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. **Introduction**

There are many day to day examples where gyroscopes and their stabilisation can be seen, the most obvious of such is a 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 mentions of using a gyroscope of vehicle stabilisation came in 1904 by Louis Brennan, who patented his manually controlled system for imparting stability on unstable bodies [4].

Unlike the designs of Brennan, this project is investigating of an automated control system, which self regulates to correct for any external influences. 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

Two main reasons why introducing gyroscopes into the vehicles like bikes is for increased safety and better 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. In increase in popularity would greatly benefit in locations where traffic congestion is a major issue, as the road presence of a single tracked vehicle to that of a car comparison is greatly reduced and more economical.

1. **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 of which the wheel is spinning at.

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

(1)

Where M­w 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 we can find the angular momentum for a given speed of rotation:

(2)

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

ωprecession

P

ωspin

CM

*l*

Figure 1 - A spinning flywheel with precession ωprecession about a pivot point P

To explain the precession motion of the gyroscope we can look the motions in a simple example in figure 1. The wheel is rotating about the rod with angular velocity of , and rotating about point P with . 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 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 axis, as at that instance there is only one radial force created from the precession motion.

(3)

If we want to look at the torque in this system about the point P, there is only the force from gravity that contributes. So, to find the torque **,** the cross product of the which is in the negative direction and :

(4)

This is a non-zero toque 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.

If we now look at the wheel rotating about its centre of mass, as showing figure 3.

**θ**

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

If we look at the tangential velocity it can be expressed as the rate of change in which is only changing in θ, so:

(5)

If we now look 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. points along the axis and along the . Looking at the wheel first we can find:

(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 direction.

(7)

This directional change is at the precession rate, so making the change in angular momentum of the wheel:

(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 (:

(9)

But the linear momentum is only dependant on the change in as the radius *l* is fixed, resulting in only dependant on which is also constant. 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 we have already 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:

(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.

**(For figure 4, take a picture of the gimble setup on Monday)**

**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 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 rotates 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 bring 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 from the gyros.

The lighter feel to the handling of the bike would not only be the only added benefit. 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 4 - Directions of a slipping bike without a stabilisation system (left) and with (right)

As can be seen in figure 2 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 tires 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.

