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The Development of Ackerman Steering System for 1/10th Scale Autonomous Mining Shuttle Design

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Abstract

The usage of Autonomous mining vehicles at mining sites leads to remarkable improvement in the mining industry with efficient truck hauling, safety, and driving assistance. The steering mechanism is one major component of mining shuttle anatomy design. A significant share of failure in safety measures of the mining shuttle is due to steering imbalance. Steering stability is one of the key components of any mining truck design specifically in the recent emerging technology of intelligent transportation systems such as autonomous truck haul. The earlier steering mechanisms for the heavy truck such as the Davis steering mechanism and other steering mechanisms available in both sliding and turning pairs will be present in the front wheel axle which has less stability of tires in a curved path. To overcome the problem, this paper proposes the design of an enhanced Ackermann steering system to meet the stability, control, and other steering capability of mining trucks by turning the front wheels at different angles. This paper also discusses the methodology to implement the designed principles using 1/10th scale of an original vehicle prototype built using STM 32 microcontroller by 3D printing, whose movement is controlled with Remote Control (RC). Hence the designed prototype model prototype with its innovative gear system provides mobility to the mining shuttle without loss in energy due to friction leading to fuel efficient, safe, stable intelligent transport system with green technology.

Keywords: *1/10th Scale Prototype, Ackermann Steering, Autonomous Mining Shuttle, PID Algorithm, STM 32 Microcontroller, Turning Stability*

1.0 Introduction

The increasing demand for fueling is a pressing pressure on the mining industry which is enabling the industry to drift towards automation. The dump truck plays a major role in the metals and minerals transportation from the mine site and it's the most expensive and challenging part of the entire mining cycle. To reduce the expense and ensure the safety of the labor the Intelligent Transportation System (ITS)[1] is a solution and the usage of an autonomous mining shuttle is a promising solution to have sustained green technology at the mining site. The remarkable improvement in automobile technology has led to the usage of autonomous Mining shuttles. To ensure the safe transportation of the autonomous mining truck having an efficient steering balance is crucial. The autonomous mining shuttle will have a generic anatomy havingan ECU, steering and suspension system, and fuel monitoring system deployed over a chassis. The Steering system is the driving force for the vehicle and its function is to turn the wheels at the front whenever the driver offers the input, so it has to produce directional control of the vehicle. The angles of steering are modified by the geometry of the suspension and the steering system geometry of the front wheel. This steering system is built by various steering mechanisms such as the Davis

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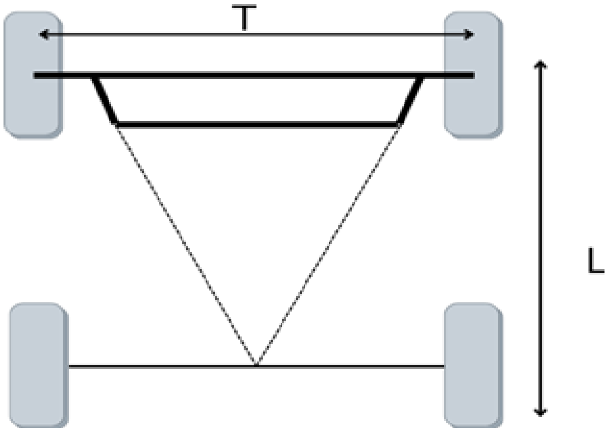

Figure 1. Generalized steering geometry of Ackermann concept.

mechanism, Ackermann mechanism, Rack and pinion mechanism, and so on[2].

Ackermann steering geometry[3] is a systematic design of steering linkages in a geometrical way for the Mining shuttle, solving the issues of turning wheels inside and outside radii to identify circles of different radii. This also provides the simplest form of implementation with high stability. The geometry of steering is considered to be the important entity for a designer to make the vehicle to obtain maximum performance from all wheels.

Basically, Ackerman's mechanism is a "four bar steering system" as shown in Figure 1, Where 'L' is the length of chassis and 'T' is the length between the frames with wheels which sends the driving direction from the driver to one wheel which through the Ackermann linkages will propagate to other wheel and stabilizes the wheels of the Mining shuttle over a point called Instantaneous Center of Rotation (ICR), through which the motion can be analyzed as pure rotational motion.

In a low-speed scenario during the cornering movement all the wheels will be having the regular rolling condition and leads to safe movement of vehicles without sliding. In a curve path the linkages will make the wheels to cover various speed and distance with the corresponding safe angle. The Ackermann mechanism will be designed so that the rear wheel will have constant turning angle at the center over a straight line. Whenever an automobile travels in a curves the front wheels will have a specific unique angle of trajectory surrounding the center axis. Therefore, Ackermann's principles is to develop a precise geometric pattern to properly coordinate the front inside and outside arcs according to the steering action. Further to improve the performance of the technique development of the PID based prototype implementation and testing is to be done, using industry standard scale such as 1/10th, 1/18th, 1/24th scaling method[4]. However, the paper discusses about 1/10th scale vehicle design using 3D printing of chassis.

