Active Stabilizer
Independent Project in Electrical Engineering

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Abstract

Active Stabilizer

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This report describes the process of designing and constructing an active camera stabilizer. The goal was to create a system that is lightweight and useful for stabilizing video footage taken by an action camera. The system is based on pairing electric motors with a position sensor in order to compensate for unwanted movement. This can for example make sure the camera stays level with the ground at all times and can give stabilized video footage.

The stabilizer arms were built out of aluminum paired with the motors to establish two axes that are perpendicular to each other. The entire device is hand held and is operated with two handles which makes for easy user operation.

The final product performed relatively well with the ability to compensate motions around the pitch and roll axes. The system turned out quite bulky but lightweight enough to be controlled easily with both hands. However, the control system was a bit shaky and slow which was visible in the video footage when the system was exposed to sudden rotations. The system could also crash occasionally, requiring a reset to resume operation.

All in all, the system operated as desired and thus fulfilled its purpose. For further development, the primary area of improvement is the regulator to make the compensation smoother. Also, the system could be shrunk down significantly to reduce size and weight.
1 Vocabulary

- Active stabilizer - A system that compensates for user inputs and vibrations with electric components.
- Arduino IDE - Programming platform based on the programming language C++.
- Bit - Binary unit, a piece of information containing either a zero or a one.
- BLDC - Brushless Direct Current, often used in electric motor design.
- Byte - A unit of information containing eight bits.
- CAD - Computer aided design, software intended to design objects in three dimensional space.
- ECU - Electronic control unit - A microprocessor or similar that executes calculations and commands.
- GoPro - Small action camera.
- H-Bridge - Part of the L6234 which consists of several power transistors.
- I2C - Inter-integrated circuit, a communication protocol used in programming.
- IMU - Inertial Measurement Unit, a general term for electronic position and movement sensors.
- L6234 - An integrated circuit intended to drive electric motors.
- MPU-6050 - An IMU containing a three axis accelerometer as well as a three axis gyroscope.
- PWM - Pulse width modulation, see Section 3.7
- RPM - Revolutions per minute
2 Introduction

2.1 Background

Active stabilization or active power stabilization is starting to find its way into modern technology and has great applications in film making. The technology is used in suspension for certain high-end car models and also has applications in medical treatment.

The idea is to use electrical sensors that output angular velocity and acceleration in three perpendicular directions. With the help of an electric control unit (ECU), the data can be used to interpret the position and movement of the sensor in a three dimensional space. The basic types of sensors used are known as “gyroscopes” and “accelerometers” respectively but the most common is a combination of the two.

By combining the position sensor, the ECU and some kind of electrical power train, such as a motor, the sensor values can be used in order to compensate for changes in position with the help of one or several motors. This way, the platform on which an object is placed can for example be kept level with the ground or reduce vibrations from the user or its surroundings.

With this in mind, one could imagine how this is useful to filmmakers who aim to get a smooth footage without unwanted movements, as seen in Figure 1, or perhaps to stabilize an eating utensil for a Parkinson’s patient.

![Figure 1: An application of an active power stabilization system in the film industry used for filming car scenes.][3]

2.2 Objective

The goal of this project is to build an active stabilizer suited for controlling a GoPro action camera. The system should be able to compensate for unintended motions in the pitch and roll axes to keep the camera level to a set reference plane. The finished product should be handheld in the sense that it is relatively lightweight and easy to handle with one or two hands.

2.3 Limitations

Because of the potential complexity of designing and creating an active stabilizer from scratch, a few limitations were made. The main focus of the project was to construct the stabilizer itself and then use the sensor data to control the motors effectively. Therefore, configuration and communication with the IMU was not prioritized and existing solutions were used or modified to suit the needs of this project. Furthermore, the use of a third axis in this project was excluded due to the increased complexity.
3 Theory

3.1 The Active Stabilizer

There are two major types of camera stabilizers available today, the passive and the active stabilizer. While the passive stabilizer relies on remaining balanced with counterweights, the active stabilizer uses motors to keep the camera in the correct orientation. To be able to counteract unwanted movements the system needs to know if the camera is rotated out of its reference plane. This is most often done with an inertial measurement unit (IMU) that senses acceleration and angular velocity to determine the angle of the camera in the three dimensional space.

An intuitive way of presenting the angle is to separate it into three different axes, namely pitch, yaw, and roll. This definition is often used to describe rotation of aircraft but it translates well to the cameras movements as well. The orientation of the axes are shown in Figure 2. All three axes are perpendicular to each other and therefore all possible rotations can be decomposed to its yaw, pitch and roll components.[5].

