of the wheel, are given in the equations (1), (2). This mimics the kinematics of the wheels when the robot is in skid steer (non-holonomic) configuration. As the model is for the single wheel this concept can be developed for the whole robot.

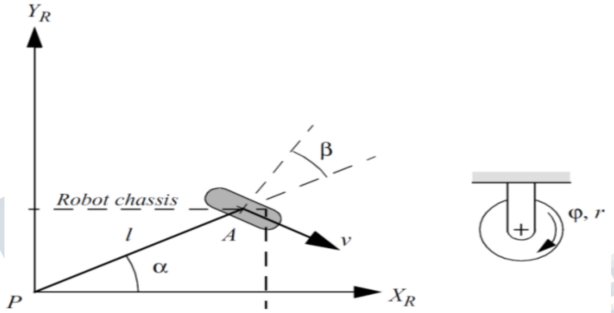


*Fig. 3.kinematics of Standard Non-steered wheel*

$$[\sin(\beta+\alpha)\ \ -\cos(\beta+\alpha)-l\cos(\beta)]\,R(\theta)\dot{q}_I - r\dot{\phi} = 0 \quad (1)$$

$$[\cos(\beta+\alpha)\ \ \sin(\beta+\alpha)\ \ l\sin(\beta)]\,R(\theta)\dot{q}_I = 0 \quad (2)$$

$$R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3)$$

$$\dot{q}_I = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} \quad (4)$$

The above equations both (rolling and sliding constraints) are the kinematic equation that incorporates the kinematics of the wheel and the motion of robot's COM due to the rotation of these wheels.

#### 2) Kinematics of Standard steered wheel:

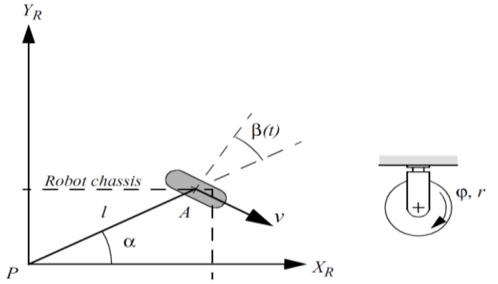


*Fig. 4.Kinematics of Standard steered wheel*

As our robot should behave as both non-holonomic and holonomic, this kinematics of standard steered wheel model when developed for whole robot will mimic the holonomic form of robot. The model will be similar to the standard non-steered wheel but the angle made by the wheels with the chassis will be the function of time i.e. $\beta(t)$ instead of $\beta$.

### 2.2.2. Dynamics:

Torque calculations: Drive motors**:**

The amount of torque required for the forward motion is dependent on the payload, inclination of the plane radius of the wheel and the acceleration, the basic torque calculation is given below.

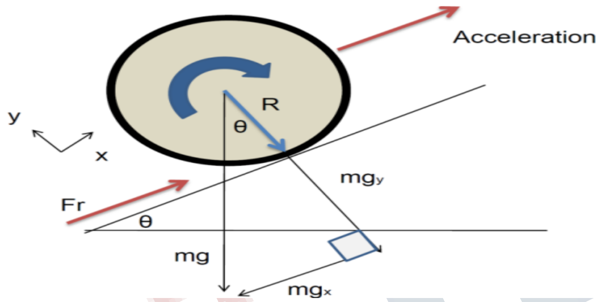


*Fig. 5. Drive wheel free body diagram.*

$$\boldsymbol{T = \frac{Rm(a+g\sin\theta)}{N}} \qquad \textbf{(5)}$$

Where,
T=Torque Required per Motor Drive
N= Total No. of Motor Drive Wheels
a=Acceleration Required
R=Drive Wheel Radius
m= Mass of the Robot (Including Motors)
g= Acceleration due to gravity
Θ= Inclination angle

### 2) Scrubbing effect (Skidding friction):

Skid steer mobile robot forms the limiting condition for the maximum torque required to drive the robot. Therefore the dynamics of the skid steer robot are considered and are as follows. The model is for only two motor powering the robot. Similarly the model for the 4 motor drive can be generated [3].

