Development of Dual Pendulum Based System for Two-wheeler Vehicle Safety

Dr.S.M.Awatade, Rushikesh Gujarkar, Gitesh Mendhe, Yash Borkar, Shailesh Dekate, Raghv Adhav

Dr.S.M.Awatade : Assistant Professor, Department of Mechanical Engineering, Priyadarshini College of Engineering, Nagpur, India

Other authors: B.Tech students, Department of Mechanical Engineering, Priyadarshini College of Engineering, Nagpur, India

Corresponding author e-mail: mahendra.shivaji@gmail.com

Abstract

2-wheeler riders are at high risk of injury if they fall. This paper details the design, construction and initial testing of a cost-effective dual pendulum system to detect a sudden change in angle and alert the user via their mobile phone. Each pendulum contains a single AS5600 magnetic angle sensor. One pendulum is primarily sensitive to the longitudinal direction (front to back) whilst the other detects the lateral movement (side to side). Both sensors' angles are picked up by an Arduino Nano controller. This uses these values to classify the user into either Normal, Medium or Critical using the angle of tilt, duration and encoder RPM. The information is sent to the Android app created with MIT App Inventor through an HC-05 Bluetooth module. The app then uses this information to display the user readable data. The app is also set up to send a SMS alert including the phone's GPS location. Calibration of the encoder to the speed showed a linear relationship where RPM = 105.28v + 80.75 with R^2 = 0.9877. This prototype has been designed for demonstration purposes to students. Accuracy of detection, response time, false alarm rate and performance on the road has not been verified. Therefore, no claims can be made. This is not a certified safety device.

Keywords: 2 Wheeler Safety, Dual Pendulum, AS5600, Arduino Nano, Accident Alert System, Bluetooth, MIT App Inventor

1. Introduction

Two wheeled vehicles like motorcycles and scooters are an essential source of cheap transport in developing countries. However they are also some of the most vulnerable on the roads. Conventional safety equipment is used to avoid or limit the effects of accidents occurring. In most two wheeled vehicles there is no inbuilt detection system to determine if an accident has occurred and call for help. This can be a problem if the rider is hurt or stunned as they may be unable to manually contact emergency services. Electronic accelerometers and gyroscopes are commonly used but the use of a pendulum provides a mechanical method of detection. The deflection of the pendulum can be detected using an angle sensor, when the support moves the pendulum will deflect due to inertia and gravity. A single pendulum only detects movement in one direction so using two can detect different directions as a motorcycle can be affected in a longitudinal, lateral or diagonal direction.

The main issue is that false readings can occur. When hitting a pothole, speed breaker or heavy braking and cornering the pendulum will move. This means an angle is not enough to detect an accident has occurred. The classification takes into account the amount of displacement, the duration, change in time, response of the second pendulum and the settling time.

2. Related Work

There were 6 previous studies that inspired my mechanical design and instrumentation:

- Pendulum Response to Complex Input Ground Motion. When subjected to complex input ground motion, the pendulum will react to the combination of inertia, gravitational force and motion within the support (2008). This is relevant as the real-world road motion would not be ideal like in a lab, so regular disturbances should not cause an alarm.
- Pendulum Impact Testing Machine for Automobile Steering Devices. Structural elements include rigid frames, in-line joints and consistent testing (2013). This inspired me to design the joints, frame and mass carefully.

- Dynamic Response of a Pendulum Isolator System. These factors will affect how the controller interprets the angle (2015).
- Optical Characterisation of Pendular Impact. How the pendulum is measured is very important if it is moving quickly. In this project, I am using embedded electronic sensors to measure the angle. However, in the optical method, this would be ideal for controlled measurements in the lab (2020).
- Zero-Time Trigger Sensor for Inertia Switch Design. This will only trigger when it meets the conditions of the switch. However, it does not measure any direction or multiple classifications (2025).
- Measurement of Compound Physical Pendulum Using Rotary Optical Encoder and Arduino. My project has expanded on this by having 2 directions, classifications, wireless communication and a phone application (2025).

Gap in Research

The previous research looked at pendulum dynamics, impact testing, switches and encoder measurement. None of them had a dual pendulum sensor measuring direction, classifying using a microcontroller and alerting using a phone for two wheelers. There are some issues with the additional components. GPS can only show where the device is and cannot show if there was a crash. This project has a simple, integrated solution to measure direction, classify electronically and communicate via a phone.