Organization of the Paper: The paper is organized next as the following Sections; Section 2 will provide insight into the related literature to indicate state of the art. Section 3 provides the overall system overview and the design. The Section 4 further provides the algorithm designed and the related results. Finally, the paper is concluded with the conclusion section.

2.0 Literature Survey

This section discusses the few noticeable works that are Mining shuttle ride out in the Ackermann steeringdesign technique and the summary of those literature which is the groundwork for implantation is as follows,

Adria Fung *et al.*,[5] discussed the importance of steering mechanism in the automobiles and proposes that it can designed through various technique. The paper focuses on one of major mechanism which is the "Ackermann steering system". Here it discusses the usage of the CAM Pulley technique which is developed using a microcontroller and various sensors such as UV, RF, and IR. They work independently of each other to track the curves and distance with multiple iterations to reach accuracy. This model makes use of RC based prototype with PWM implementation.

FC Braescu and CF Caruntu[6], provide the prototype model Car design mainly to implement vehicle platooning using navigation control techniques. The model Mining shuttle is designed using the modulations and consists of a variety of sensors. The car control module is an embedded application that is developed in compatibility with the FreeRTOS real-time operating system with highly customized features and is composed of a PIC microcontroller and STM32 F3 DISCOVERY board. Life. Augmented[7], explains the STM32 working principle and the architecture involved in STM32 microcontroller.

VK Saini, *et al.*,[8] discuss the finding of a more cost-effective steering mechanism for any mode of the vehicle. Here the anti-Ackermann steering geometry is used with

Table 1. Summary of the literature review

Sl. No.	Authors	Year	Title of Paper	Key points
1	Andria Fung and William Parker	2015	Enhanced Ackermann steering platform	• Ackermann steering and other steering system • RC controlled car
2	F C Braescu and C. F. Caruntu	2017	Prototype model car design for vehicle platooning	• Chassis design and vehicle platooning • About controller implementation
3	V. K. Saini, Abhishek Saxena, Ujjwal Tripathi, and et. al.,	2020	Design and development of the steering system of an all-terrain vehicle	• Ackermann steering parameters • Vehicle design parameters
4	Chejarla Santosh kumar, Anjali T and et al.,	2021	A Cost-effective framework for developing and testing autonomous RC Cars	• RC car design • Testing of RC Car
5	Jonathan Vog	2017	Ackermann steering Geometry	• About slip angles and turning angles • Calculation of front steering angles
6	Life-augmented datasheet	2015	STM32F100xft Reference Manual	• STM32 working principles • STM32 Architecture

multiple parameters acceptable for the flexible design of the Mining shuttle. Its working principle is to convert the rotational motion into travel motion using "Rack and Pinion" and the steering column using fabricAL6082-T6. The steering wheel is optimized using self-design in terms of its size and weight. Throughout the look of the wheel, technology doesn't seem to be compromised. Here the mobility of the steering wheel is shifted to the wheels using thetied rods which together with the wheel hub is connected to the steering arms.

Chejarla Santosh Kumar, *et al*.,[9] propose an efficient framework for developing and testing autonomous RC Mining shuttles. In addition, they presented ongoing work on developing an autonomous toy RC Miningshuttle that is being built using a laptop/computer for detecting and ranging the distance instead of LIDARand smartphones instead of picam.

Jonathan Vogel[10], describes that the steering geometry is one of the many tools at a race Mining shuttle designer's disposal to ensure the Mining shuttle extracts maximum performance from all four tires. In this, they cover the origins and purpose of Ackermann Steering geometry and how its variations can affect tyreperformance across a vehicle's operating range

Adolfo Martinez[11], gives the information about the PID controller which helps to minimize or reduce the error of the system by comparing the output of the controller then comparing with respect to the given reference value. This also provides the idea about the designing of the PID controller by considering its proportionality, integral, and differentiator constants.