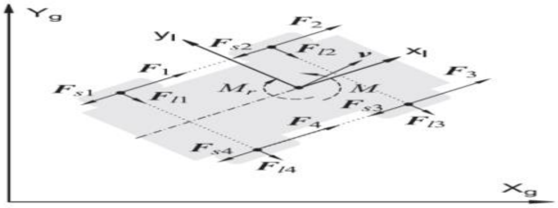


*Fig. 6.Dynamics of skid steer mobile robot.*

$$\boldsymbol{M}(\boldsymbol{q})\,\ddot{\boldsymbol{q}} + \boldsymbol{R}(\dot{\boldsymbol{q}}) = \boldsymbol{B}(\boldsymbol{q})\,\boldsymbol{\tau} + \boldsymbol{A}^T(\boldsymbol{q})\,\boldsymbol{\lambda}, \qquad \textbf{(6)}$$

$$\boldsymbol{M} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix} \qquad \textbf{(7)}$$

$$\boldsymbol{R}(\dot{\boldsymbol{q}}) = \begin{bmatrix} F_s(\dot{\boldsymbol{q}})\cos\theta - F_l(\dot{\boldsymbol{q}})\sin\theta \\ F_s(\dot{\boldsymbol{q}})\sin\theta + F_l(\dot{\boldsymbol{q}})\cos\theta \\ M_r(\dot{\boldsymbol{q}}) \end{bmatrix} \qquad \textbf{(8)}$$

$$\boldsymbol{B}(\boldsymbol{q}) = \frac{1}{r}\begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ -c & c \end{bmatrix} \qquad \textbf{(9)}$$

Where:
m = Mass of the robot.
Θ = angle made by the robot wrt the y axis.
$F_l$= Skidding force or the scrubbing effect.
$M_r$ = Resistive moment.
r = Radius of the wheel.
c = width of the robot.
I = Moment of Inertia of the robot about the "Z" axis.
$F_s$ = Resistance Forces.
$\dot{q}$ = velocity of the COM of the robot on the plane.

### 3) Orientation motor torque calculation:

Total torque required should be able to overcome 2 resistances, one is the moment of inertia of the drive-set and non-drive set and second is the disc friction (2 contact patches). The following equation are used to calculate the torque for orientation motor.

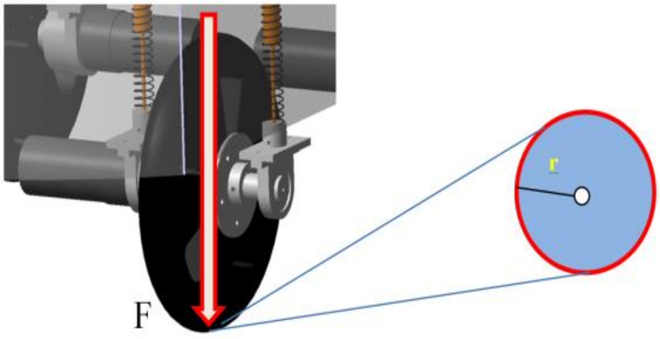


*Fig. 7. Orientation motor contact patch*

$$\boldsymbol{T_1 = \frac{2}{3}\mu F R} \qquad \textbf{(10)}$$

$$\boldsymbol{T_2 = \alpha I} \qquad \textbf{(11)}$$

Total torque required for the orientation motor is the summation of twice the $T_1$ and $T_2$ depending on the type, either the drive set or the non-drive set. Where:

$T_1$= torque required to overcome disk
Friction.
$T_2$=Torque required overcoming self-inertia.
$\alpha$=Angular acceleration of rotation.
I=Moment of inertia.
F = Normal reaction.
R = Radius of point of contact (radius of
Contact patch).

## III. PERFORMANCE TESTING

### 3.1. Performance Metrics Considered

As, already mentioned we have considered some performance metrics for testing the robot.