3. System Design

3.1 Concept and Operation

The fundamental components of the system are:

- A strong base/frame structure.
- Two pendulums connected in a sensing and communication system.
- Pendulum A - Longitudinal movement (Acceleration and Deceleration).
- Pendulum B - Lateral movement.

When the support structure moves, the pendulums move away from their equilibrium point. Due to gravity, they will have a moment to return to equilibrium however the friction at the pivot point and air resistance will reduce the amplitude of the pendulum.

3.1.1 Physics

The weight of an object is calculated by: Weight = $W = m\ g$

Gravitational Potential Energy is calculated by: $PE = m\ g\ h$

Kinetic Energy for rotation is given by: $KE = \frac{1}{2}\ I\ \omega^2$

where I is the mass moment of inertia and ω is the angular velocity.

Moment around the pivot is given by: Moment = $M = F \times r$

However this gives an ideal model which may not represent the prototype well due to friction at the pivot, air resistance, and play at the joints. Therefore the theoretical calculations will give an overview of the trends whilst the actual experiment will confirm this.

3.1.2 Ensuring Independence

With two pendulums there will be a risk of mechanical coupling causing complex dynamics.

3.2 Mechanical Design

The pendulum arms themselves are made using Aluminium 6061 due to its high strength, low weight and machinability. Mild steel was selected for the pendulum bobs because it provides the required density while remaining readily available and easy to source. The pivot shaft is made from EN8 steel and the rotation is provided by standard steel bearings. Brackets are used to attach the arms to the sensors and the main frame. The base and main frame provide a stiff setup for the pendulums and electronics. CAD modelling was used to ensure that the pendulums have the correct geometry and that there are no collisions with the main frame, each other or any hardware throughout their range of motion. After assembly, the pendulums were manually moved through their expected range of motion to ensure they weren't blocked, had no friction issues and nothing was interfering.



Fig. 1. Pendulum assembly mounted on the frame

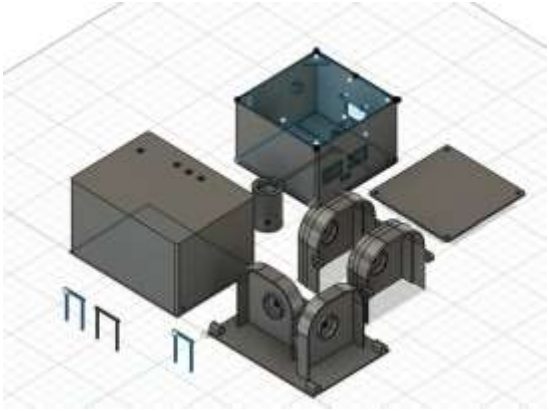


Fig. 2. CAD model of the enclosure, pendulum supports and base

3.3 Electronics and Power Supply

Each pendulum contains a permanent magnet which rotates over a 12-bit AS5600 magnetic angle sensor. This provides 4096 different positions for each rotation (approximately 0.088° per step).

Since both AS5600s have the same I2C address (0x36), an I2C multiplexer (TCA9548A) is used to separate the two devices on the bus.

Both sensors are read by an Arduino Nano running the classification logic. The power supply takes the nominal 12V supply from the motorcycle. This passes through a 1A fuse and main switch. The voltage is then stepped down using an LM2596 buck converter to approximately 5.3V which powers the electronics. In the event of a power failure, the 18650 cell can be used instead. This is charged using a TP4056 module and stepped up to approximately 5.3V using an MT3608 converter. Two 1N5819 diodes automatically choose whether to take the power from the bike or the backup cell. An emergency override button, second 1A fuse, PCB and jumpers complete the circuit. Some optional additions to the design include a display, MPU6050 IMU, GSM module to send SMS messages without needing the phone and threshold potentiometer.