The summary of all the papers is tabulated in Table 1, as shown below

3.0 System Design

This section provides the overview of the Ackermann steering system and prototype of 1/10th RC Miningshuttle with a degree of freedom of rotational motion, ranging from 60° to 120° with respect to a straight line joining two tires with a positive camber. The advantage of positive camber is that the vehicle can turnin any direction with less effort and thereby provide stability, whereas the negative camber used in high-speed vehicles the cornering is

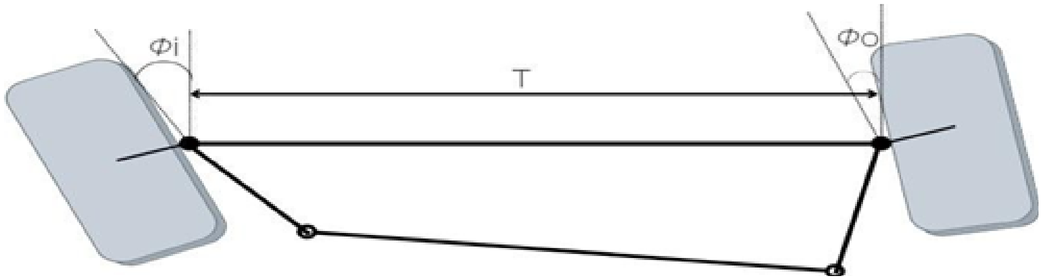

Figure 2. The Ackermann steering mechanism.

made as the bottom of the wheel is not in contact with the surface. The Ackermann steering mechanism works on the principle of rotation angle of the inner wheel slightly sharperthan the outer wheel as shown in Figure 2, so that slippage of wheels in the curved path will be reduced.

Figure 3 gives the chassis design of the prototype Mining shuttle. Here 'ϕ' represents the turning angle which needs to be varied according to the steering action in which ϕi is the inner angle and ϕo is the outer turning angle. 'W' is the length of the central frame of the freewheeling front wheels and 'T' is the length between the frames of the rear and front wheel. 'R' is the side length which is so chosen that the pitch curveof the frame should not be a parallelogram instead must be a trapezoid and 'Instantaneous Center of Rotation (ICR)', through which the motion can be analyzed as pure rotational during steady state. In fact, the motion can be analyzed based on the intersection of all the turning angles at appoint called InstantaneousCenter for Curvature (ICC). The ICC is the point about which the vehicle body should rotate, that is lying inline with the common right as well as common left wheel axis. Hence in general both of them are the reference points used to calculate the turning angle of the tires either inwards or outwards.

This helps the body to perform the rolling action. In this design, it can be observed that the front wheels of the vehicle will tilt at different angles during curves based upon Freudenstein's Equation[12] as it is making use of four bar mechanism. The equation helps to know the outer angle of the wheel when the inner angle is fed using the equation,

$\boldsymbol{\phi}o = \boldsymbol{\phi}i - \text{pack}(\boldsymbol{\phi}i - \boldsymbol{\phi})$ Equation (1)

Where, pack is the Ackermann percentage to change the outer angle

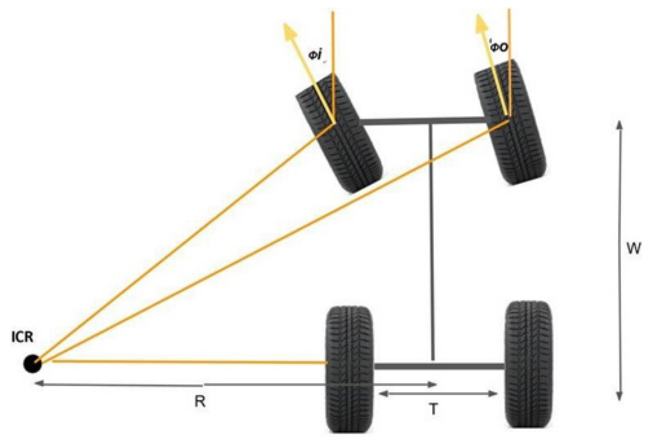

Figure 3. Chassis design of the prototype Mining shuttle.

3.1 Design Equations

The Ackermann steering equation can be obtained by having the three triangles formed by the verticalside *l* and the side *r*± \frac{w}{2}2*w*.

Therefore, it can be obtained that,

$$\begin{aligned} \tan\phi &= \tfrac{l}{r} \\ \tan\phi_i &= \tfrac{l}{r-w/2} \\ \tan\phi_o &= \tfrac{l}{r+w/2} \end{aligned} \qquad \text{Equation (2)}$$

Now, by subtracting the reciprocal of the latter two equations, the Ackermann steering equation can be obtained as,

$$\frac{1}{\tan\phi_o} - \frac{1}{\tan\phi_i} = \cot\phi_o - \cot\phi_i = \frac{r+w/2}{l} - \frac{r-w/2}{l} = \frac{w}{l}$$