### a) Control Metrics

The electro-mechanical design of a system has great influence on the performance of a system. Yet, a good control system can boost the performance of an existing system to a level even further, which cannot be attained naturally. In order to gain control over a system a suitable control algorithm along with proper selection of electronic components such as sensors like encoders, IMU unit, ultrasound, camera etc. drastically improves the system robustness. We have implemented P (Proportional), PD (Proportional and Derivative), and PID (Proportional Integral and Derivative) controller for testing of the robot. It is simple to design and easy to implement on a system due to which it is widely used. PID is the basic linear control algorithm used in a system, which involved a constant feedback gain fed to the input. A PID controller determines error values as a difference between required value and measure process variables. PID involves three parameters i.e. Proportional (P), Integral (I) and Derivative (D) where P is accountable for present values, I for past values and D for future values.

### b) Operational Metrics

The operational parameter metrics parameters are the composition of telemetering data or derived products of the data obtained during the operation of the system. The data may consist of the distance travelled, navigation speed, positioning accuracy and repeatability of operation. These data can easily be obtained from the sensor implemented like optical encoder and ultrasonic sensors etc.

c) Mobility Metrics

Mobility performance is the most important criteria for an all-terrain mobile robot as it helps us understand the locomotive capabilities of the system. Mobility metric can be segregated into three main factors like maneuverability i.e. the ability of robot to change its directions avoiding obstacles in its path, trafficability which refers to the ability to generate traction to overcome resistances, and terrainability which is the ability of mobile vehicle to negotiate through rough terrain without compromising its stability. During our testing we have consider both indoor and outdoor terrain like ceramics/marble, concrete road and asphalt paved road.

d) Friction Requirement

Traction generation for vehicle moving in rough terrain is one of the biggest problem. Since the entire wheel are in continuous contact with uneven terrain, the load on each wheel changes with the contact surface. Hence, the torque required must be set accordingly as the terrain demands. This in turn effects the power consumption by the system. These parameters is computed as a derivative to the data obtained from current sensor, the PWM requirement for the motors to generate enough traction to overcome the frictions. The friction requirement can be calculated using the following formula

$$F_T \leq \mu . \times F_N$$

Where $F_T$ is traction force, $F_N$ is Normal Force and μ is frictional Coefficient.

The maximum traction force supported by ground is equal to μ. $F_N$. If it exceeds ($F_T > \mu .\ F_N$) slip occurs. Hence Friction coefficient is given by

$$\mu = \frac{F_T}{F_N} = \frac{T/r}{F_N}$$

a) Maximum Torque

The torque required to overcome the obstacles in its path or to travel smoothly through different surfaces or terrains vary as per the requirement of the system based on the operation performed by it. Example the system requires more torque when it is taking point turn when compared to straight motion or swing turn. This information can be extracted by relating the angular velocity of the system and the consumed current that is obtained from the current sensor. Torque can be calculated by

$$T = \frac{P}{\omega}$$

In the above equation, P is the electrical power i.e., P=V*I, ω=2π/T, where N is the number of wheel rotations and T is time for one revolution.

### f) Maximum obstacle height and Slip

Maximum obstacle height refers to the ground clearance available to the robot and is also dependent on the maximum torque it can generate to overcome it. Slip exist in system in various forms such as slide slip, turn slip and roll slip. This information can be obtained from the odometer data, which can be related to the encoder counts, and hence slip can be calculated

## 3.2.Analysis method and circuitry

The testing of the robot is done for the Skid Steering Configuration for forward and backward motion and point turn. P, PD and PID control algorithm is used for the control of the robot for better robustness and accuracy. The robot position is determined using encoder count required to travel the distance. A detailed calculation for the necessary counts is also shown in this paper. The robot is four wheel drive where power, direction of each can be manipulated to perform the necessary actions. The control board used is mbed LPC 1768 clocked at 96 MHz. The motors used are Maxon RE-40 motors having torque of 43.2Nm with built in encoders. These encoders have resolution of 500 PPR (Pulse per Revolution of wheel). These motors run at 24V and can draw upto 6A current each under full load condition. The motors are controlled through high performance motor driver IC known as Hercules motor driver IC which has operating range of 24v to 36v and current capacity of 16A. The circuit diagram of the robot is represented in fig.