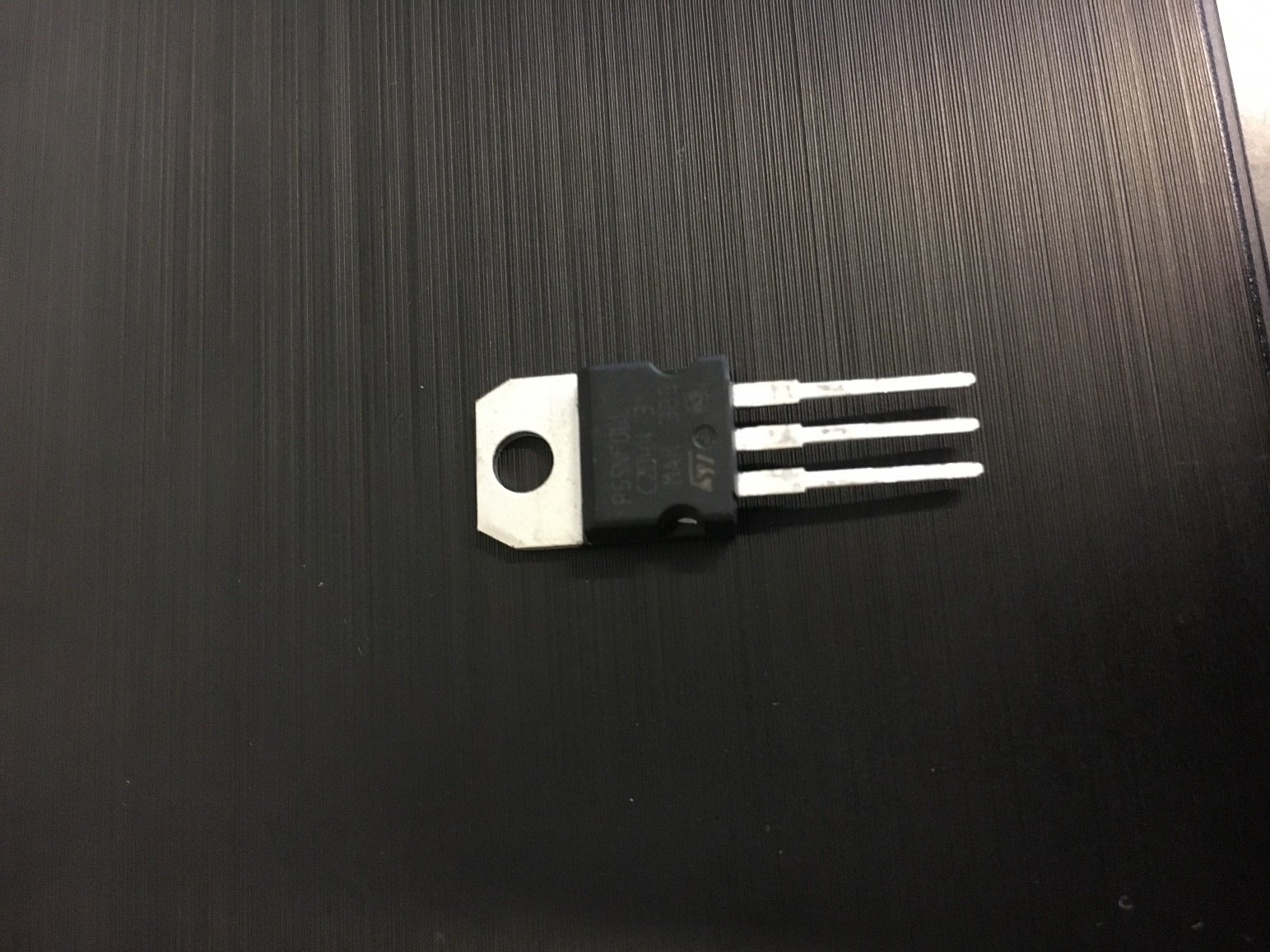
**2.3 Electronic theory**

When constructing an electronic circuit to build the control system to control and regulate the gyroscope, there is a need for a few key electronic devices when working with motors, servos and microcontrollers.

**2.3.1 n-channel MOSFETS**

A metal-oxide semiconductor field effect transistor or MOSFET is a n type transistor, which essentially acts of the valve of current to control external electronic devices like motors.

As shown in figure 3 they have three pins known as gate, drain and source. As their names suggests, the drain is the pin in which the current drains into, while the source leads to the ground. The gate is the control pin which is used to change the current flow between the drain and source pins via a control voltage. Logic level MOSFETS will be used in this project as they only require a 5V source to activate and deactivate the device, which can be provided from an Arduino microcontroller.



**Gate**

**Drain**

**Source**

Figure 5 - n-channel MOSFET

The MOSFET does not act as a switch but a variable resistor with an activation voltage, which is 1.7V [5] for *P55NF06L* in figure 3. This means that not only can the MOSFET be used to turn on something like a motor, but also how fast the motor is running from the gate input voltage.

Since MOSFETS are used in high current applications, it is also important to check the Power dissipated using:

(11)

Where RDS is the resistance between the drain and source controlled by the gate and *I* is the current flowing through the MOSFET. To find the maximum power that a MOSFET can handle without using a heat sink we can use the equation:

(12)

The gate of the transistor has a couple of limitations of the control voltage to switch the transistor on and off. The signalling voltage should typically be kept below 15V to avoid damages. However, the drain and source voltages are a lot more flexible and dependent on the transistor, but can support much greater voltages.

**2.3.2 Voltage Regulators**

A voltage regulator is a device that takes an unregulated input voltage which can be changing overtime and outputs a smooth output voltage, but with a few implications:

* Linear voltage regulators are not very efficient.
* They have a drop-out voltage.

To look at the efficiency of a voltage regulator, the power dissipated across it is found:

(13)

To avoid inefficiencies and high device temperatures high input voltages are avoided high input voltages, but making sure to avoid Vin fluctuating below the drop out-voltage.

The dropout voltage refers to the minimum input voltage that you have to pass to the regulator to guarantee a stable output. To provide this stable output, the “head room” voltage will be dependent on the voltage regulator used but in case of a *TL780-05* which is a 5V [6] regulator, that has a 2V dropout voltage.

Most regulators will have the same naming convention, looking something like:

\*\*78XX\*\*

where the \*'s will be some letters and the XX an indication of the Voltage it will supply. For example:

**2.3.3 Resistors**

When working a microcontroller like an Arduino, care is needed not to over current the pin connectors, damaging them. One of the most common ways of protecting sensitive electronic components like these pins is to add a resistor. Ohms law can be used to find the resistor needed to protect a pin from an over current.

Another feature of working with logic circuits with Arduinos is pull up/down resistors. A pull-down resistor is connected to the ground in the circuit and pull down any voltage so that a device like an Arduino pin rests at logic zero when no other devices are connected or a high impedance component acts like a disconnection. A pull-up resistor does a similar role but pulls the resistance up to the expected logic level in the same case of disconnected like circuit.

