ABSTRACT

This paper presents an exploratory evaluation on how to build an electric unicycle vehicle controlled by using the Arduino board development. For electric unicycle, it will move forward when the user lean their body forward and vice versa. The discussion is majorly includes the way to achieves the stability with the help of the latest electronic sensor technology called gyroscope and accelerometer. The gyroscope will read any changing of angle while the acclerometer is used to detect any changing of acceleration the unicycle exerts. As both sensors tend to produce noise and disturbance, Kalman Filter that will combine the data from both sensors is applied to produce a better and accurate data. All the information is then processed by Arduino IDE software that acts as the brain of the unicycle system and to determine the unicycle action based on the information received. The data outputs then are analyzed by displaying them on “Serial Chart” software that will creates a line chart based on serial monitor set on Arduino IDE. This software helps the researcher to observe any unwanted noise in the data and perform a correction upon the problem. Moreover, the discussion are also includes on how to use “SketchUp 8” software to design the unicycle body frame. All the considerations in the sketching then are used for real hardware making that used high power electric machine. By taking all the measurement, the experimental results confirm that the resulting system meets the design goal which to design an electric unicycle controlled by using Arduino and to create a stable electric unicycle with the latest technology.

Keywords: unicycle, arduino, sensor fusion, kalman, inertial measurement unit.

INTRODUCTION

The unicycle is a one wheel bike that needs the rider to balance it without falling down. It usually can be seen at the circus show where the clown riding them in a dangerous form to entertain the audiences. The rider needs to find the center of gravity by balancing their body and also controlling the pedal. The bike could fall in four directions which are left, right, forward and back [1]. It means that the rider have to balance the bike from falling down by balancing all directions. In the modern era, the unicycle has advances to more sophisticated design. The movement of the bike is control by using a DC motor.

The balance of the bike is controlled by the sensors called gyro meter and accelerometer. This will prevent the bike from falling forward and backward. Meanwhile, the left and right are control by the rider inertia's [1]. However, in building the electric vehicle, the stability issue needs to be considered and measured accurately. As it is one wheel, the speed of the motor also needs to be controlled properly to get the stability.

The smoothness is an important matter need to be considered during the ride. The vehicle will achieve the balancing at some constant speed. But to stop the vehicle, the speed needs to be reduced smoothly without sudden stop. All the works of controlling the motor is centered in a programming device called Arduino. It acts as the brain of the whole system in order to keep the vehicle upward without fall.

LITERATURE REVIEW

a) Inertial measurement unit

The inertial measurement unit consists of three different sensors that soldered together on one board. The three sensors are accelerometer, the gyroscope and the magnetometer. The accelerometer is used to measure the change of velocity at a time (acceleration) [2, 3].

When the object is at rest (in this case unicycle at 90° upward), the velocity is zero. When it fall forward or backward, there is a change in velocity. The change in velocity over the time will be measured by accelerometer. The used of gyroscope is to measure the rate of change of angles [3]. The complete three axis gyroscope will measure the changes at all angle. The angles are called the pitch (x-axis), roll (y-axis) and yaw (z-axis).

Both accelerometer and gyroscope must work together to balance the unicycle. This is because with accelerometer alone, there is much noise produces although when the object is at rest mode [4] and accelerometer cannot differentiate between the acceleration caused by the movement or the gravity [5]. So, the tilt angle could not be defined well because of these noises. If the gyroscope is used alone, there will be drift phenomenon occurs. The drift phenomenon is an error that the object is producing an output although the motor is not moving [5]. Thus, the object cannot stand still and it is hard to achieve the stability.

b) Kalman filter

In order to create such a smooth and efficient system, the data taken from accelerometer and gyroscope need to be mixed together by using some kind of filter. The filter will combine the data's and given out a true tilt angle of the unicycle. This exact tilt angle will be used to create a quick response on the motor. One of the well-
known and commonly used filters is the Kalman Filter which named after the inventor’s name Dr Rudolf Kalman. Basically the filter will update the error from the IMU continuously to keep the stability of the unicycle itself. It will then produce a single angle value which is much accurate and less noise.

c) Brushless DC hub motor
The brushless motor is different from conventional brushed motor as it required three phase interchanging supply to create a rotation. So, it needs a special controller to drive the motor. The most used design of motor controller is three phase H-bridge [6]. The circuit consists of six transistors as in Figure-1. The commonly used transistor is the MOSFET.