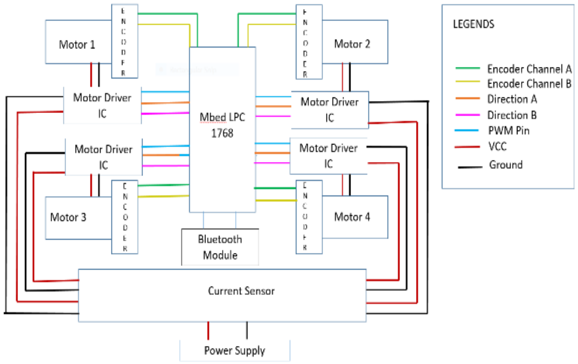


*Fig.8 Basic Circuit Diagram of the robot*

### 3.2.1. Straight Motion

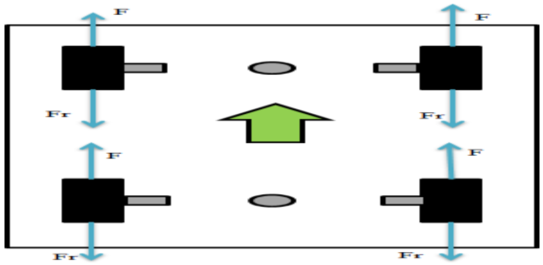


*Fig.9 Wheel movement configuration for forward motion*

The robot is tested on different indoor and outdoor terrains like ceramics/marbles, concrete surface, asphalt paved road for 5m and 7m for several iterations, and the average of them is considered. The necessary calculation for the encoder counts required is given below.

To calculate the encoder counts

Wheel diameter = 20 cm

Counts in one full rotation = 500

Circumference of wheel = πD = 62.8 cm

Total Counts required for 5m (500cm) is 3981

Total Counts required for 7m (700cm) is 5573

**a. *Forward direction on Ceramics for 5m***

| Controller | Encoder Count | Time Taken | PWM |
|---|---|---|---|
| P | 4103 | 15.717 | 10 |
| PD | 4001 | 15.599 | 10 |
| PID | 3962 | 15.518 | 10 |

**b. *Forward direction on Concrete for 5m***

| Controller | Encoder Count | Time Taken | PWM |
|---|---|---|---|
| P | 4000 | 12.464 | 20 |
| PD | 3945 | 12.371 | 20 |
| PID | 3899 | 12.364 | 20 |

**c. *Forward Direction on Asphalt for 5m***

| Controller | Encoder Count | Time Taken | PWM |
|---|---|---|---|
| P | 4210 | 15.530 | 10 |
| PD | 4000 | 15.522 | 10 |
| PID | 3962 | 15.518 | 10 |

**d. *Forward direction on Ceramics for 7m***

| Controller | Encoder Count | Time Taken | PWM |
|---|---|---|---|
| P | 5655 | 31.132776 | 10 |
| PD | 5501 | 31.132776 | 10 |
| PID | 5540 | 31.132776 | 10 |

*e. Forward direction on Concrete for 7m*

| Controller | Encoder Count | Time Taken | PWM |
|---|---|---|---|
| P | 5819 | 16.919 | 20 |
| PD | 5688 | 15.956 | 20 |
| PID | 5438 | 15.256 | 20 |

*f. Forward Direction on Asphalt for 7m*

| Controller | Encoder Count | Time Taken | PWM |
|---|---|---|---|
| P | 5711 | 39.521 | 10 |
| PD | 5679 | 39.269 | 10 |
| PID | 5570 | 38.976 | 10 |