**2.3.4 Breadboards**

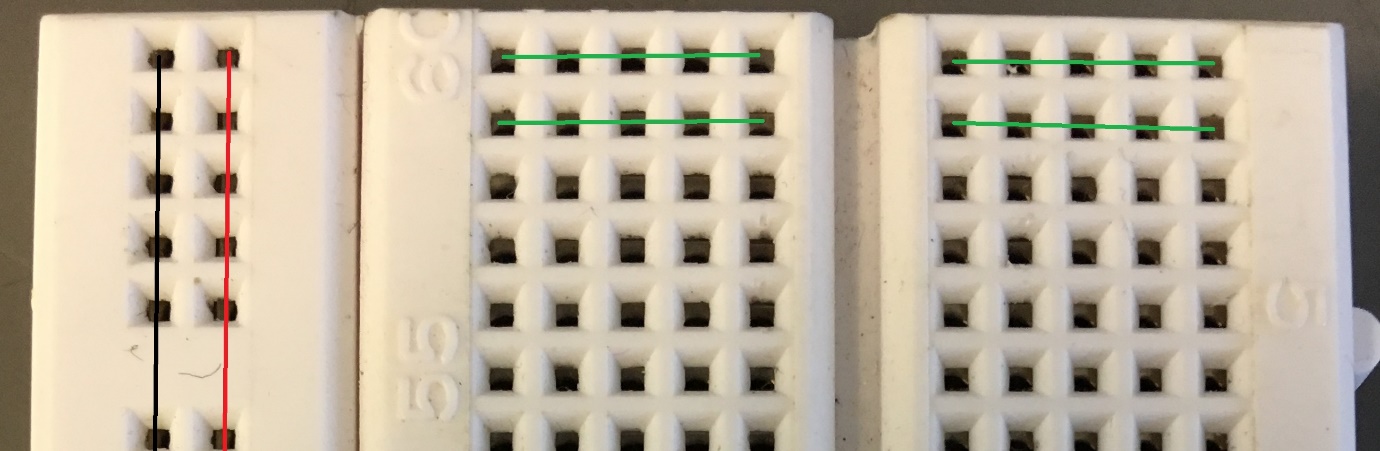
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Figure 6 - Breadboard and the connection directions

Breadboards are a device used to allow circuits to be created without the need to solder the components together. Figure 4 shows a picture of a bread board, highlighting the power rails/buses in red and black, and electrical connections in green. The break in the centre of the bears is designed so microchips can be placed into the board with full connectivity. All the components are held in place with small metal clips, which also act as the electrical connection.

**2.4 Microcontroller**

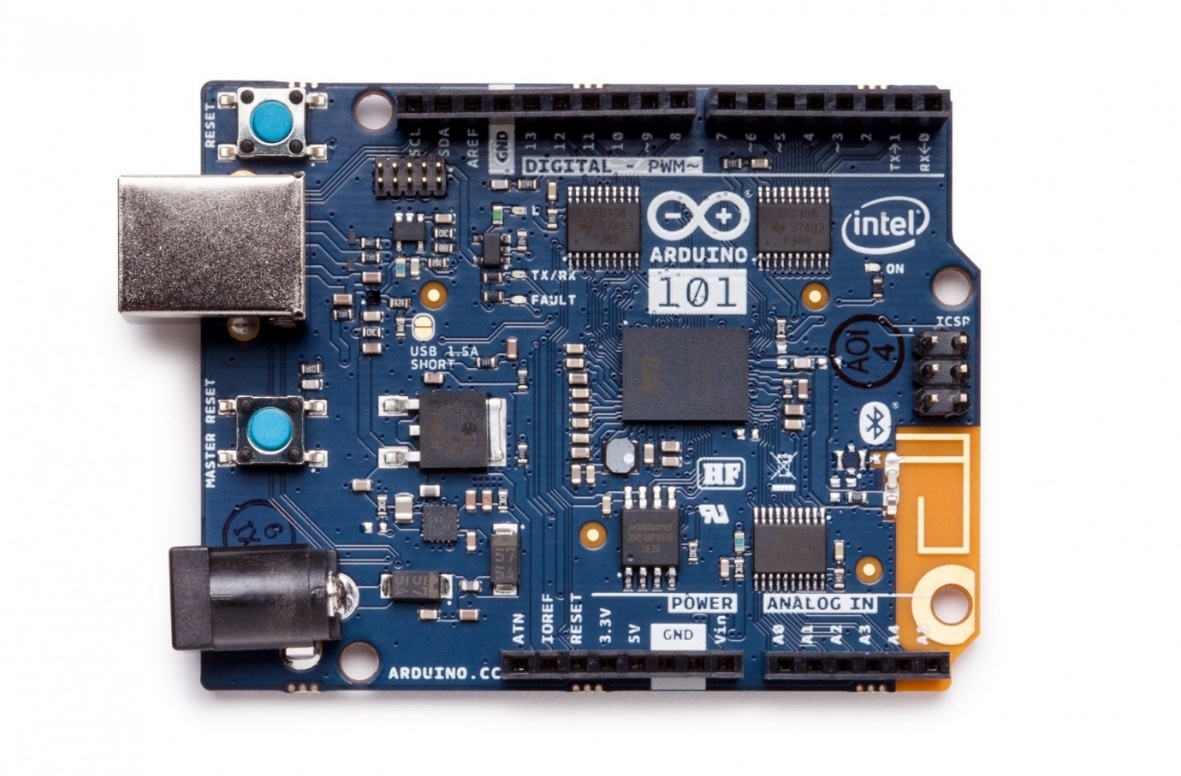
Microcontrollers are small electronic devices, also known as logic chips. These chips are processors housed in a microchip, which can be used in electronic circuits. For this project we are using microcontrollers that are already integrated into an electronic circuit to allow the quick and easy use in other electronic circuits. The two that boards in question are the Arduino Uno SMD, which uses an 8-bit chip called ATmega328 [7], and the Genuino 101, which uses a more powerful 32bit chip called the Intel Curie [8]. Both boards are of very similar design, the Genuino pictured below in figure 5**.**

