Development of a control system for the lean angle of a motorcycle using the gyroscopic effect of a rotating fly wheel

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1.0 Introduction

There are many day to day examples where gyroscopes and their stabilisation can be seen; the most obvious of such are cycles and motorcycles. These vehicles travel balancing on two wheels with relative stability. This is all thanks to the gyroscopic effect of the rotating wheels as the bike travels forwards. This effect, generated by the conservation angular momentum, can be used in many types of applications including satellite orientation and even tunnelling systems to maintain their direction [1], since satellite navigation does not work under ground and magnetic guidance is not accurate enough.

The term gyroscope comes from the Greek words for “turn” and “observed”, but was first seen in a scientific scene by Jean Bernard Leon Foucault in 1852 [2]. He experimented trying to observe the rotation of the earth using a long heavy pendulum, swinging it north to south [3]. One of the earliest uses of a gyroscope to stabilise a vehicle came in 1904 by Louis Brennan, who patented his manually controlled system for imparting stability on unstable bodies [4].

There are two main reasons why introducing gyroscopes into vehicles such as bikes could be advantageous. These are safety and handling. A bike that cannot fall over in poor road conditions would prevent many accidents every year. The bike would also appear to feel lighter to the rider with the gyroscope contributing to the forces required to lean the bike. An increase in popularity would greatly benefit in locations where traffic congestion is a major issue, as the road presence of a single tracked vehicle in comparison to that of a car is greatly reduced and more economical. It’s the increased fuel efficiency and running costs that make motorcycles more popular in developing countries like Thailand, which has the second highest motorcycle to car ratio ownership for its population. [5]

In countries such as Nigeria they are already making large movements forward to using motorcycles as a common form of public transportation after the collapse of their intra-city transport system [6]. The increased number of motorcycles has had large positive impacts socially and economically, improving the mobility to the population increasing employment rates. The downside of such a large number of bikes is the high number of traffic related accidents now recorded [6].

Cases like this demonstrate the need for improved safety mechanism in motorcycles. Devices like the toque compensator look to improve the stability of motorcycles using variable velocity flywheels, controlled by the angular momentum of the wheels to adjust the gyroscopic effect of the stability flywheel [7]. An increased stability at both high and low speeds would reduce the number of accidents due to loss of control.

This project builds on these concepts and ideas and is investigating an automated control system, which self regulates to correct for any external influences for a changing angle of lean. The design and concept for the system in development is that of a motorbike, or any single tracked vehicle, which can roll about its pivot axis. The aim is to induce a precession into a spinning disk resulting in a torque which can be used for any angular corrections of the vehicle. This precession can also be used in the forcing of a lean into the bike for cornering purposes.

2.0 Theory

2.1 Gyroscopic Theory

If a wheel is spun, then it produces a given angular momentum, which is dependent on the mass and size of the wheel, and the angular velocity the spinning wheel.

To find the angular moment which is expressed as $\bar{L}$, the moment of inertial for the wheel must be calculated first. It can be found using:

$$I = \frac{1}{2} M_w R^2 \tag{1}$$

Where M_w is the mass of the wheel and R is the radius of the wheel. Therefore, I is constant for a particular wheel. Using the moment of inertia of the wheel the angular moment can be found for a given speed:

$$\bar{L} = I\bar{\omega} \tag{2}$$

Where ω is the angular velocity. This angular momentum must be conserved, which is what gives rise to gyroscopic precession.

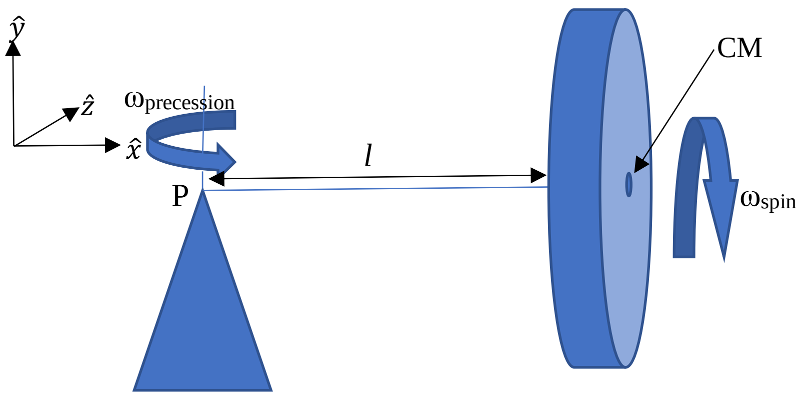

Figure 1 - A spinning flywheel with precession $\omega_{precession}$ about a pivot point P

Figure 1 shows a simple example of gyroscopic precession which can be used to explain this motion. The wheel is rotating about the rod with angular velocity of $\omega_{spin}\hat{x}$, and rotating about point P with $\omega_{precession}\hat{y}$. The horizontal and vertical forces can be seen below for this system in figure 2.