### 3.2.2 Point Turn

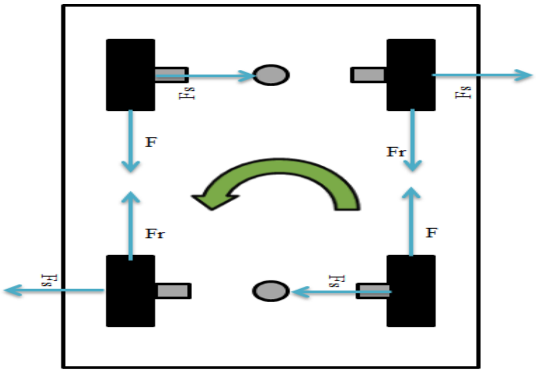


*Fig.10 Wheel movement configuration for point turn*

Point turn is also known as zero radius turn as the center of rotation lies within the robot as shown in fig. It is one of the ability of a mobile robot which required the most power to perform the operation. It helps in determining most of the metrics parameters. The calculation for the encoder count to perform $90^o$, $180^o$ and $360^o$ is given below

We know,
Wheel diameter = 20 cm
Encoder Count in one full rotation = 500
Circumference of wheel = $\pi D^2$ = 62.8 cm
$S=R\theta$
Where, S = Arc Length
R = Radius of Turn (Distance between two wheels of the robot)
$\Theta$ = Angle of Turn (Radian)

1. R = 20 cm
   $\theta = \pi/2$
   $S = 20 * \pi/2 = 31.4$cm
   Hence, count required for $90^o$ turn is 250
2. R = 20 cm
   $\theta = \pi$
   $S = 20 * \pi = 62.8$ cm
   Hence, Counts required for $180^o$ turn is 500.
3. R = 20 cm
   $\theta = 2\pi$
   $S = 20 * 2\pi = 125.6$ cm
   Hence, Counts required for $180^o$ turn is 1000

*a. On Ceramics or ceramic surface*

| S.N | Controller | Turn Degree | Encoder Count | Time Taken | PWM |
|---|---|---|---|---|---|
| 1. | P | $90^o$ | 566 | 11.789 | 40 |
| | PD | $90^o$ | 410 | 11.012 | 40 |
| | PID | $90^o$ | 300 | 9.896 | 40 |
| 2. | P | $180^o$ | 884 | 13.899 | 40 |
| | PD | $180^o$ | 711 | 12.929 | 40 |
| | PID | $180^o$ | 624 | 12.420 | 40 |
| 3. | P | $360^o$ | 2117 | 31.435 | 40 |
| | PD | $360^o$ | 1632 | 24.752 | 40 |
| | PID | $360^o$ | 1202 | 21.751 | 40 |

*b. On concrete Surface*

| S.N | Controller | Turn Degree | Encoder Count | Time Taken | PWM |
|---|---|---|---|---|---|
| 1. | P | $90^o$ | 464 | 11.789 | 60 |
| | PD | $90^o$ | 405 | 11.012 | 60 |
| | PID | $90^o$ | 306 | 9.896 | 60 |
| 2. | P | $180^o$ | 1275 | 13.899 | 60 |
| | PD | $180^o$ | 710 | 12.929 | 60 |
| | PID | $180^o$ | 610 | 12.420 | 60 |
| 3. | P | $360^o$ | 2569 | 31.435 | 60 |
| | PD | $360^o$ | 1772 | 24.752 | 60 |
| | PID | $360^o$ | 1422 | 21.751 | 60 |

*c. On Asphalt*

| S.N | Controller | Turn Degree | Encoder Count | Time Taken | PWM |
|---|---|---|---|---|---|
| 1. | P | $90^o$ | 320 | 8.461 | 50 |
| | PD | $90^o$ | 299 | 6.697 | 50 |
| | PID | $90^o$ | 182 | 5.738 | 50 |
| 2. | P | $180^o$ | 700 | 13.001 | 50 |
| | PD | $180^o$ | 621 | 11.989 | 50 |
| | PID | $180^o$ | 450 | 10.052 | 50 |
| 3. | P | $360^o$ | 2156 | 28.890 | 50 |
| | PD | $360^o$ | 1650 | 21.090 | 50 |
| | PID | $360^o$ | 98 | 19.112 | 50 |