Figure 7 – Genuino 101 Board [9]

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.

**2.5 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.

(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 (KP). For example, a system that has an error value of a magnitude 2 times that of the setpoint which has a KP 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 (KI­). 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.

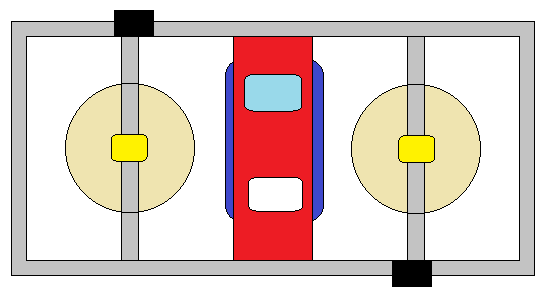
**2.5.3 Derivative**

The derivative factor (K­D) is a response which accounts for the rate of change of error from the setpoint. An increase in KD will produce a stronger response and greater speed of change to the output. When this factor is too large in 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.

1. **Methodology**

**3.1 Test system construction**

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



**8.**

**7.**

**6.**

**1.**

**2.**

**3.**

**4.**

**5.**

Figure 8 - Bike frame setup

1. DC motor
2. Flywheel
3. Gimble Arm
4. Rotation Servo
5. Genuino 101 control board
6. Perspex anti-vibration bridge
7. Bread-board
8. Battery Pack

The concept of this setup is relatively simple, the two flywheels are spin 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 then centre of the bike produces 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 [10] 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 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.