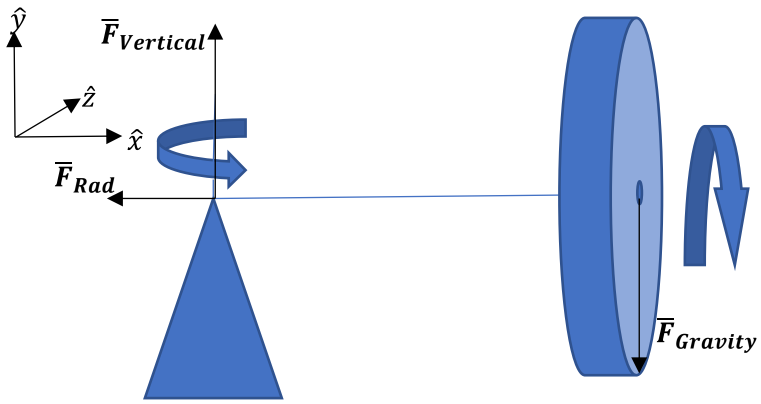

Figure 2 - The forces acting on the spinning wheel

Looking in the $\hat{y}$ axis only there is only two forces, the force from the mass acting through the centre of mass of the wheel and the restoring force on the pivot point P. Since there is no change in this axis, the sum of these two forces must equal zero. This is not the case in the $\hat{x}$ axis, as at that instance there is only one radial force created from the precession motion.

$$\bar{F}_{Rad} = M_{wheel} l \omega_{precession}{}^2 \tag{3}$$

Looking at the torque in this system about the point P, there is only the force from gravity that contributes. So, to find the torque $\bar{\tau}_P$, the cross product of the $\bar{\boldsymbol{F}}_{\boldsymbol{Gravity}}$ which is in the negative $\hat{y}$ direction and $\widehat{lx}$:

$$\bar{\tau}_P = lM_{wheel} g\hat{z} \tag{4}$$

This is a non-zero torque so the angular momentum must be changing. For a steady state system like the one in figures 1 and 2, the rotation speed is constant, therefore the angular momentum vector is only changing in direction and not magnitude.

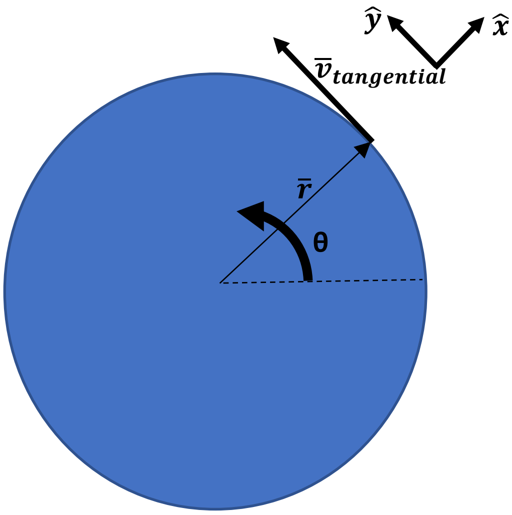

Figure 3 - The face of the spinning wheel, with the tangential velocity of a point on the wheel

Now looking at the wheels rotation about its centre of mass, as showing figure 3.

The tangential velocity it can be expressed as the rate of change in $\bar{r}$ which is only changing in θ, so:

$$\bar{v}_{tangential} = r\frac{d\theta}{dt} \tag{5}$$

Looking back at figure two and the angular momentums associated with the two rotations, one about point P and the other around the centre of mass of the wheel. $\bar{L}_{wheel}$ points along the $\hat{x}$ axis and $\bar{L}_{precession}$ along the $\hat{y}$. Looking at the wheel first:

$$\bar{L}_{wheel} = I\omega_{wheel}\hat{x} \tag{6}$$

Where I is the moment of inertia of the wheel. Since the wheel is still rotating at a constant speed, the only change in the angular momentum is in the direction, which is in the positive $\hat{z}$ direction.