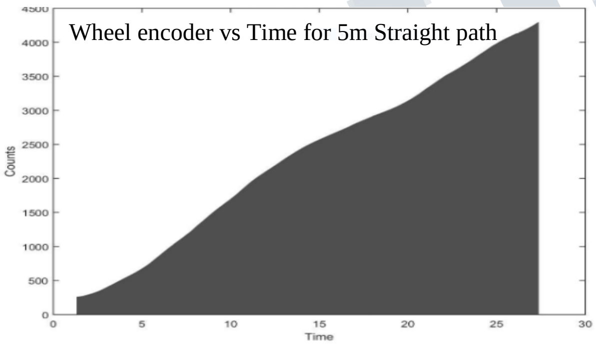
## IV. RESULTS

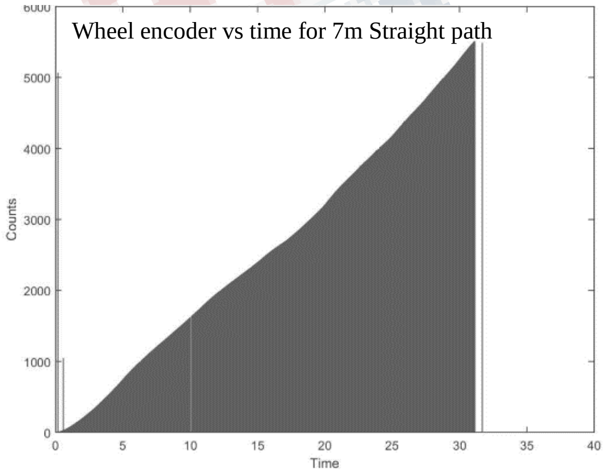
### 4.1 Obtained Graphs

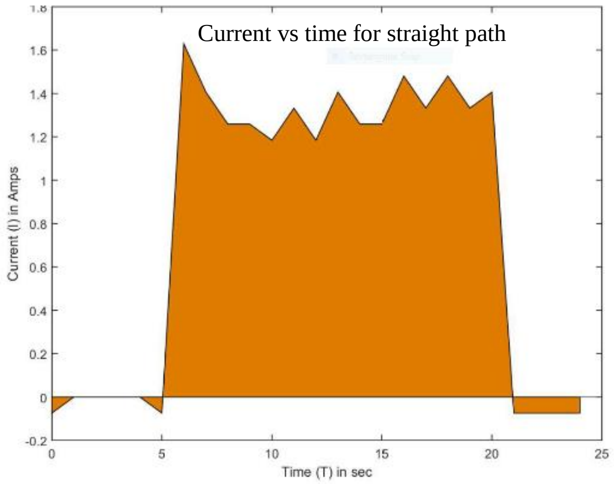
In this experiment, we have recorded the system current consumption and encoder counts with its corresponding time while the robot is performing different tasks on different terrains. These values are plotted in the below graphs.

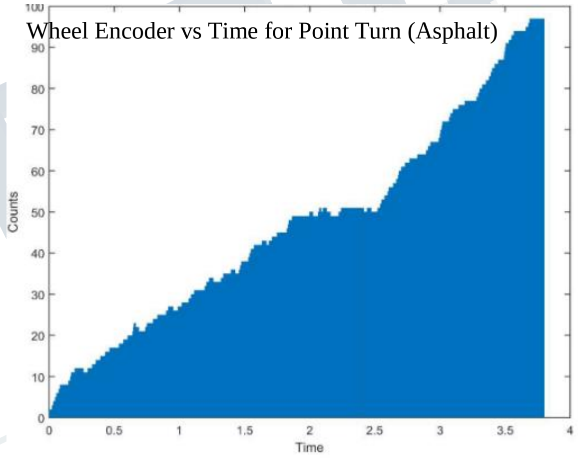
It can be observed in the encoder vs time graphs that encoder counts increases linearly with time, as the robot is moving with linear velocity. The small aberration from the linear line on either side is due to uneven texture of the terrain, which has affected the smooth rotation of wheels.