Equivalently, the two cotangents can be expressed with the base angle ϕ as follows

$$\begin{aligned} \cot\phi_i - \cot\phi &= \tfrac{r-w/2}{l} - \tfrac{r}{l} = -\tfrac{w}{2l} \Leftrightarrow \cot\phi_i = \cot\phi - \tfrac{w}{2l} \\ \cot\phi_o - \cot\phi &= \tfrac{r+w/2}{l} - \tfrac{r}{l} = +\tfrac{w}{2l} \Leftrightarrow \cot\phi_o = \cot\phi + \tfrac{w}{2l} \end{aligned}$$

Equation (3)

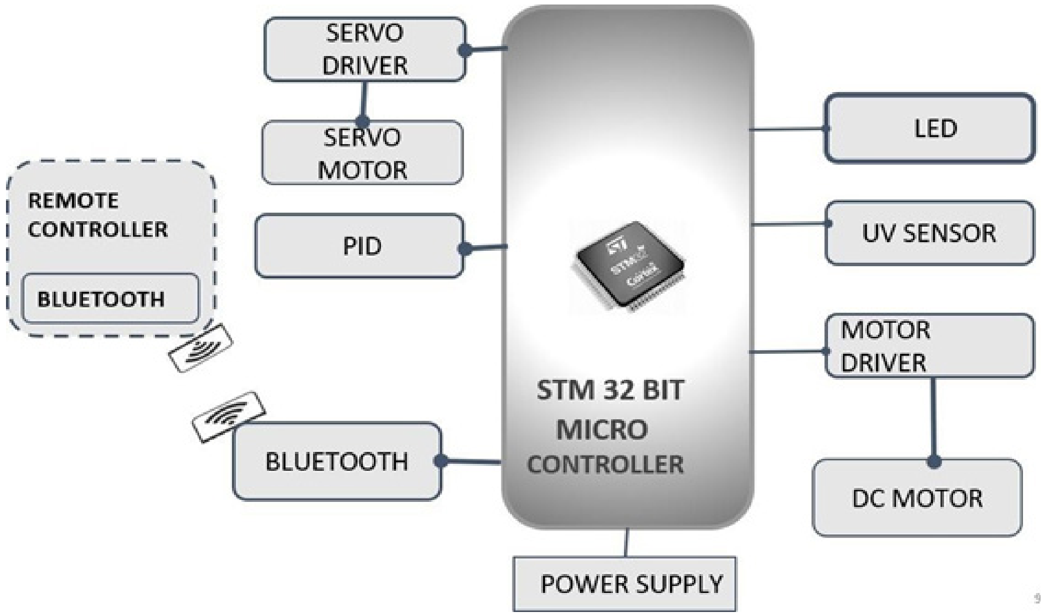

Figure 4. Overall block diagram of microcontroller interface for steering angle and RC.

These equations have a problem for the case $\phi = 0$, since cot(0) is not defined. However, when considering the fact that cotα =cosα/sinα, we can reformulate the equation as

$$\begin{aligned}\phi_i &= \tan^{-1}\left(\frac{2l\sin\phi}{2l\cos\phi - w\sin\phi}\right)\\ \phi_o &= \tan^{-1}\left(\frac{2l\sin\phi}{2l\cos\phi + w\sin\phi}\right)\end{aligned} \quad \text{Equation (4)}$$

To sense the angles of the wheel the ultrasonic sensors with a range of around 200 cm are deployed onthe rim of the wheel, in the prototype vehicle through which the data will be obtained to the STM 32microcontroller which is an industry standard microcontroller with its own IDE deployed over the steeringsystem of the prototype vehicle as shown in Figure 4. The PID controller will read the sensor value do error calculation and nullify the error close to expected value which is described in the PID algorithm in Table 2. The obtained estimated angle is fed to servomotors for the accurate turning angle of the wheel.

The functionality of each block is explained below,

- System/circuit and software present in 1/10th scale Mining shuttle
- Microcontroller: Microcontroller STM32 series is the heart of this project, which is used to interface with IR Sensor, Ultrasonic Sensors, Bluetooth, Servo motors, and DC motors. It is programmed to develop an interfacing software stack for peripherals and control logic for the vehicle.
  - * Servo motor: Servo motor is interfaced with MCU to work as Ackermann steering (attached to front wheels) of the vehicle. Servo motor angle is changed based the commands sent by PID control logic.
  - * Bluetooth: Bluetooth unit is used during manual mode driving for communication between vehicle and remote control. In other modes it will transmit information/warning to user display present in remote control.
  - * DC motors: DC motors are interfaced with microcontroller via driver circuit to enable motion ofthe vehicle. DC motors are connected to rear wheels to control the speed of the vehicle.
- Remote control present with user/driver: It will be used to switch from manual driving mode to platoon mode or autonomous mode through commands sent via Bluetooth module.
- Power Supply Unit: Power supply unit consists of batteries and other circuits to provide required power to system.