$$\frac{d\bar{L}_{wheel}}{dt} = |\bar{L}_{wheel}| \frac{dz}{dt} \hat{z} \tag{7}$$

This directional change is at the precession rate, so $\omega_{precession} \equiv \frac{dz}{dt}$ making the change in angular momentum of the wheel:

$$\frac{d\bar{L}_{wheel}}{dt} = |\bar{L}_{wheel}| \omega_{precession} \hat{z} \tag{8}$$

But the total angular momentum about the point P is the sum of both this and the precession motion. The precession component can be found from the cross product of the vector from point P to the centre of mass and linear momentum in the tangential direction ($\bar{p}$):

$$\bar{L}_{precession} = l\hat{x} \times \bar{p} \tag{9}$$

But the linear momentum is only dependant on the change in $\hat{z}$ as the radius *l* is fixed, resulting in $\bar{p}$ only dependant on $\omega_{precession}$ which is also constant. $\bar{L}_{precession}$ is therefore a constant.

This implies that the total angular momentum change of the system about point P is equal to the changes in momentum of the wheel, which has already been shown is in equation 8, but the torque about point P is also the change in total angular momentum at that point, leading to the precession frequency to be:

$$\omega_{precession} = \frac{\bar{\tau}_P}{|\bar{L}_{wheel}|} = \frac{l M_{wheel} g}{I \omega_{wheel}} \tag{10}$$

Equation 10 shows that a wheel with a mass rotating that is experiencing an acceleration will produce a precession from the resulting torque from the system.

This example of a simple gyroscope shows the same basic concepts for a gyroscope in a torque induced system. When a gyroscope is spinning and rotated in a system like the one shown in figure 4, the precession is induced resulting in an acceleration in the direction shown. It is this setup that is used in the stabilisation system to produce corrections to the bikes lean by inducing a precession.

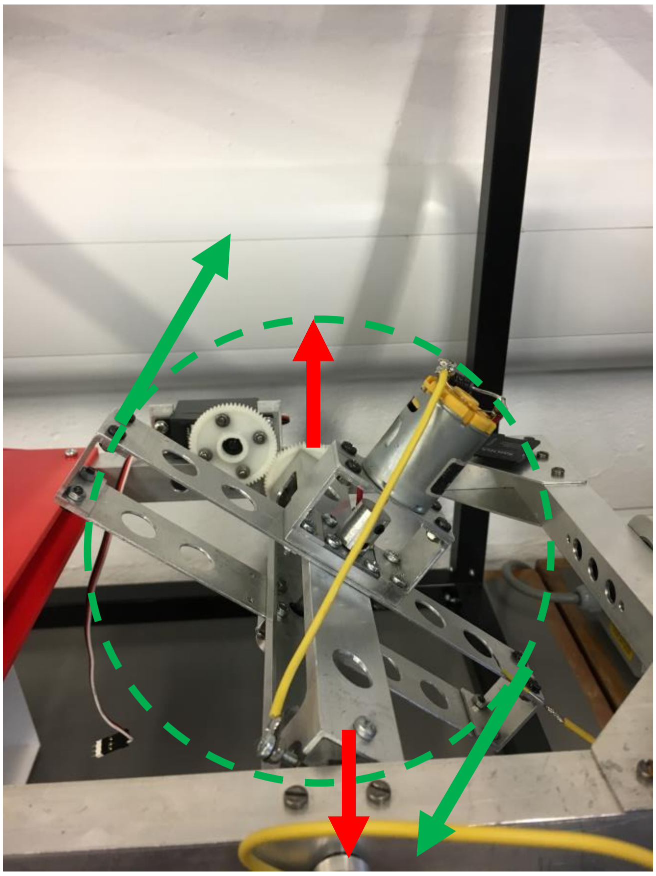

Figure 4 - Gimble set up, the green arrows shows the direction of travel, the green circle the induced precession and the red arrows the resulting τ_{roll}.