![Figure 2: A visual representation of the yaw, pitch and roll axes.][5]

For a camera stabilization system, the pitch and roll axes are most important because unintentional movements around these axes make the recorded video seem shaky. Stabilization in the yaw axis can also be desirable in cases where the movement should be smooth and consistent, for example in panoramic shots. Most camera stabilizers consist of three motors positioned along the yaw, pitch and roll axes, see Figure 3.

![Figure 3: An example of a handheld three axis active stabilizer.](image)
3.2 Accelerometer

A piezoelectric accelerometer is based on the concept of having a mass with “springs” on a microscopic level where the mass exerts tension on the springs when moved around. The accelerometer outputs a value that correlates to the applied acceleration in three perpendicular directions.

When the accelerometer is at rest and perpendicular to the surface of the earth, the accelerometer will output a value that, with the help of a simple multiplication, is one G or about $9.82 \text{m/s}^2$ and zero in the two other directions. When the angle of the accelerometer is changed, the output value of the three directions change and the total value can be calculated with the Pythagorean theorem, as seen in equation (1) and the result will be equal to $9.82 \text{m/s}^2$ in this case as well. Furthermore, this applies to every movement of the accelerometer and after the total value of the acceleration has been obtained, the inverse cosine as seen in equation (2) can be used with the total value and the original value in each direction to calculate the angle of the accelerometer in comparison to the surface of the earth. The biggest problem with the accelerometer is that it is sensitive to vibration, which can be mitigated by averaging out the values. However, these vibrations do not cause the raw values of the accelerometer to drift unlike in the gyroscope as seen in section 3.3, [1].

$$a_{tot} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$ (1)

$$\cos^{-1}(a_{tot}/a_x) = \theta$$ (2)

3.3 Gyroscope

There are a few types of electronic gyroscope types but most of them are based on tiny vibrating masses that get affected by the Coriolis effect when they are rotated. The gyroscope outputs a value that correlates to the angular velocity of the module. By multiplying the raw data value of the gyroscope with a constant, the value in degrees per second, that the module is moving, can be obtained. However, this data is still not useful in this project.

To get the actual position of the gyroscope, an integration must be done. By summing the raw values and multiplying them with the elapsed time, an actual position in degrees is obtained. This data is useful but if the gyroscope is subjected to vibrations from the motors, a problem arises. The gyroscope will slowly drift and change its value over long periods of time. However, unlike the accelerometer, the gyroscope is not very susceptible to vibrations in the short term, [1].

3.4 IMU Sensor Placement

Choosing a suitable position for the sensor may sound like a simple task, but the placement significantly impacts the method of controlling the system. There are two primary options to place the sensor, either on the camera side or the support side.

Placing the sensor on the camera side means that the camera and IMU share the same reference plane. This results in that the 3 dimensional angles of the camera are identical to the angles of the sensor. By knowing the exact orientation of the camera at all times, the position of the camera can be controlled with great precision. However, all angular compensations from the motors will move the IMU and therefore impact the sensor data. If the control system is insufficient, abrupt and jerky movements caused by the motors can lead to faulty sensor values and the camera will easily vibrate around its reference point, [7]. Alternatively the sensor can be placed on the support side of the system, which in this case is the handle. This positioning enables the angle of the camera and the sensor to rotate independently of each other. Choosing this approach greatly reduces the risk of vibrations on the camera side because the motors will not impact the sensor readings. Unfortunately, this sensor placement aggravates the ability to determine the camera angle. Because the camera and sensor do not share the same reference plane, the angle of the
camera has to be estimated from the sensor data. This could be done quite effectively and work well with proper motor control, but small estimation errors could lead to permanent angle offsets until the system is re calibrated, [7].

### 3.5 Traditional BLDC Driving

The traditional use for a Brushless Direct Current (BLDC) motor is for high RPM uses, for example in electric vehicles. A lot of the times, sensors are used in order to determine the position of the rotor in order to choose which phase of the motor to turn on and in which order. The way this works is by utilizing hall effect sensors which sense changes in magnetic fields. Because the rotor is commonly built with strong permanent magnets, the sensors can tell when the different polarities of the rotor are passing by. If a simple model of a BLDC motor is used, it can be imagined as three electromagnets coupled in a Y-connection controlled by three half bridges with the ability to choose in which direction the current should pass in each winding as pictured in Figure 4.

![Figure 4: A simple version of an alternator made for driving a BLDC motor in the traditional way.](image)

In traditional BLDC motor drivers, only two of the phases are active at one time. The current must always have one way to enter and one way to exit so no more than two transistors in the triple halfbridge are active at one time. This results in six ways to combine transistors and therefore six different steps to go through in order to make one electrical revolution of the motor, [2]. The relationship between electrical and mechanical revolutions is one to one in the simplified model and will differ from motor to motor.