The designed angle of turning is implemented using the PID algorithm developed as shown,

The flow diagram below in Figure 5 shows the stable freewheeling movement of the wheel which is generated based on the signal generated by the STM-32 microcontroller depending upon the turning anglewhich is tuned using the PID algorithm.

The Figure 6 gives the overall communication block diagram of the prototype Mining shuttle model which is divided into two sub blocks where in the first subblock showing the communication interface at the prototype Mining shuttle built by 3D print and another module showing communication inter face at RC.

Table 2. PID algorithm to obtain the error approximation

1) Initialize the set or value expected from the sensors
2) Read the sensors to get the value
3) If an error has occurred between the set and the value from the sensors pass it through the PID controller
4) Tune the PID to get the values like K_p (Proportionality constant), K_d, K_i, critical oscillation.,
5) The proportionality block in PID improves the difference value by the amount of K_p
6) Differentiator block differentiates the difference within the given time and tries to predict the error within the time
7) Integrator integrates the difference within time and minimizes the overshoot
8)It reduces the error difference regularly to get the expected value
9) At each step the error is compared with a minimum and maximum value of the error
10) It tries to bring the error closer to the expected value

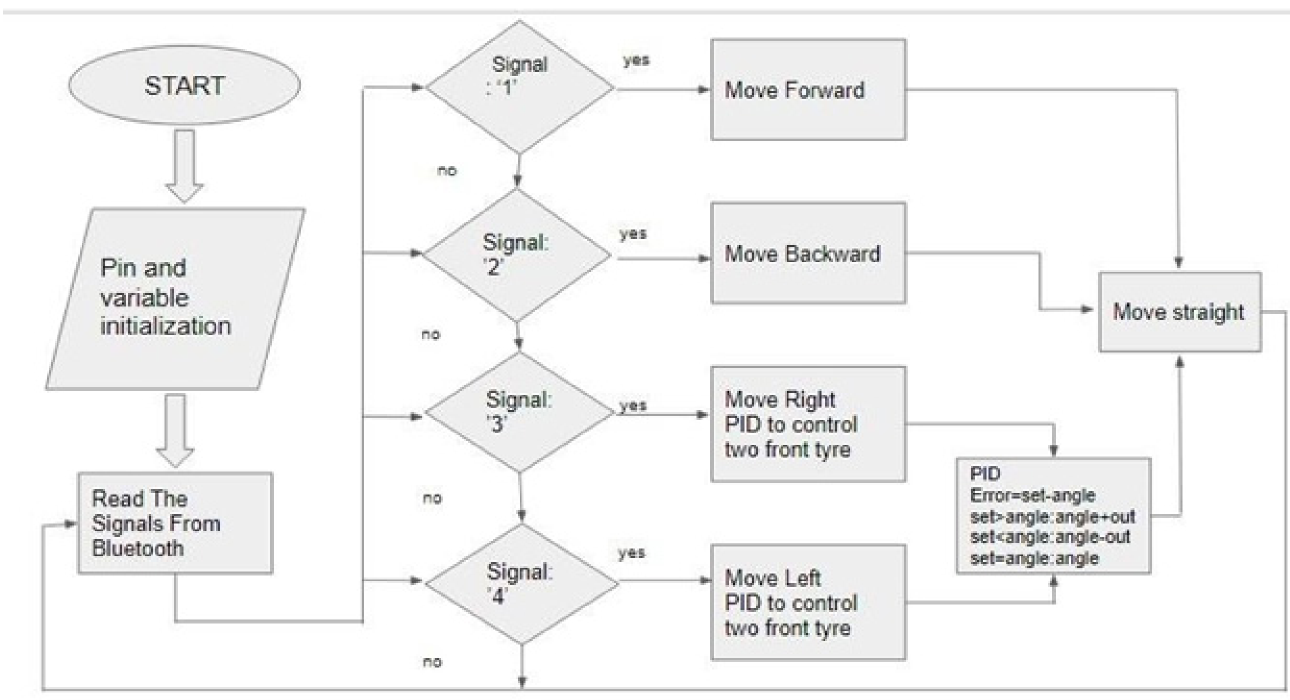

Figure 5. Flow diagram of the wheel control using PID.