In this setup the torque produced from inducing precession can be determined:

$$\tau_{gyro} = I_{wheel}\omega_{wheel}\omega_{precession} \tag{11}$$

This produced torque can only be partly used for stabilisation corrections due to the two components of the torque as the flywheel rotates through the angle θ, a roll torque and a yaw torque:

$$\tau_{roll} = \tau_{gyro}\cos(\theta) \tag{12}$$

$$\tau_{yaw} = \tau_{gyro}\sin(\theta) \tag{13}$$

This shows that response torque for angular corrections is non-linear

2.2 Motorcycle mechanics

When a motorbike is travelling along at a relative speed the upright angle of the vehicle is considered stable, as it would require a large external force on the bike to knock it over. The stability is due to the rotating motion of the wheels producing a gyroscopic effect. The angular velocity of the wheel produces an angular momentum which must be conserved. To change the orientation of the bike requires a force to overcome the resulting precession torque from rotating wheels, as explained above. This gyroscopic motion of the wheels also explains the requirement for leaning when cornering on a motorcycle. As the handlebars rotate the wheel in order to turn, a torque would be produced, leaning the wheel into the corner.

The addition of spinning flywheels inside of a motorcycle almost seems counterintuitive initially as a rider would have to "fight" the angular momentum of the flywheels to corner, thus reducing handling of the bike.

However, if we link these flywheels to the steering, to rotate the angle of lean of the bike from the gyroscopic forces produced in the flywheels when they change orientation, then the vehicle will feel lighter to the rider. The force needed from the rider will "feel" reduced compared to the weight of the bike, as the majority of it will be produced from the rotation of the flywheels, but controlled by the rider's handlebars and weight.

This also brings potential cornering benefits, as the bike would be able to lean for corners faster and maintain the correct angle during the corner allowing for a greater use of throttle through the bend. This could allow for greater acceleration out of a corner, especially with the added benefit of having the angle brought back up to level assisted by the gyros.

The lighter feel to the handling of the bike would not only be the only added benefit. Bikes are inherently unstable vehicles and much more accident prone then there 4-wheel counterparts [8]. A bike which internally controls the angle in which it is leaning with respect to the road is also safer, especially in poor road conditions.

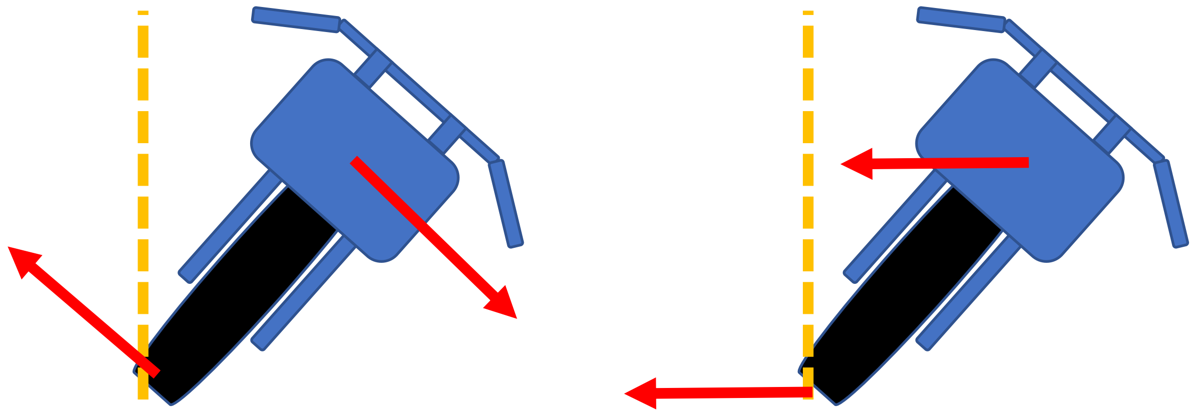

Figure 5 - Directions of a slipping bike without a stabilisation system (left) and with (right)

As can be seen in figure 5 above, when a normal motorcycle is cornering in poor road conditions the wheels loose traction and the bike "slips" causing the bike to completely fall on its side, likely injuring the rider in the same instance. In the case where the angle of lean can be controlled from the flywheels rotation inside of the bike, when the tyres loose traction with the road surface the bike would appear to drift along the surface, whilst maintaining its rotational position. This will give the rider a greater chance of recovering from the slide without losing total control of the bike.

Both safety and handling performance would increase with the use of flywheels to exert internal torques on the bike, but would come with the disadvantage of a greater amount of weight on the bike. Even though this weight would not be felt by the rider, it would negatively affect the acceleration of the motorcycle.