![Figure-1. Arrangement of transistors (red box).](image)

There are many advantages of brushless motor compared to conventional brush motor. The brush is used as a bridge to transfer the current from supply to the rotor. While the rotor is keep moving, the brush will keep touching the end part of the rotor. For a long period, the brush may become thin as a result of friction. The brush need to be replaced for a new one. So, with the absence of the brush, there will be less maintenance to the motor. It used the concept of magnetic field to generate the movement of the rotor.

Secondly, it has a great torque power. The torque produce will depend on the load it received. When the load is heavy, the speed is decrease while the torque is increase. So, one should be no worried about the strength of this type of motor. The third advantage of brushless motor is about the voltage drop. As the motor used the magnetic field to generate the movement, there is no voltage drop produce in the rotor. So, the transfer of energy from source to the motor will be much efficient.

d) Arduino as the center of the system
The Arduino is design to interface with various kinds of sensors including digital sensors as well as analog sensors [7]. There are also features that enabled the Arduino to interface with mobile phone operating system like Android. This could be advantage for the system as it can be controlled by phone without using wire.

Some Arduino boards serve with wireless communication that required no USB wire to transfer the data. Thus, it makes the data can be read or write at some distances without having to connect them through them. This feature is really useful whenever the system is located at deep or hard to reach location. All kinds of features that serve in a single Arduino are actually to serve a platform that is easy to use [8].

All the Arduino development board is compatible with the Arduino IDE software programming. This software would enable the user to create a coding to be inserted into the Arduino development board. The coding contains of several declaration of what are the sensors being used, which pin is used as the input, which pin used to give out Pulse Width Modulation signal or anything else [8].

UNICYCLE DESIGN

The traditional unicycle as in Figure-2 is made up of several main parts. There are the saddle, crank, pedal, seat post, rubber tire, and rim. These parts are all same through out of the world.

![Figure-2. The parts of unicycle.](image)

For the electric unicycle, it is hard to control the stability of the bike since it depends on motor instead of the rider's pedal force to create the movement. The design considers the rider's comfortable. It comes with cushion seat, the handle for grip, the foot rest, speedometer and the front light for night travelling. So, there will be a large space for the battery to power the motor and for other electronics devices. The design also needs to be validating with the weight of the unicycle that reach about 25kg.

Figure-3 and Figure-4 show the side view with parts label and isometric view of unicycle design.

![Figure-3. The side view of unicycle.](image)
The unicycle is must interconnected with Kalman parameter to overcome the disturbance from IMU as well as to achieve the stability. The Kalman filter parameter can be divided into two categories which are prediction and measurement.

a) Prediction

Firstly, the filter will try to estimate the current state based on all the previous states and the gyro measurement. That is also called a control input, since it is used as an extra input to estimate the state at the current time k called the a priori state.

\[ \hat{x}_{k|k-1} = F \hat{x}_{k-1|k-1} + B \hat{\theta}_k \]  

The next thing is that estimate the a priori error covariance matrix based on the previous error covariance matrix which is defined as:

\[ P_{k|k-1} = FP_{k-1|k-1}F^T + Q_k \]  

This matrix is used to estimate how true the current values of the estimated state. It is obvious that the error covariance will increase since the last updated estimation of the state, therefore the error covariance matrix is multiplied by the state transition model and the transpose of that, and add the current process noise at time k. The error covariance matrix, in this case is a 2×2 matrix as below:

\[ P = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \]  

b) Measurement

The first thing is to compute the difference between the measurement and the a priori state. This is also called the innovation.

\[ \tilde{y}_k = z_k - H \hat{x}_{k|k-1} \]  

The observation model, is used to map the a priori state, into the observed space which is the measurement from the accelerometer, therefore the innovation is not a matrix.

\[ \tilde{y}_k = \begin{bmatrix} \tilde{y} \end{bmatrix}_k \]  

The next thing is calculating the innovation covariance:

\[ S_k = H P_{k|k-1} H^T + R \]  

It is used to predict how true the measurement based on the a priori error covariance matrix, and the measurement covariance matrix. The observation model is used to map the a priori error covariance matrix into observed space. The bigger value of the measurement noise, the larger the value of innovation covariance. So, the incoming measurement cannot be trusted. In this case it is not a matrix and is just written as:

\[ S_k = \begin{bmatrix} S \end{bmatrix}_k \]  

The next step is to calculate the Kalman gain. The Kalman gain is used to indicate how true the innovation and is defined as:

\[ K_k = P_{k|k-1} H^T S_k^{-1} \]  

If the innovation is small, the innovation covariance will be high and if the state estimation is trusted then the error covariance matrix will be small. The Kalman gain also will therefore be small and opposite if the innovation is used instead of the estimation of the current state.