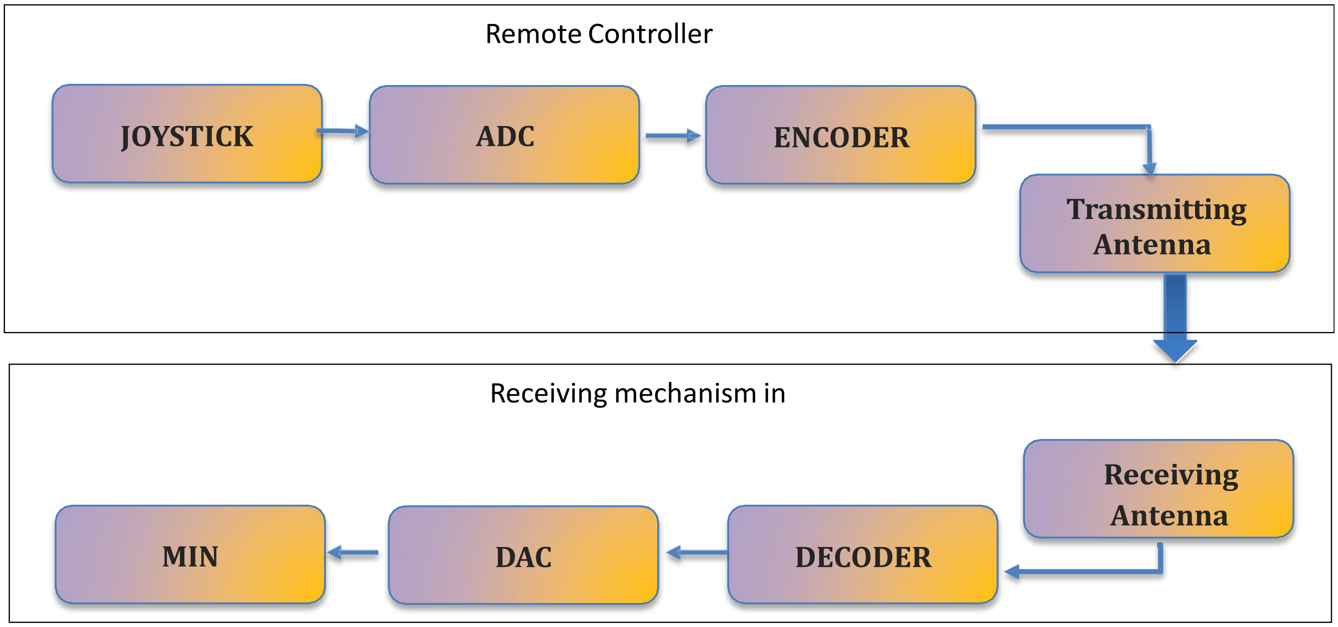

Figure 6. Block diagram of RC Car communication.

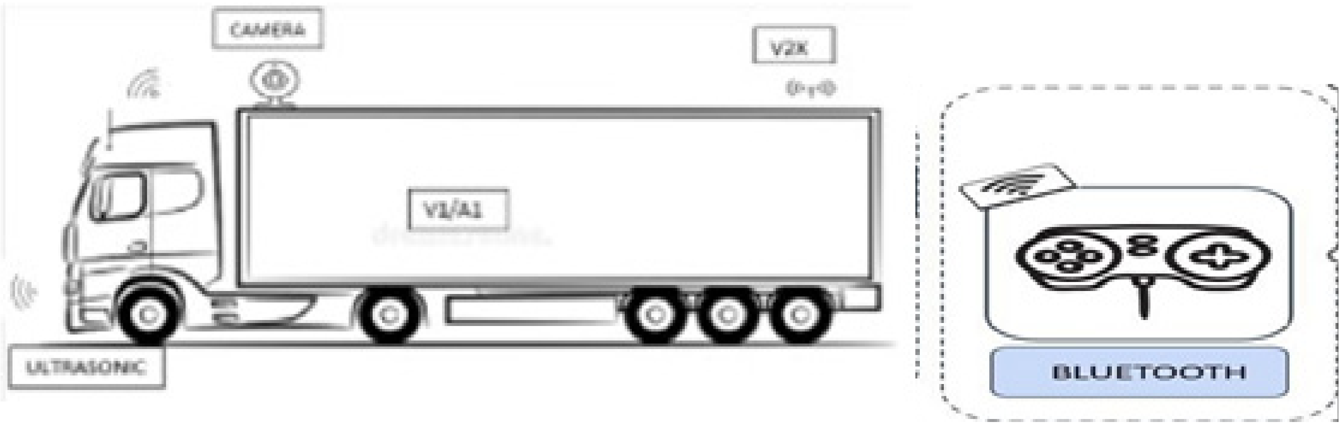

Figure 7. The overall system view.