### 3.6 Running a BLDC Motor as a Servo

As opposed to running the BLDC motor in a high RPM configuration, the idea is to be able to run it at extremely low speeds. The theory behind this is to actually run the motor more like a synchronous motor by rotating the magnetic field in small steps with the help of sine waves but at the same time be able to control the speed of the rotating field instead of having it fixed like in a synchronous motor. This method uses no hall effect sensors or similar ways of sensing the rotor position and one could say that this seems like driving the motor blindly but that is not the case, [6].

Instead of using position sensors inside of the motor, the accelerometer/gyroscope can be used in order to determine the error of the position instead of the rotor position itself. With this error, a regulator can be
constructed and programmed into the ECU in order to correct for the errors by “stepping” in the opposite direction of the error to correct for it. More about this stepping is mentioned in Section 3.7.

3.7 Pulse Width Modulation

Pulse width modulation is a method used in nearly all power electronic application and is used to regulate the applied power to a system. To begin with, a PWM frequency is chosen and when choosing this frequency and a few things need to be taken into mind. The most important one is to chose a PWM frequency that is higher than 20kHz in order to make it inaudible to humans but if there is alot of noise in the area in which the unit is supposed to be used, a frequency that is far from the noise frequency must be used so that the noise can be filtered out.

The idea behind PWM is to create a square wave that can only attain a positive voltage or the reference voltage. With the help of either microprocessors or other timer based integrated circuits, the relationship between how long the signal is turned off and on can be changed. This relationship is often referred to as duty cycle given in percent where zero percent means that the signal is always turned off (minimum power) and 100 percent means the signal is always on (maximum power). Any value between 0 and 100 can be chosen in order to control the power consumption of the system as seen in figure 5.

![PWM Signal with Different Duty Cycles](image)

Figure 5: A PWM signal with different duty cycles, 10%, 40% and 90%

With this in mind, the theory behind the PWM to run the motors slowly can be described. By forcing the bottom three transistors of the triple half bridge to always be active, we can move the reference voltage of the motor, which is usually 0 volts, to half of the supply voltage. This removes the need to use negative voltages and can rotate the magnetic field in the stator of the motor with very small steps. To do this, one can utilize the duty cycle of three different PWM signals with the same frequency.

A discretization of a single period of a sine function is used to create an array containing 360 values. Each of the 360 steps correspond to the amplitude of the sine function from 0 to 360 degrees. One thing to keep in mind is that since the reference voltage of the motor has been moved to half of the supply voltage, the sinusoidal array must be offset to start with half of the maximum value. Now, three of these PWM signals using the same array can be used with an offset of 120 electrical degrees in order to always get a rotating
magnetic field and by simply taking steps forwards or backwards through this sinusoidal array, the motor will rotate, [6].

3.8 I2C Communication

The IMU used in this project uses the I2C communication protocol. I2C, or Inter- Integrated Circuit, is a protocol widely used for communication between several devices and peripherals. A typical system consists of one master unit, usually a microcontroller or processor, and multiple slave units. Aside from the required common ground connection, the I2C protocol uses only two lines for communication between all units. These are serial clock (SCL) and serial data (SDA) lines, where the clock line controls the timing while the data is sent via the data line. Each unit is given a unique address, making it possible for all devices to share the same SCL and SDA lines. The master initiates and terminates each data transmission by sending a start or stop condition containing the address of the unit the master wants to communicate with. Because of the single data line, information is transferred bit by bit. After each transferred byte, the slave unit sends an acknowledgement bit to ensure that the transfer was made successfully, [8].

3.9 Power Electronics

The power electronics are based on the L6234 integrated circuit which is used to step up the voltage from the ECU and it also handles more current, giving more power to the motors than the ECU can provide. The L6234 consists of three half bridges. Similar to an H-bridge, these can be used to control the flow of current in different directions of the three motor windings even though it is powered by a DC voltage. A half bridge consists of two power transistors in series that can be controlled individually and by pairing several of these half bridges, one can construct alternators of different types. This is done by connecting a motor winding between two of the middle sections of the half bridges, creating a connection in which the ECU can choose a direction of the current to flow. [2]

3.10 PID-Regulation

The active stabilizing system is a closed system that uses feedback from a position sensor in order to change its output signal accordingly. One popular way to control or regulate systems like this is PID-regulation and is based on subtracting the input signal with the desired signal in order to get the error. This error is then used to change the output signal until the error is equal to zero. Three components are used in order to accomplish this result:

- **Proportional Regulation**
  By multiplying the error with a constant and using this value to change the output signal, a proportional part of the regulator can be created. This is the most simple type of regulator and is also the most common one because it is often sufficient in many systems. The drawback of this is that it can often cause “self oscillation” and can often overshoot the desired value which results in the error not always converging to zero.