The transpose of the observation model is used to map the state of the error covariance matrix into observed space. The error covariance matrix then is compared by multiplying with the inverse of the innovation covariance.

The observation model is used to extract data from the state error covariance and compare that with the current estimate of the innovation covariance. Note that if the state at startup is unknown, it can be set by setting the error covariance matrix likes below:

\[ P = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \]  

Where: \( L \) represents a large number

For this unicycle, the state is assumed known at startup. So the error covariance matrix is initialized like below:

\[ P = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \]  

In this case the Kalman gain is a 2×1 matrix:

\[ K = \begin{bmatrix} K_0 \\ K_1 \end{bmatrix} \]
Now the a posteriori estimate of the current state can be updated. This is done by adding the a priori state with the Kalman gain multiplied by the innovation.

\[ \hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k \]  \hspace{1cm} (12)

Remember that the innovation \( \tilde{y} \) is the difference between the measurement and the estimated priori state. So, the innovation can both be positive and negative. A little simplified of the equation can be understood as it simply corrects the estimate of the a priori state that was calculated using the previous state and the gyro measurement, with the measurement (accelerometer). The last thing is to update the a posteriori error covariance matrix:

\[ P_{k|k} = (I - K_k H) P_{k|k-1} \]  \hspace{1cm} (13)

Where \( I \) is called the identity matrix and is defined as:

\[ I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \]  \hspace{1cm} (14)

So the filter is basically self-correcting the error covariance matrix based on how much the estimation is corrected. This is true as not only the state based on the priori error covariance matrix is corrected, but also the innovation covariance.

**MAPPING**

The last step of the design is the process to find the suitable speed of the unicycle. The process is done by doing “try and error” in the Arduino coding. The instruction is called “map”. The “map” will divide the PWM signal within a selected range. The instruction is done as in Figure-5.

\[ \text{PWM} = \text{map}(\text{angle}, 1, 90, 60, 180); \]

**Figure-5. Mapping instruction.**

The calculation:

\[ \text{Angle} = 10 - 900 \]
\[ \text{PWM} = 60 - 180 \]

\[ \text{increment} = \frac{(180 - 60)}{(90 - 1)} = 1.33 \text{ PWM per degree} \]

**RESULT AND DISCUSSION**

a) **Data analysis**

The gyroscope gives the “prediction” value of the current state of the IMU. The graph obtain as seen in Figure-6 contain lots of noise. This is due to the gyroscope got high tendency of drift as effect from the time and the temperature of the environment. The Figure-6 shows the data of gyroscope as angle change.

**Figure-6. Gyroscope data.**

The accelerator gives the “observation” value of the current state of the IMU. The graph obtained as in Figure-7 contains too many disturbance as angle change. This is due to the accelerometer cannot distinguish whether the acceleration is caused by the movement or gravity.

**Figure-7. Accelerometer data.**

The Kalman filter combines the reading from both accelerometer and gyroscope. It produces much stable and smooth graph as seen in the Figure-8. So, the value comes with better accuracy and the motion sensing response is improved a lot.

**Figure-8. Result of Kalman filter.**

b) **Comparison with simple algorithm filter**

The result also comes with analysis of other filter to find the differences between each filter. By looking to the condition of the IMU when the angle is zero as seen in Figure-9, the Kalman filter gives an exact and constant value of zero compare to simple algorithm filter. The algorithm tends to produce a noise a little bit. Although the noise is small, it can disturb the PWM signal sent to the motor controller.
For the situation of positive and negative tilt angle, both graphs as seen in Figure-10 and Figure-11 seem to have no difference between in term of smoothness. But when the both filter is implemented in the unicycle, the Kalman would give the better result. The motor starts slowly and partially increase the speed without any noise. Meanwhile the algorithm makes the motor rotates with a little noise, thus making the unicycle unbalance.

It proves that the Kalman filter is more accurate as it updated the noise every time at every angle and corrects it while the algorithm only uses a single reference noise value to correct the angle.

The unfiltered signal is much unstable compared to the filtered signal that maintains at the angle zero degree. It tends to get away from the zero value although the unicycle is completely not moving. It proves that the IMU need a special filter to remove any unwanted signal that disturbs the real reading of the IMU.