2.3 Microcontroller

Microcontrollers are small electronic devices, also known as logic chips. These chips are processors housed in a microchip, which can be used in electronic circuits. For this project we are using microcontrollers that are already integrated into an electronic circuit to allow the quick and easy use in other electronic circuits. The two that boards in question are the Arduino Uno SMD, which uses an 8-bit chip called ATmega328 [9], and the Genuino 101, which uses a more powerful 32bit chip called the Intel Curie [10]. Both boards are of very similar design, the Genuino pictured below in figure 6**.**

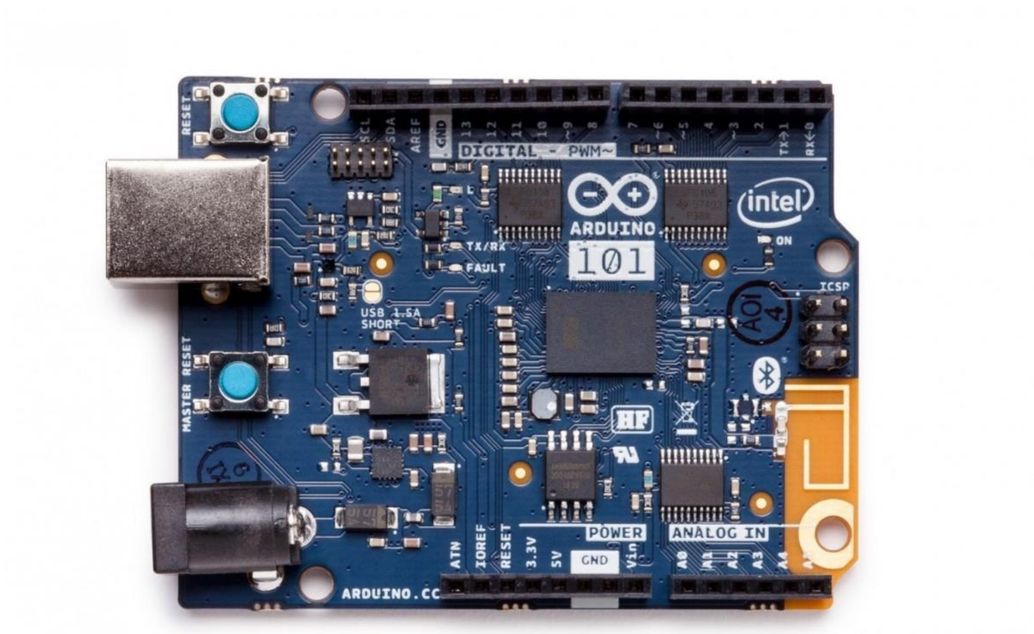

Figure 6 - Genuino 101 Board [11]

Both the Genuino 101 and the Arduino have the same form factor but with a few differing functionalities. The important similarities between these boards are the control pins which can provide up to 5V power supple and have PWM pins, represented by the (~) symbol on figure 5.

Using PWM pins on an Arduino board allows the changing of pulse times of the output voltage, allowing for a stable and changeable average voltage to be produced. This is incredibly useful, for example it can be used in conjunction with the gate on a MOSEFT can be used to control the current output for an external device, like a motor and therefore it’s speed.

2.4 PID Theory

Proportional-Integral-Derivative (PID) control is commonly used in response systems. The basic concept of the controller is to read a sensor and calculate the appropriate response depending on how the system under observation is reacting. As the name suggests, PID is the summation of three response type to provide the best response, with a system specifically tuned, changing the amount of each response contributes to the resulting response.

PID works on the concept of a set point and the error (ε) in that value, with the error referring to the difference between the systems current point and the setpoint.

$$K_p \varepsilon(t) + K_I \int \varepsilon(t)dt + K_D \frac{d\varepsilon(t)}{dt} = Response\ output \quad (14)$$

2.5.1 Proportional

The proportional factor is a simple proportional response to the error value, with a value known as the proportional gain (K_P). For example, a system that has an error value of a magnitude 2 times that of the setpoint which has a K_P factor of 5 would produce a response output of 10. This results the proportional factor or PID to be the "speed" of response to a reaction, the higher the factor the more the system will respond. A proportional factor which is too high will also result in failure as the system will oscillate, with greater error each time.

2.5.2 Integral

The integral component of PID is an error over time factor (K_I). The integral response factor will increase over time if an error in the setpoint value is apparent in the system. This effect is there to produce steady-state error to try and produce a long term stable system. The integral component has the danger of saturating the controller without the zero-error state ever being achieved, resulting in long term failure of the system.

2.5.3 Derivative

The derivative factor (K_D) is a response which accounts for the rate of change of error from the setpoint. An increase in K_D will produce a stronger response and greater speed of change to the output. When this factor is too large it introduces a large "noise" factor to the output especially in noisy input signals from the sensor. A small derivative factor is generally used to avoid over sensitivity of the system.