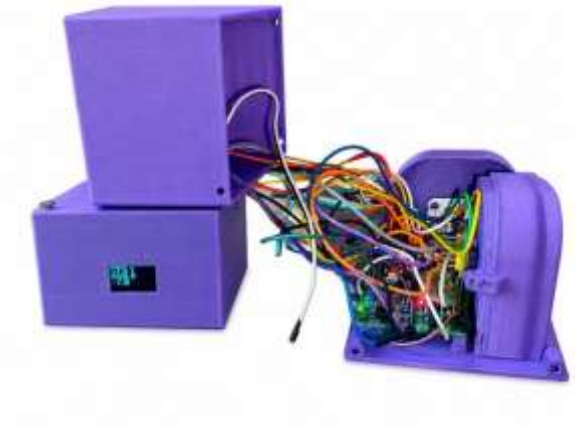


Fig. 3. Fabricated prototype with electronics

3.4 Mobile Application

This application was created using MIT App Inventor for Android. It allows the user to communicate with the HC-05 Bluetooth module. It can receive live data from the system, showing the user live angles of the pendulums and a summary about the status of the system. The user can easily disconnect and connect to the application.

If there is a major impact the application will show an alert to the user, record the phone's GPS co-ordinates and send an emergency SMS. For the system to work properly there must be a Bluetooth connection, location permissions, SMS permissions and mobile data.

4. Event Classification

4.1 Measuring Angles

When the system first starts up the controller will record and store the starting angle for each pendulum. The angular displacement is calculated in real time relative to this stored starting angle.

When analysing the angular data special consideration needs to be made for the 0°/360° transition. Whilst the sensor noise can be reduced using digital filtering or averaging, the quick short duration impact events should not be removed.

4.2 Three Level Classification

In order to reduce the number of misses and false positives the events are classified into three categories (Normal, Medium and Critical). The classification uses angular displacement, duration of displacement, angular velocity, the reaction of the second pendulum and the amount of time to

get back to the neutral position. The two pendulums can help give an indication of the direction of the event. If there is mainly a longitudinal displacement then Pendulum A should react more, if it is mainly a lateral displacement then Pendulum B should react more and if the displacement is oblique then both should react. If this can be used to gain any advantage in detection, this could be found out using experimentation. These levels aren't guaranteed severity levels but are programmed in based on the tilt and duration values. The encoder RPM reference points used are shown in Table 1.

Table 1. Speed and encoder RPM reference points

Speed (km/h)	Encoder RPM	Speed from calibration (km/h)
15	1500	13.5
20	2000	18.2
25	2600	23.9

5. Experiments and Results

5.1 Speed vs Encoder RPM Calibration

Speed was measured against encoder RPM on the front of the system. Means

$\bar{v} = (2+3+4+5+8)/5 = 4.4$

$\overline{RPM} = (260+400+520+640+900)/5 = 544$

Step 2: Slope and intercept

$S_{xx} = \Sigma(v - \bar{v})^2 = 5.76 + 1.96 + 0.16 + 0.36 + 12.96 = 21.2$

$S_{xy} = \Sigma(v - \bar{v})(RPM - \overline{RPM}) = 2232$

$m = S_{xy} / S_{xx} = 2232 / 21.2 = 105.28$

$c = \overline{RPM} - m \cdot \bar{v} = 544 - 105.28(4.4) = 80.75$

So RPM = 105.28v + 80.75.

This was done at 5 different speeds and a linear curve was fitted to the data using least squares regression (Table 2, Fig. 4).

Table 2. Predicted encoder RPM from fitted equation

Speed (km/h)	Predicted RPM	Remark
2	291.31	Calibrated
3	396.59	Calibrated
4	501.87	Calibrated
5	607.15	Calibrated
8	922.99	Calibrated
10	1133.55	Extrapolated
50	5344.75	Extrapolated

$SS_{res} = \Sigma \text{ residual}^2 \approx 2928$

$SS_{tot} = \Sigma(RPM - 544)^2 = 80656 + 20736 + 576 + 9216 + 126736 = 237{,}920$

$R^2 = 1 - 2928 / 237920 = 0.9877$

Step 5: Extrapolation: plug into the equation, e.g. at 50 km/h:

105.28(50) + 80.75 = 5345 RPM.

The average values were mean v = 4.4 km/h and mean RPM = 544. Using these values along with Sxx = 21.2 and Sxy = 2232, the line of best fit can be found. This gives a gradient of m = 105.28 RPM per km/h and an intercept value of c = 80.75 RPM. This gives the equation:

$$RPM = 105.28\, v + 80.75$$

This gives a residual sum of squares of approximately 2928 compared to the total sum of squares of 237,920. This gives us a value of R^2 = 0.9877 showing that the relationship between these variables is roughly linear within the range tested.