The second condition is when the unicycle is lean forward and the tilt angle is positive. The position of unicycle indicates that the tilt angle is now kept away from the reference angle with 5 degree positive as shown in Figure-13. At this angle, the motor starts to rotate with minimum speed.

The third condition is when the unicycle is lean backward and the tilt angle is negative. The position of unicycle demonstrates that the tilt angle is now kept away from the reference angle with 5 degree negative with as can be seen in Figure-14. The motor starts to rotate with medium speed.

The first condition is when the unicycle is at stationary mode and is placed in horizontal state. The tilt angle is same with the reference angle which is zero. Both tilt angle and PWM readings are zero as depicted in Figure-12. Hence, the motor is in stationary and not moving.

The unfiltered signal is much unstable compared to the filtered signal that maintains at the angle zero degree. It tends to get away from the zero value although the unicycle is completely not moving. It proves that the IMU need a special filter to remove any unwanted signal that disturbs the real reading of the IMU.

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The third condition is when the unicycle is lean backward and the tilt angle is negative. The position of unicycle demonstrates that the tilt angle is now kept away from the reference angle with 5 degree negative with as can be seen in Figure-14. The motor starts to rotate with medium speed.
d) Mapping results

Table-1 illustrates the result of experiment that was carried out by using different range of angle and PWM to get the suitable speed for the unicycle to balance. For the combination (1°-90°, 60-180), the rate in PWM increment is 1.35 per degree. At this rate, the unicycle has its forward limit rotation from 1° degree until 90°. When the range is tested on the unicycle system, the unicycle move very slowly as the rate is too small. So, the unicycle is not balanced well and tends to fall from side to side.

<table>
<thead>
<tr>
<th>Angle (1°-90°)</th>
<th>PWM (60-180)</th>
<th>Angle (5°-30°)</th>
<th>PWM (60-125)</th>
<th>Angle (1°-180°)</th>
<th>PWM (60-180)</th>
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<th>PWM (60-125)</th>
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<tr>
<td>1°</td>
<td>65</td>
<td>5</td>
<td>60</td>
<td>1</td>
<td>60</td>
<td>5</td>
<td>60</td>
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<tr>
<td>2°</td>
<td>61.55</td>
<td>6</td>
<td>66.5</td>
<td>2</td>
<td>68.57</td>
<td>6</td>
<td>62.6</td>
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<tr>
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<td>62.7</td>
<td>7</td>
<td>73</td>
<td>3</td>
<td>77.14</td>
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<td>6</td>
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<td>95</td>
<td>7</td>
<td>111.42</td>
<td>11</td>
<td>75.6</td>
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<tr>
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<td>8</td>
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<td>128.56</td>
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<td>20°</td>
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For another combination of angle and PWM (5°-30°, 60-125), the rate of increment is 2.6 per degree. When the range is tested on the unicycle system, the unicycle is much stable at the starting movement but tends to suddenly accelerate as the rate of increment is big. The unicycle also will make a sudden stop when the angle is reached above 30° as the limit is only at this angle. This situation is very dangerous to the cyclist as they can fall forward and damage the unicycle.

CONCLUSION AND RECOMMENDATION

For the conclusion, the Arduino plays its role perfectly to process the whole balancing system of the unicycle. It also manages to save space and at the same time makes the wiring connection looks neat and tidy. Then, Gyroscope sensor and accelerometer sensor works together to provide the tilt angle of unicycle. With the help of Kalman filter, both reading from gyroscope and accelerometer is successfully combined together to get only a value that immune to any noise or disturbance in the reading which then will be used to control the motor.

The first recommendation in order to improve the unicycle system is to use a broad tire that much wider and has more contact area to the ground. It also designs with straight contact surface that would prevent the unicycle to fall to both right and left side. For the current circuit, the reverse switch of motor controller used the 5V relay to turn on and off. This relay is not suitable for high speed switching and it also draw a great current that can affect the PWM signal sent to the motor controller. As a result, the signal received by the motor contains delay and the unicycle reacts slowly. The relay also uses a great space thus making the circuit look messy. It is recommended to use opto-coupler or opto-isolator that is much smaller and sensitive to a small change of input signal. Lastly, PID system which is a control loop feedback mechanism (controller) can be applied in the system. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error in outputs by adjusting the process control inputs.

REFERENCES