3.0 Methodology

3.1 Test system construction

The basic frame of the bike is shown in figure 8 below.

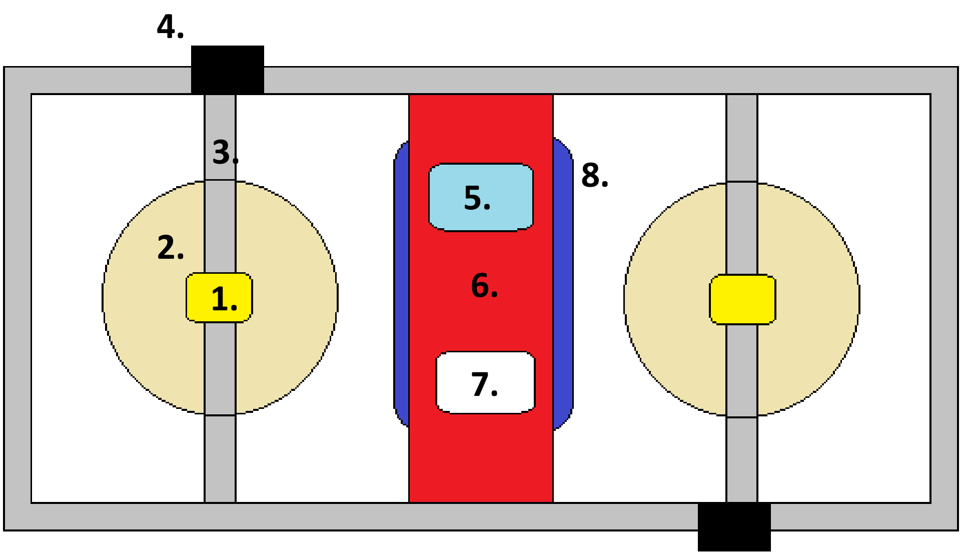

Figure 7 - Bike frame setup from above

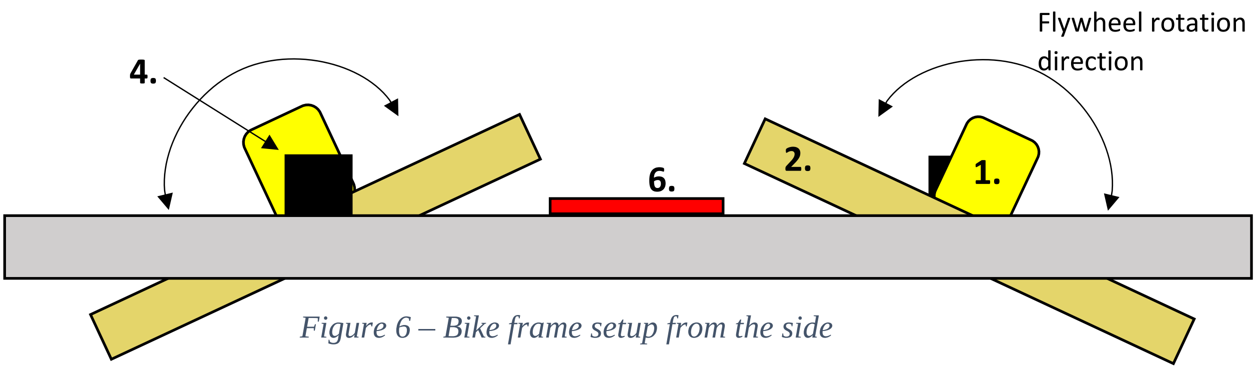

Figure 6 – Bike frame setup from the side

Key:

1. DC motor
2. Flywheel
3. Gimble Arm
4. Rotation Servo
5. DC motor
6. Flywheel
7. Gimble Arm
8. Rotation Servo

The concept of this setup is relatively simple, the two flywheels are spun to a high rpm using the DC motors, then rotated in the plane of the paper with the servos to produce a torque. Since this torque moves with the induced precession angle of the flywheel, two components are produced, one that is used for stabilising the bike and the other a yaw force. This is why the two flywheels will be used, rotating in opposite directions to counter act and yaw torque that is produced. Care will be required to ensure that the flywheels rotate the same amount in opposite directions to fully remove the yaw torque, that could easily destabilise a bike.