- Joystick is used to control the steering of the Mining shuttle, ADC is to convert the analog signalsto a digital signal, Transmitter antenna is to transmit the signal from RC to Mining shuttle
- Receiving antenna is used to receive the signal from the RC side, DAC is used to retrieve the original analog information.

Therefore, the overall designed prototype Mining shuttle is as shown Figure 7 where, the ultrasonicsensors deployed over the rim which are interfaced with servo motor on the front and DC motor onthe rear wheel to sense the path and give the turning angle accordingly to give stability in the curved path. To demonstrate the motion of the prototype Mining shuttle it is remote controlled through Bluetooth.

4.0 Results

The following section provides the importance of PID algorithm in the stability gain and also the 3D design part of chassis. The PID algorithm is implemented and executed in the MATLAB environment and the response

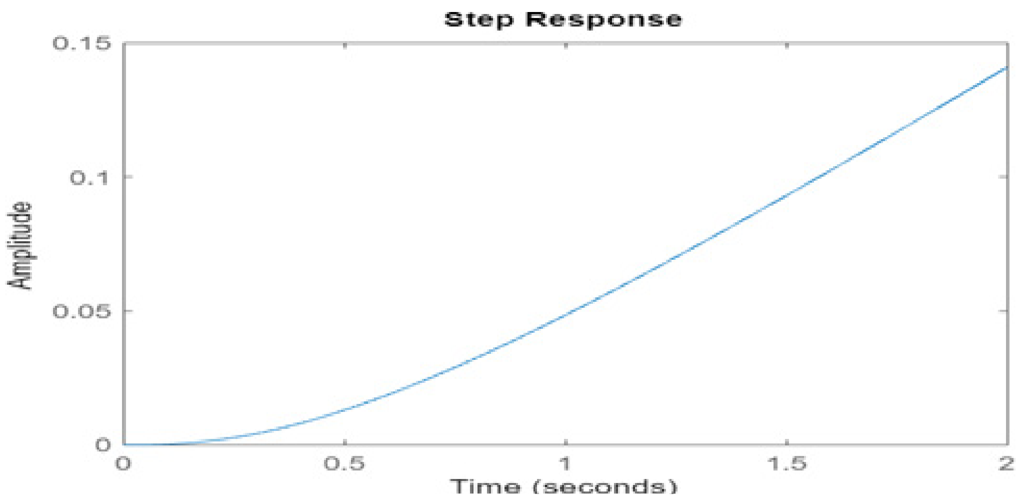

Figure 8. Graph of time vs amplitude for gain without PID.

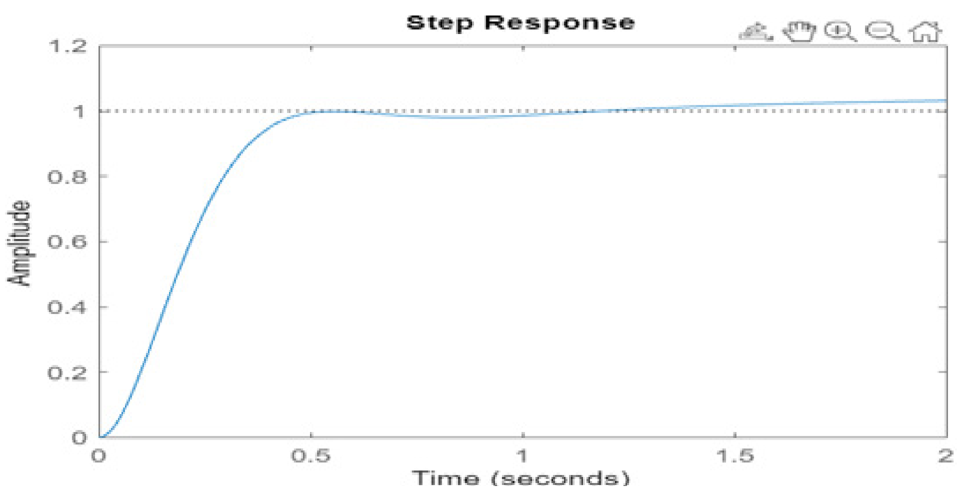

Figure 9. Graph of time vs amplitude for unity gain with PID.

is shown for without and with PID algorithm as shown in Figures 8 and 9. The graph in Figure 8 shows that the system is reaching stability slowly and even after 2 seconds the system is not obtaining the stable unity gain and also will have overshoot leading to slipping specifically at curved path.

However, with the help of PID the system will reach the unit gain within 0.5 seconds itself. The tuning parameter given for the PID are, s = tf('s'); sys = 0.01/(0.005*s^3+0.06*s^2+0.1001*s) as a step response which gives the value of PID tuning parameters as kp = 40; ki = 10; kd = 30 which can be tuned accordingly.

