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Convertible Uni-Bike Based on Inverted Pendulum Model and Prototype Using Additive Manufacturing

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Abstract. This paper explores the methodology used to develop the miniature working concept (prototype) of a Uni-wheel Electric bike (E-bike) convertible to an E-bike where the Uni-wheel works on an inverse pendulum mechanism and the prototype model is manufactured using Poly Lactic Acid (PLA) filament-based additive manufacturing using a Fused Deposition Modelling based 3D printer. Uni-bike, which can be converted into a normal bike as per the convenience of the rider. Because of the growing awareness of pollution and the energy scarcity situation, vehicles and motorbikes are no longer the ideal modes of mobility. As the cost of petroleum products rises, a more cost-effective and efficient form of transportation is required. This miniature prototype might be utilized to create a human-ridable model in the future.

Keywords. Uni-wheel, Inverse pendulum mechanism, Additive manufacturing, Cost-effective.

1. Introduction

A unicycle is a one-wheeled vehicle that is driven by the rider's pedaling or by motors that rotate the wheels. A unicycle works on the same principles as an inverted pendulum. In a unicycle problem, the rider's pedaling, or wheel torque, helps to stabilize the unicycle in the wheel's plane. In an inverted pendulum model, the movement of a movable platform, which is a linear translational motion, impacts the pendulum's stability.

A standard pendulum is in an equilibrium position; since there is no external force or torque acting on the pendulum, it will remain stationary, and if there is any displacement, it will come under the effect of a restoring torque that will bring it back to the initial position. An unstable equilibrium point is reached when a pendulum's bob is inverted and maintained exactly above the pivot with the help of a solid rod. Since the bob is exactly 180 degrees from its stable position, there is no torque acting on the pendulum at this point, but even a small displacement will generate a gravitational torque, accelerating it away from its prior position and causing it to lose balance.

A feedback control system has been implemented to balance the pendulum in the inverted position. It inputs the pendulum's angle at regular intervals and varies the position of the pivot when the pendulum starts to displace from equilibrium to keep it in a stable position, i.e., 180 degrees from the standard pendulum equilibrium position

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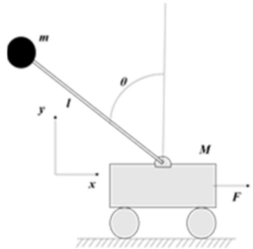

Figure 1. Inverted pendulum mounted on a cart.

Equations of motion correspond to the given problem statement using Lagrange's equations.

$$(M+m)\ddot{x} - ml\ddot{\theta}cos\theta + ml\dot{\theta}^2 sin\theta = F \quad (1)$$

$$l\ddot{\theta} - gsin\theta = \ddot{x}cos\theta \quad (2)$$

These equations are used as equations of motion for unicycle and are imported as an input for the control algorithm, which works as the basis of the Arduino code uploaded to the micro-controller for the self-balancing of the given prototype.

2. Literature Review

[1] A. Kadis, D. Caldecott et al. (2010) The kinematics of the unicycle were derived and described in this study. This deduction was verified using numerical simulations. This data was then utilized to create a computer simulation of a PD controller, whose performance was compared to that of the practical Micycle system. The creation of a model-based non-linear controller and a backstepping controller is among the projects planned for the future. The best control technique will be integrated into the Micycle design when it has been compared and benchmarked. To reduce the high tendency to saturate, a greater capacity motor controller should be added to the system. The introduction of active stabilization in the roll direction is another planned enhancement. This actuator will enable the Micycle to be a totally self-electric unicycle by using either a response wheel or a control moment gyroscope.

[2] Manjunatha G et al. (2020) The completion of this project results in a sleek design and self-balancing structure, which is helpful for customers to handle and drive easily. The air pollution and parking /spacing problems can be solved by the foldable and electric features of our "Monowheel Electric Vehicle." Due to its compact and foldable design, it can be carried easily on the subways, metro, trains, etc. And it produces very low noise, which reduces sound pollution.

[3] D. Hazry M. Sofian A. Zul Azfar et al. (2009) performed an investigation into the inertial measurement unit (IMU). The author has conducted a thorough investigation into the different kinds of IMU sensors on the market and offers useful advice on how to combine IMU sensors with GPS tracking in order to use additional functions in machines like unmanned vehicles and aircraft.

[4] N. K. Nasir, M. A. Ahmad, R. M. T. Raja Ismail et al. (2010) used MATLAB software to compare the input tracking and disturbance rejection capabilities of various stability regulating strategies such as LQR and PID for most non-linear vehicles. In

comparison, both the LQR and PID control systems have been demonstrated to be effective in regulating non-linear vehicles in both linear and angular modes.