The perspex bridge across the centre of the bike provides space to mount components on a breadboard, battery, and the Genuino 101 microcontroller. The material has the added advantage of reducing vibrations from the spinning of the flywheels, which might affect the readings for the accelerometers and gyroscope inside the Genuino.

The plan for the first half of this work is to design and work on the system inside a frame which provided several benefits.

- More stable system, the point of rotation is in the same plane as the flywheels, so forces needed for corrections will be smaller
- Due to the stability the PID values will be easier to initially tune, but will need adjustment later.
- Easier to work on, the frame holds the bike in place before, during and after test.
- Adds a level of protection between the operator and the high velocity flywheels.

Once a system has been produced that provides a stable output inside the frame, the bike will be moved and mounted onto two wheels at each end of the bike, simulating a bike to a greater accuracy. Due to the roll of the bike around the pivot of the wheels being a greater distance than what was in the frame, greater correctional torques will be required. A lot of adjustments will be needed to again stabilise the system.

For the tuning of the PID values, the Ziegler-Nichols [12] method will be used, rather than just trial and error. This involves setting both I and D to zero then adjusting P until the system beings to oscillate. This critical value is then used to adjust I then D.

3.2 Controller and Code development

The Genuino 101 and the Arduino both can be programmed using C++ "sketches" developed in the Arduino IDE, which brings simple integration to the boards and uploaded the sketches. The IDE also incorporates a set of open source and publicly developed libraries which are very useful when creating sketches that perform common tasks, like servo control.

The microcontrollers and the code make it a very simple task to communicate with other hardware, whether it would be reading sensor inputs from the analog in pins, or to control servos and motors with the PWM digital out pins.

Code will be developed for the intention of testing certain aspects of the control system, i.e. motor speed control, but the main stabilising control program will be built upon and versioned. This history of this code will be stored in GitHub, presenting a full development tree of the sketch.

3.3 Project progression targets

The Gantt chart below shows the project targets with predicted durations for each stage of the development. It is hoped that by the end of week 10 that the first stable system will be produced, leading into further lean angle control and wheel stable systems in the second term.

Tasks	Duration (days)	Start Date	End Date
Creat basic circuit for basic motor and servo control on the bike frame	5	16/10/2017	20/10/2017
Basic responses to system perturbations, and PID tunning	12	23/10/2017	03/11/2017
Bike upgrades; new flywheel design, installation of two flywheels, upgrade servos.	5	06/11/2017	10/11/2017
Produce a stable balance in the frame, allowing for correction for external influences	26	06/11/2017	01/12/2017
Holidays and exams	40	04/12/2017	12/01/2018
Produced a controled lean and return to stable position	19	15/01/2018	02/02/2018
Remove the bike system from the frame and install the wheels	2	05/02/2018	06/02/2018
Produce the same stable balance, again allowing for corrections from external forces	19	05/02/2018	23/02/2018
Produce a controlled lean with correction back to stable.	19	26/02/2018	16/03/2018
Holidays	28	19/03/2018	15/04/2018
Write Dissertation	36	02/04/2018	07/05/2018