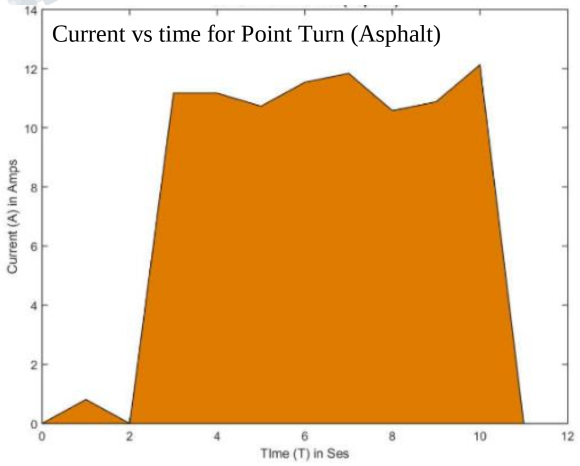
In the current vs time graphs, it can be seen that current requirement for the whole robot to perform a straight line motion is very less compared to that of when it is performing point turn, since the wheels undergone through very high stress and scrubbing effect against terrains. Since there is a constant change in texture of the terrain, current consumption is not constant with time.











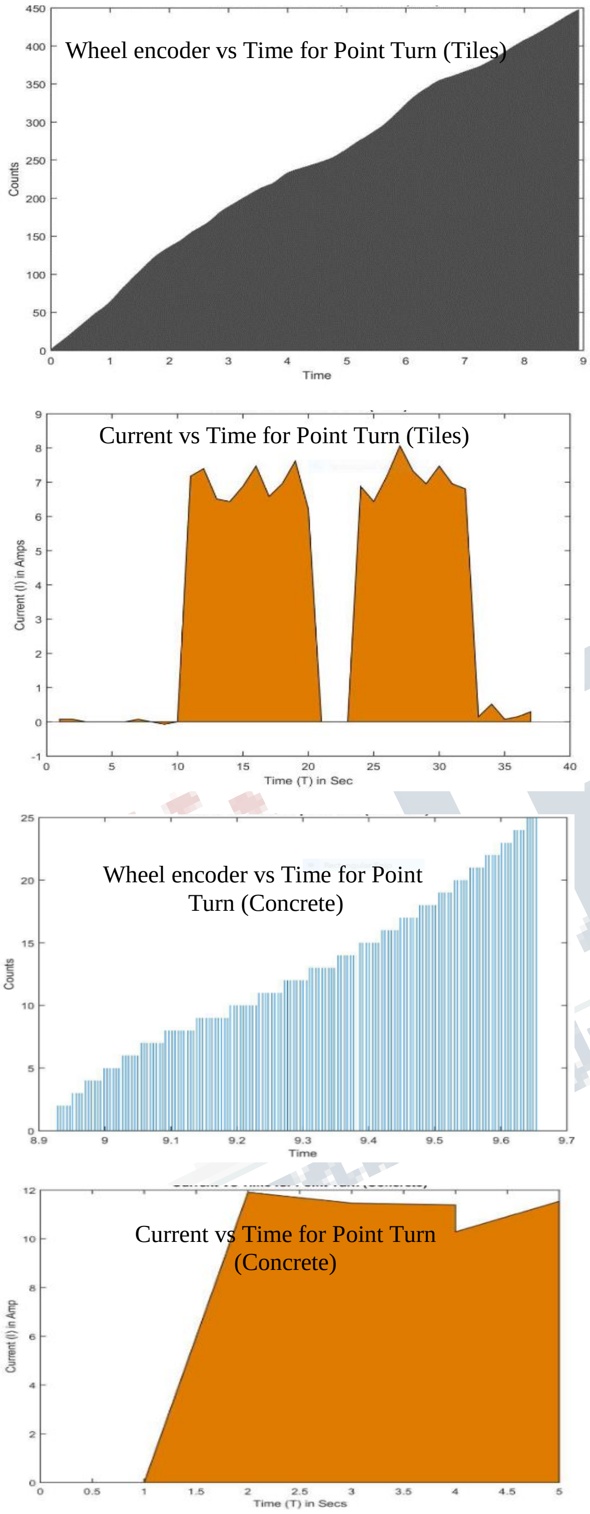


*Fig 11. Graphs Plots for Current and Encoder Counts vs. Time for Real-Time System*

**4.2. Derived parameters:**

Performance of the robot is quantified by certain parameters like angular velocity, power consumption, torque required by the system and coefficient of friction. These parameters are calculated with the formulas mentioned in performance testing section. The experiment is conducted on three different terrains and with the employment of three different controllers like P, PD and PID. The calculated results are tabulated below.