[5] Yohanes Daud, Abdullah Al Mamun, Jian Xin Xu et al. (2013) discussed the many issues that arise when balancing a lateral pendulum unicycle. Three linear control strategies for developing the controller in terms of their longitudinal and lateral form have been proposed for these balancing challenges. The author analyzed several initial postures that pose a threat to balancing and came to the conclusion that it shows very little balancing, i.e., just for initial conditions.

[6] Sreevaraham Kumar, Bangaru Akash, and T. Delsy et al. (2014) designed and built a monowheel by deploying a self-balancing algorithm. The MPU6050 sensors were utilized, which have both an accelerometer and a gyroscope built into one chip. While employing similar strategies as others in their project, such as a microcontroller that aids in the execution of the program and provides the output to power the drive. The MPU6050, in conjunction with a 16 MHz external resonator tiny Arduino ATmega 328. This monowheel has a top speed of 20 kilometers per hour.

[7] Desna Nugroho, Raden Sanggar Dewanto, Dadet Pramadihanto et al. (2016) discussed the PENS wheel, which is a mono-wheel and self-balances, assuring rider's safety in either direction. The author suggests using a few key components in the design of PENS wheels, such as a BLDC motor and an IMU sensor. The PID controlling technique is used by the PENS wheel to automatically maintain its equilibrium. After completing all of these steps in the experimental model, the author concluded that the PID controller was effective within a ±10° tilt angle.

[8] Mukesh Sahu, Naved Shaikh, Saurabh Jadhao, Yash Yadav et al. (2017) recommended an investigation of RYNO motors which is based in Portland, Oregon, to see where the genesis of the RYNO motor comes into play. In RYNO, the driving source of energy is primarily a gyroscope and accelerometer unit, controller, DC motor drive, and battery. The authors have also mentioned a number of benefits and drawbacks, such as the ease with which the remaining battery charge can be checked and the ease with which the remaining battery charge can be checked. A 12V DC battery can be used to charge a personal tablet or phone. It can be parked anywhere, but there are a few issues because only one device controls both speeds.

[9] P. Sarala, S. F. Kodad, and B. Sarvesh et al. (2017) did a study that compares a variety of converters for BLDC motors, including simple Buck converters, Bridgeless Buck converters, and Hybrid Buck converters, as input supply needs to be rectified for varied applications to correct the power factor. Simulink models developed in MATLAB/SIMULINK software are used to compare the results. The power factor angle was always given in comparison, and hybrid buck converters were shown to be considerably superior to basic buck and bridgeless buck converters.

[10] Prof. Yogesh Risodkar, Mr.Ganesh Shirsath, Ms.Monali Holkar, Mr.Mayur Amle, et al. (2015) have discussed the necessity for alternate modes of transportation, as well as a basic overview for constructing the prototype, such as the monowheel based on inverted pendulum model, which will be used for modeling. It has also been suggested that gyroscopic sensors will be required for an intelligent car to detect the rider's angle and steer or brake the vehicle properly.

3. Methodology

The following objectives were set for the project.

1. To design and manufacture a chassis using additive manufacturing with PLA as the raw material and optimizing the same through varying the different printing variables.
2. Convertible Uni to bike through trailing arm mechanism.
3. To carry out the balancing of the uni-bike prototype on the pitch axis using the principle of inverted pendulum model, stepper motor, Inertial Measurement Unit (IMU), and Proportional, Integral, Derivative (PID) control.
4. To carry out the balancing of the uni-bike prototype on the roll axis through wheel geometry.

The following components were selected for materializing the prototype, followed by the factors considered.

1. Lithium-Polymer Battery (LiPo) – High energy density along with availability.
2. Microprocessor Unit (MPU) 6050 – Micro Electro Mechanical System technology-based single chip with both the accelerometer and the gyroscope embedded.
3. Arduino Nano – Small-sized Atmega328-based microcontroller.
4. HC-05 module – Bluetooth Serial Port Protocol with master and slave mode, connection with the smartphone using a terminal application.
5. A4988 stepper motor driver – micro-stepping motor driver designed to operate bipolar stepper motors up to $1/16^{th}$ step modes.
6. NEMA 17 – Hybrid stepping motor with 200 steps per revolution, precise position control with holding torque of 3.2 kg-cm.
7. PLA spool – Polylactic acid is a cheap thermoplastic filament extracted from renewable resources with a low melting point, making it easy to work with.
8. Wheels

3.1. PITCH CONTROL ALGORITHM

To explain the general algorithm of the pitch controller of our unicycle, we first have to define a few key terms that are often used while referring to PID control.