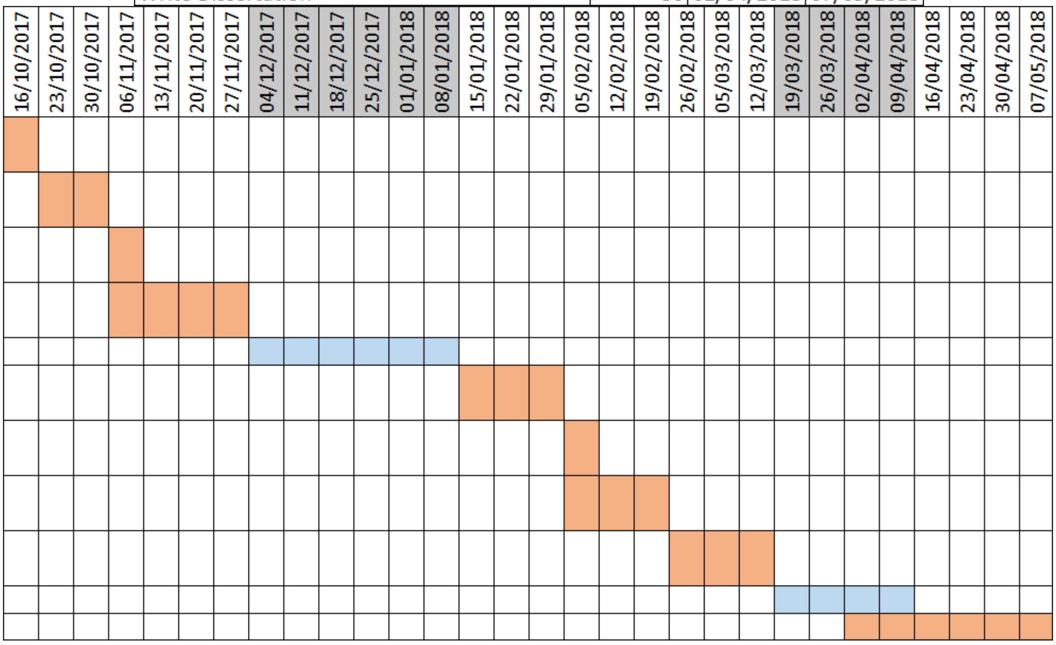

Figure 7 - Project projection targets

4.0 Discussion

4.1 Previous work

The aims and targets of this project have been built around the work completed in the previous years, most recently by James Scott in the development of an active stabilisation system for a motorcycle. This project provides a good grounding and proof of concept for a gyroscopic stabilisation system. The work starts by investigating a passive stabilisation system which decays in the angular position due to the slow natural procession of the flywheel. After showing that the system can be corrected by a flywheel, the work moves onto inducing a rotation into the flywheels resulting in a stabilised system within a (5±0.19) degrees of oscillation from the stable point with just a small singular flywheel. This was achieved in the frame and not on the mounted wheels. This result was further improved when using a larger flywheel allowing for greater torque responses, producing a stable system with a reduced error in the angular position (1.1±0.04 degrees of oscillations). What was never achieved in this work was long term stability when mounted to the wheel system. It is these encounter issues that builds the foundations for this project, to resolve them and produce stability.

4.2 Expected issues

4.2.1 Component torque reduction for controlled lean

As shown by equation 12 and 13, the torque produced by the gyro during an orientation rotation is non-linear, and is reduced the further the flywheel is rotated. This will cause an issue when trying to produce a controlled lean, and the return to the stable position as the corrective forces required will be large. The flywheels angular position will be at a non-zero θ to allow the system to lean, but resulting a reduced τ_{roll} to correct back to stable.

There are a few solutions to this problem that need to be investigated.

- Adaptive RPM, to maintain a linear force the angular velocity of the wheel can be increased with θ.
- Non-linear response, so the rate at which the flywheel rotates also increases with θ.
- Increased gyro torque, a flywheel with greater angular momentum would require a reduced θ, reducing the τ_{roll} depreciation.

4.2.2 Servo Limitations

The servos currently installed onto the bike test frame have limited rotation angles, torque and rotation speeds. With larger flywheels this will be a limiting factor when producing the correction torques, especially against large external forces or during a controlled lean.

Upgrading the servos to a higher specification allowing for greater response torques would allow the effective use of flywheels with greater angular momentums, increasing the τ_{roll} whilst reducing the dependency on large θ changes.

4.2.3 PID linearity

The general use of PID control assumes that the output (torque from the rotation) to a response would be linear, therefore providing a linear answer to any system changes. This presents a large issue when θ, the angle of which the flywheels have rotated through, have become large enough to noticeably reduce τ_{roll}.

Two solutions that will be trialled in this project:

1. Non-linear PID values, allowing the controller to have stronger responses dependant on the current system state.

2. Non-linear response, this is the easier option as it involves the output response to have a $\sin(\theta)$ proportionality to account for the $\cos(\theta)$ torque reduction.

4.2.4 Controller performance

As was shown in the project completed by James Scott, the controller had performance issue when trying to respond to the system and record data for analysis. It resulted in increasing loop times for the code and severe impacts on the servo response, leading to system decay. This was mostly due to the write times for the SD card for the data.

This problem can be eliminated using a second microcontroller and MPU board for measurements only. This means any slowed cycles would only cause data dropout and not control signal drop outs.

4.2.5 Weight Distribution

If the bike is not constructed such that the weight distribution across the width of the frame is even distributed, the flywheels will be needing to correct for the imbalance. The ideal system will be responding to system perturbations, and reducing recovery times. This will have a larger impact when transitioning to the wheels, as these imbalances would have a larger torque.

To reduce this factor, components on the bike frame will be adjusted to have better weight distributions, and tested with system responses to external forces, rather than steady state stability.

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