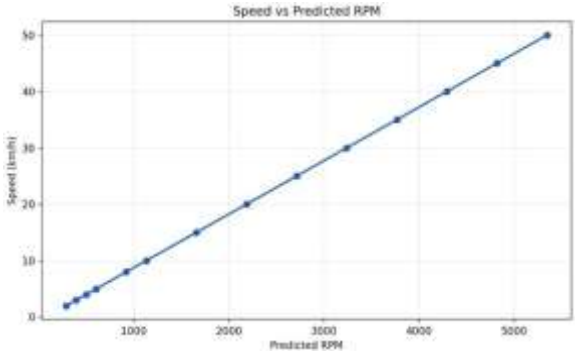


Fig. 4. Speed vs predicted RPM

Firstly, the data fits only five data points from 2 to 8 km/h. This shows that the calibration is not very detailed. The values are being extrapolated outside of the data range, for example if we were to find the RPM when the speed was 10 km/h it would give 1,133.55 RPM. Or 50 km/h giving 5,344.75 RPM. Secondly, by turning the equation upside down we can work out what the speed needs to be to reach the RPM values stated in Table 1. This gives us values of around 13.5 km/h (1500 RPM), 18.2 km/h (2000 RPM) and 23.9 km/h (2600 RPM). These values do not match exactly to the values given which are 15, 20 and 25. Thirdly, this relationship depends on the vehicle type, gearing and wheel size. This means that it will need to be set up again for any specific vehicle.

5.2 Functional Tests on Bench

Once the prototype had been assembled, functional tests were carried out using manually inputted data. The tests checked that the pendulums could move freely, both AS5600

sensors responded to changes in angle, there was communication between the Arduino Nano and the HC-05, the data was shown correctly on the application and that the pendulums all responded to inputs in both directions. This helped confirm that the mechanical, electrical and application components were working together to create one working prototype on the test bench. No numerical data was collected during this testing stage, for example the range of displacements, accuracy of detection, response time, communication delay and false alarm rate.

6. Discussion

This prototype shows that two angle sensors from two different pendulums can be used together in a chain with a low cost controller and phone app. There are two separate channels for longitudinal and lateral movement which can also help with teaching by showing the mechanical effects. The high resolution of the AS5600 (approximately 0.088 degrees per step) means that it is unlikely that the resolution of the sensors will be an issue.

The mechanical effects are more likely to be the issue. The mechanical effects of the pendulums will depend on their length, mass distribution, pivot friction, damping, mount stiffness and sensor alignment. If there is a lot of friction then the pendulums will not move freely. If there is not enough damping then the pendulums will oscillate causing multiple threshold crossings. This oscillation must be managed using filters and time gating.

Limitations. The prototype has not been tested on a moving motorcycle or on the road. It has not been tested under a variety of crash and emergency situations. The AS5600 does not provide information about the amount of force applied, just an angular position. The location and SMS will depend on the phone's GPS, permissions, and cellular signal. Bluetooth has a short range and must have a stable connection. The system will need to be calibrated each time. The mechanical effects of the bench test rig may not be the same as in a real crash. The system is a development and demonstration prototype and has not been shown to reduce injuries.

7. Conclusion and Future Scope

A prototype was designed, developed and finally implemented with two angle sensor devices using AS5600 and an Arduino Nano microcontroller along with HC-05 Bluetooth connection and Android application with GPS alert mechanism. Three-tiered classifications were developed and a speed-RPM calibration curve was developed between 2 km/h to 8 km/h. RPM was found to be $105.28v + 80.75$ where v is the speed and $R^2 = 0.9877$. The major contribution of the project is an affordable physical demonstration which uses a directional sensor with a phone alert system. Field testing needs to be carried out.

Future scope:

- Testing the system within controlled environments and on the road. This will involve testing on different surfaces, speeds, braking, cornering, speed breakers and potholes. Accuracy, false positive and negative results, response time and Bluetooth delay could be measured.
- This would include implementing a recovery timer and time-based filtering of logic
- This would help determine if the device was falling/impact or moving normally.
- This would also increase range.
- Lighten and strengthen the overall structure so it can be attached to vehicles.
- Improvements to Android application with data recording, plotting, emergency contact storing and cloud storage.

Potential applications for this system would include monitoring two-wheelers, alerting in an emergency situation, monitoring rider behaviour, smart electric two-wheelers, smart vehicle systems for the IoT and research into dynamics.

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