- <u>Proportional Gain (K_p)</u> A given level of error is maintained while increasing the control signal proportionally to the increase in K_p. Maintaining the level of error causes the closed-loop to act quickly but also overshoot the target.

- <u>Derivation Term (K_d)</u> The error increasing causes the control signal to increase, allowing the controller to dampen, thereby controlling the overshoot caused by K_p. Steady-state error is not affected.

- <u>Integral Term (K_i)</u> A steady error causes Ki to decrease the error by increasing the control signal persistently. Processing time causes the system to act sluggishly as time gets added persistently along with the control signal.

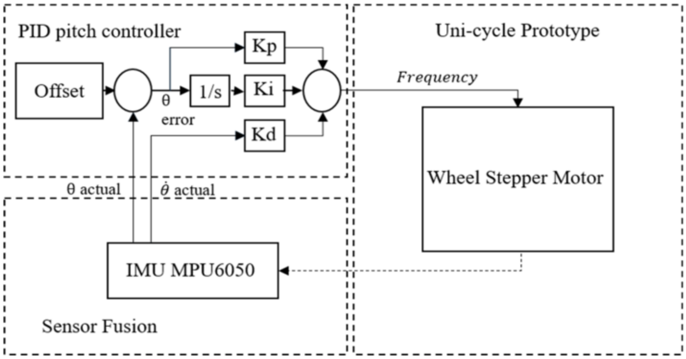

Figure 2. Pitch Control Algorithm of the Self-balancing Unicycle.

4-step calibration using the heuristic method for getting appropriate PID parameters:

1. Increase K_p until the prototype is ready to balance and starts oscillating.
2. Increase K_d to reduce the prototype's oscillation.
3. Increase K_i to stabilize the prototype.
4. Kp and Ki are reduced if a large oscillation is observed while disturbing the prototype.

By this method of trial and error, we calibrated our prototype's balance.

3.2. Design and Modeling

The CAD model was created on Solid Works 2020 software. These points were derived after a literature review after considering various CAD Models discussed. The following specifications were taken into consideration while modeling:

- The lightweight frame of the prototype.
- Only four parts (i.e., left and right frame platform and trailing arm) to make Assembly fast without any complication.
- The simple design of the parts so that they can be 3D printed easily and in less time
- Calculation according to the weight of stepper motor and battery pack because these two components are the heaviest of all other components.
- Designing the Frame symmetrical to minimize CG movement and keep it in the center Frame.

3.3. CAD Methodology

According to the stepper motor dimensions, the left and right frames were modeled. A pair of wheels with a 100 mm diameter was taken to prevent the chassis from touching the ground while leaning forward and backward. With the dimensions and size of other electronic components like the stepper motor driver, Arduino, battery pack, and Bluetooth module, the track width of the model was taken 136 mm, and the height is 160 mm to keep CG above the ground for better stability and control. The platform was designed to keep all electronic components which had a dimension of 92 mm X 140 mm and 3mm thickness, and was mounted between the left and right Frame at the height of 130 mm from the ground. To prevent the use of extra nuts and bolts, we have designed a horizontal platform with a straight slot that is inserted into the side frames slot holes to make Assembly fast and easy and to reduce the weight.

After modeling all the frame parts, these parts are assembled in Solid Works 2020 assembly with all other components and the stepper motor. The interference detection tool was used to check interference detection between the components. Minor changes were made to reduce the weight of the Frame, which brings us to the specific design shapes represented in the diagrams below.

Fig 3. Left and right Frame CAD

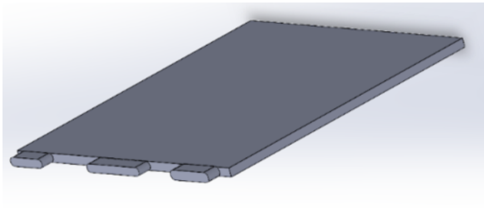

Fig 4. The horizontal platform that links to Frame represented in Fig 3

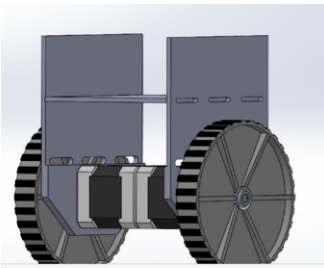

Fig 5. Front View of the Uni-bike

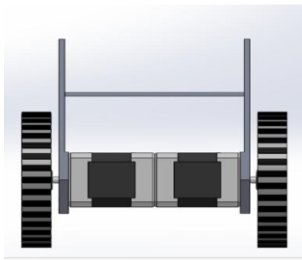

Fig 6. Final Uni-bike cad

Design and modeling of the trailing arm are done in Solid works 2020 software. The idea of the design is to slightly lean the main chassis from the vertical to increase stability by moving the center of gravity (COG) from the center of the chassis towards the rear wheel while in normal bike mode. Rear-wheel with a diameter of 73mm and a trailing arm with a total length of 170mm is designed. After modeling, all the components are assembled to check the interference detection.