1. **Conclusion**

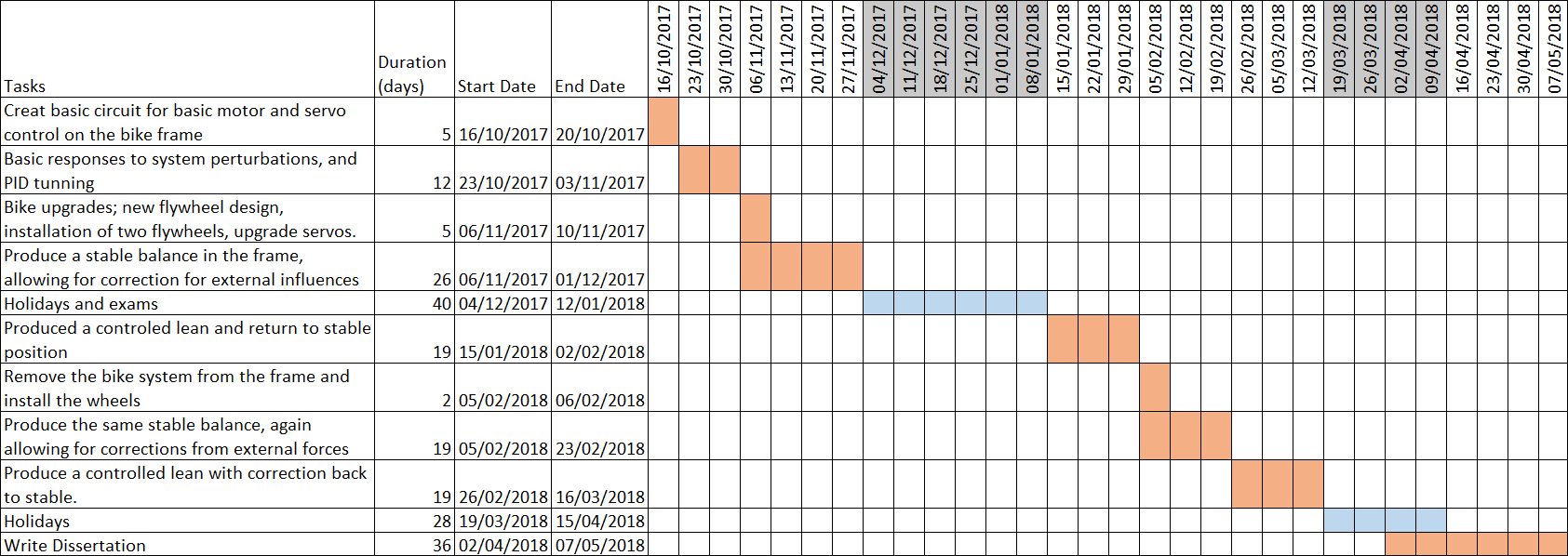
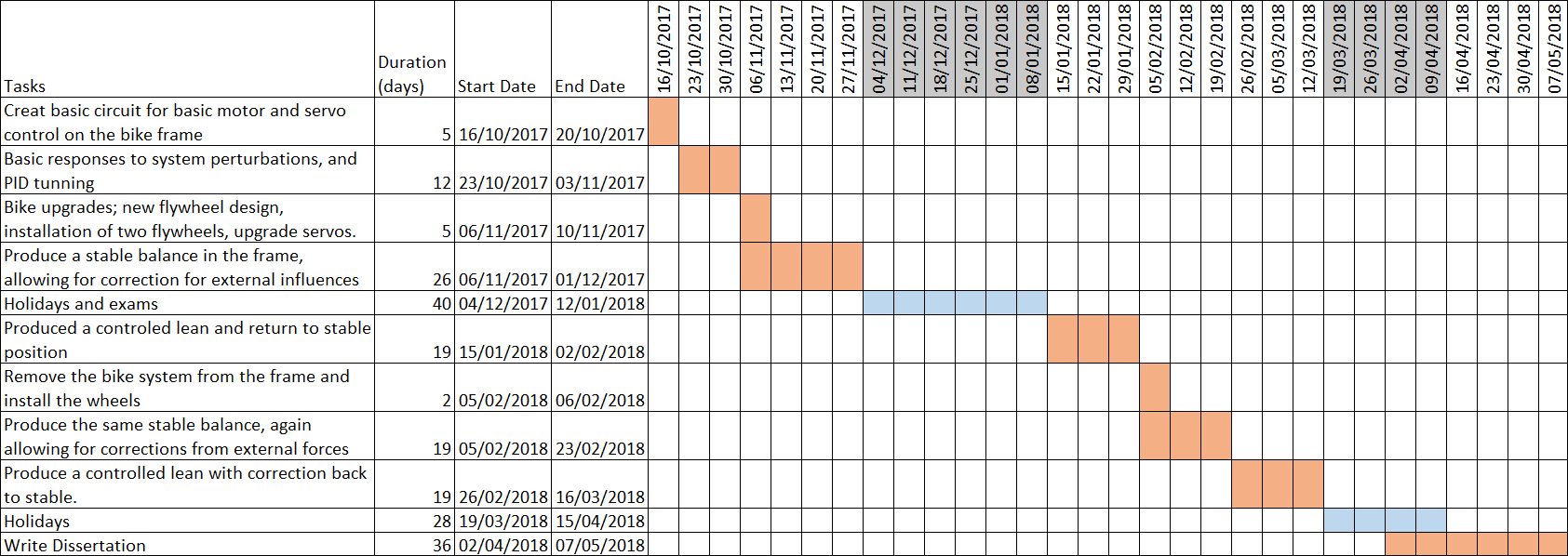


Figure 9 - Project projection targets

The aim of this project is to develop a system for a single tracked vehicle that will not only produce a stable balance for the vehicle but also one that can induce a controlled lean into the system and then correct back to the stable point. This to be achieved by using the effect of spinning flywheels to produce a correction stability torque by inducing a precession to the flywheel. The purpose of this is to increase the safety and handling of vehicles like motorbikes.

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