Calculated parameter for Robot moving in straight path

| Parameter | Asphalt | Concrete | Ceramics |
|---|---|---|---|
| Electrical Power (W) | 2.63 | 5.27 | 2.56 |
| Angular Velocity (rad/sec) | 1.362 | 2.618 | 1.675 |
| Torque (Nm) | 1.933 | 2.012 | 1.501 |
| Frictional force (N) | 13.734 | 13.73 | 3.433 |
| Generated force (N) | 19.33 | 20.127 | 15.014 |
| Voltage (V) | 1.7 | 3.4 | 1.7 |
| Current (A) | 1.55 | 1.569 | 1.48 |

Calculated Parameter for Robot to take Point Turn

| Parameter | Asphalt | Concrete | Ceramics |
|---|---|---|---|
| Electrical Power (W) | 142.59 | 130.56 | 55.89 |
| Angular Velocity (rad/sec) | 1.521 | 1.848 | 0.837 |
| Torque (Nm) | 93.71 | 70.64 | 66.71 |
| Frictional force (N) | 305.58 | 298.7 | 140.77 |
| Generated force (N) | 937.176 | 706.403 | 667.12 |
| Voltage (V) | 10.2 | 10.2 | 6.8 |
| Current (A) | 13.98 | 12.8 | 8.22 |

The minimum power required by robot to move in straight path and point turn on different terrains are given in the above table. It can be observed that torque requirements to perform the above task are also greatly affected by terrain texture and it varies on the terrains like ceramics, concrete and asphalt in an increasing order.

When the robot is performing point turn, its power consumption and torque requirement will be very high since both sliding friction and rolling friction comes into play, whereas in straight motion only the rolling friction plays major role. Power consumption and torque consumption is also a function of terrains and it increases with increase in coefficient of friction (terrain). It can be observed that on all three surfaces, the robot with PID control system performs better with more accuracy in the operation; this can be observed in the graph and table above where the counts are mentioned. PID performs better compared to P, PD controller as it provides better feedback to the control signal. Also the

From the above results, it can be seen that the robot has enough traction to overcome friction on all terrains and the can be able to perform any tasks on different terrain. From this discussion, it can be inferred that the robot can navigate through any terrain without compromising its tractionablity and terrainablity.

## V. CONCLUSION

When all terrain robot is designed many different parameter must be considered. These parameters involves different performance metrics that states how effective the electro-mechanical design of the system is during actual operation. In the above results, it can be observed that the control metrics, maximum torque, frictional requirements, mobility metrics has huge impact on system performance. It can be observed that when PID control system is deployed the torque is improved and the time consumed by the robot to perform the operation is less. In addition, the accuracy of the system is increased. It can also be seen that despite the theoretically calculated count requirement, the robot fails to reach it while performing the operation, which is due to slip. Also, the minimum criteria required to perform the operation is also addressed by the above calculations and results, this result can be used for future application The robot once the testing was completed, it has to be verified for real time operation. We designed a simple autonomous navigation system for the robot using ultrasonic sensor (LV Maxsonar). This helped in determining the maneuverability of the robot in clutter environment that is when numerous obstacles are placed in its path. It was repeated for several times on different terrains to verify the accuracy of the result obtained from it. This was done by making the robot run at a constant rpm even for navigation, to verify its grip over the entire operation such that it does not collide or trip over during the operation.

In future, the robot will be used to track humans in cluttered environment for security application. Preliminary work for the same has been done, for this it is necessary that robot has all the qualities that is that is discussed in above results.

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