The trailing arm is manually operated, i.e., when the bike is working in Uni wheel mode, the trailing is moved above the chassis as shown in fig. below, and when it is converted to a normal bike by moving the trailing arm.

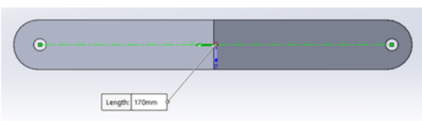

Fig 7. Trailing Arm

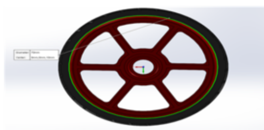

Fig 8. Rear Wheel Diameter 70mm CAD

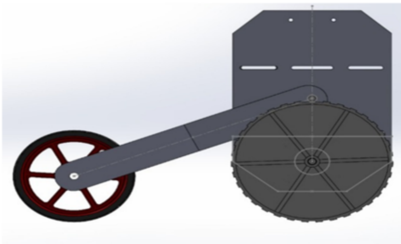

Fig 9. Complete Assembly of convertible Uni wheel e-bike prototype

Slicing the model in Ultimaker CURA to be printed on Ender 3 pro

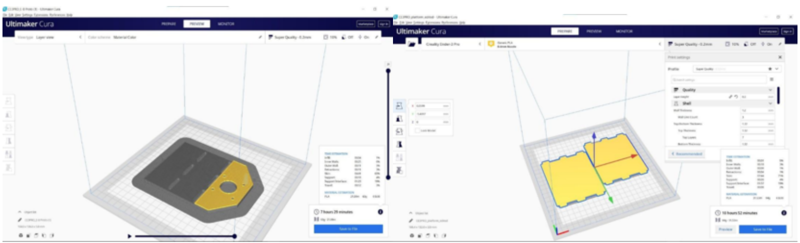

Fig 10 & 11. Side panels and linking panels are used for the main chassis assembly.

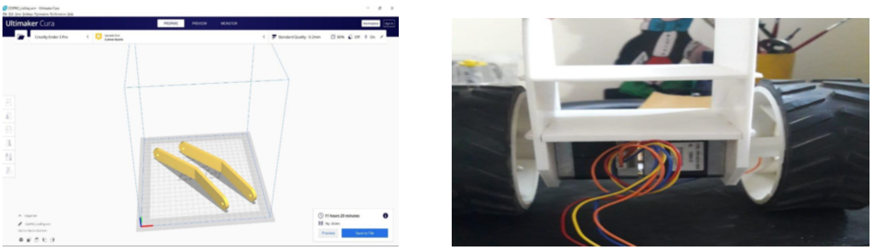

Fig 12 & 13. Trailing arm and the main chassis assembly with stepper motors.

Fig 14. The final chassis and trailing arm assembly with a total printing time of 26 hours with a 20% infill of the PLA+ filament with a 0.4 mm nozzle.

4. Results and Discussion

Balancing of the prototype was successfully achieved by installing the mentioned system. Using additive manufacturing over conventional methods gave us the opportunity to in-house manufacture this prototype in no time. Comparing the process with other conventional methods like liquid molding, etc., the time taken to fabricate the chassis was significantly reduced for the molding process, a significantly accurate mold needs to be fabricated, then the plastics or polymer along with other agents is melted, and mixed and transferred into barrels and then injected into the mold. After that, the mixture needs to be cooled down and cured. In additive manufacturing or 3D printing, we just printed the CAD model of the chassis, and after an overnight run, all the parts were ready to be combined and form a compound body without the use of any adhesive.

5. Conclusions

Comparing the overall cost of prototype production through fused deposition modeling-based additive manufacturing with conventional manufacturing methods, additive comes out superior as the filament used in the entire project was cheaper and no extra operation were performed to produce or assemble the model. For conventional, different operations needs to be performed like sheet metal cutting, drilling, welding etc. in order to achieve the final model. The entire project was completed on a single 3D Printing machine (Ender 3 Pro) that was readily available. Whereas in the case of conventional manufacturing, the number of manufacturing operations drives up the cost significantly as compared to the manufacturing method discussed.

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