The graph in Figure 9 depicts that the implementation of PID makes the system reaches the unity gain quickly with lesser overshoot hence making the system more stable and responsive. The experimental validation[13] of the implementation is done on a 1/10th scale prototype using STM 32 microcontroller overa customized chassis.

The chassis used for setting up the prototype Mining shuttle the customized chassis is built using solid works software and 3D printing[14] of the prototype is done in Nozzle printer with 50% inside filling of the 3D parts using Polylactide (PLA) material. The designed chassis is as shown in Figure 10

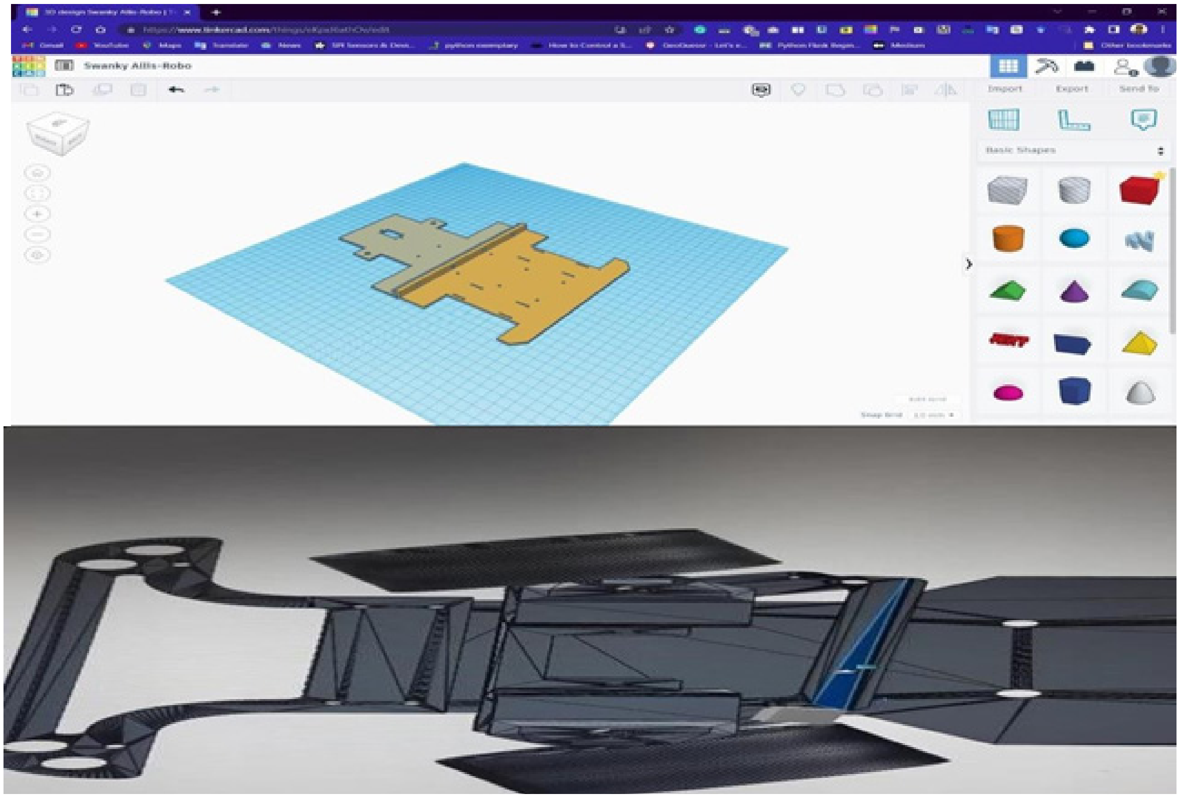

Figure 10. The 3D print chassis of the prototype Mining shuttle.

5.0 Conclusion

The steering system is one of the design critical systems in an autonomous mining shuttle and improper designs leads to instability and can become hazards leading to life threat. Ackermann's steering principle is a solution to induce stability in the steering mechanism of the vehicle and the implementation of the PID algorithm through the microcontroller will make the vehicle more stable and robust. Therefore, this paper shows the successful implementation of this principle over an RC- controlled 1/10th scale prototype mining shuttle whose chassis is designed using the 3D print technology. As the Ackermann steering mechanism provides a stable slip angle it reduces the friction on the road as well leading to reduced wear and tear of the automobile components and reduced fuel consumption leading to green technology. Due to its high stability, it can be used in one of the emergingtechnologies in intelligent transportation systems of mining truck hauling called vehicle platoon[15] applications.

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