- **Integrating Regulation**
  By summing the error over time, the integrating regulator can be used in order to eliminate the static error if present. This is important in systems that require high precision and the dominance of this regulator is determined by a constant which is multiplied to the integrator and then added to the output signal.

- **Deriving Regulation**
  A deriving regulator is based on calculating the slope of the latest value with respect to the time between the values and can be used in order to predict future values of the system. By doing this, the overshoot can be reduced and the system becomes less susceptible to sudden changes in the input signal. The dominance of this regulator is also determined by a constant which is multiplied to the deriving regulator and then added to the output signal, [4].
4 Experimental Details

4.1 Planning Process

While planning the build, a lot of things had to be taken into consideration. When having very little background in the subject of active power stabilizers, the best thing to do was to study others that had already completed similar projects. This led to finding a lot of common errors to avoid and laid the foundation of the build process. Similar projects to this are segways, self balancing robots and self leveling multicopters. These build on the same principle and often use the same type of position sensor that was used in this project. There are, however, several sources on building an active stabilizer as a hobby project and these were great inspiration sources for this project.

4.2 Mechanical Construction

The mechanical parts of this project were first designed in a CAD software in order to know what the final product would resemble. After that, the prototype was built from aluminum that was bent in to shape and screwed together with the electric motors and a simple mounting platform for the electronics as seen in Figure 6. The motors used were Tiger Gimbal motor GB36-2. On the small platform at the roll axis, a GoPro as well as the IMU was placed. The sensor was placed on the camera side of the system to simplify the angle calculations and focus more on the motor control system.

It was important to balance the system in order to reduce the load on the motors. By changing the position of the camera, the centre of mass of the entire system was shifted. If the centre of mass aligns with the axis of each motor, the system will remain in its current position if no external forces are applied. To make the system as compact as possible, the mounting arms were designed to place the centre of mass close to the midpoint instead of using the camera as a balancing tool.

![Figure 6: The stabilizing arm with motors in an early stage of construction.](image)

4.3 Electronic Assembly

The biggest part of the electronic assembly was actually the motor drivers that demand a few passive components in order to function properly. The full schematic for how the motor drivers were plugged
in can be seen in figure 10 in the appendix but the general flow of the electronics is as follows: The gyroscope/accelerometer sends data to the master microprocessor which then processes the data continuously and at the same time sends it to the slave microprocessor which runs a PID-regulator and controls the motors as seen in the block diagram in Figure 7.

![Block Diagram](image)

Figure 7: A block diagram describing the flow of the stabilizer.

The IMU used in this project was the MPU-6050 by Invensense which contains a 3-axis accelerometer as well as an 3-axis gyroscope. It uses the I2C protocol to communicate with other devices and supports data transfer speeds of up to 400 kb/s. Programmed into the chip is a digital processing unit, DMP, that performs computations of the raw data which allows for the position values to be collected by the ECU quicker.

### 4.4 Programming

The programming was all done in Arduino IDE which is an open source software based on the programming language C++ and the microprocessors used were the ATMEGA328P-PU. This programming platform can use several different communication protocols in order to communicate between different devices but since the MPU-6050 uses the I2C protocol, this is what was used to communicate between the two microprocessors as well.

Basically, one of the microprocessors takes the place as the master and the other as the slave and the basic concept is that the master can always send data to the slave independently of what the slave is doing. When the slave receives the position values, it processes these and turn them into actions to be sent to the power electronics which in turn control the motors. The PID-regulator subtracts the current position in each axis from the desired position respectively. From this, it corrects the error by stepping through an array of values that correspond to the next position of the motor as explained in the Section 3.6.
5 Results

5.1 MPU-6050 and I2C Communication

The data from the IMU was extracted to an arduino with the help of a software library written by Jeff Rowberg. Both the raw data combined with calculations on the microcontroller as well as the processed values from the DMP were obtained and compared. It was clear that the output from the DMP was superior in this case since the pitch, yaw and roll angles converged towards the “true” value faster than the raw data. It was also observed that the obtained yaw values were drifting and unreliable rendering them unusable for this application.

5.2 Motors and Motor Drivers

The motors were able to run extremely slowly, slower than ever needed for the stabilizer and with a calculated resolution of \( \frac{1}{7} \)° per step. This gives the motor 2520 different positions in one mechanical revolution which is plenty for this device. The resolution R is calculated using the relationship between mechanical and electrical degrees \( n=7 \) and the array size of the ECU, \( m=360 \) as seen in (3).

\[
R = \frac{360}{n \cdot m} = \frac{360}{7 \cdot 360} = \frac{1}{7} \text{°}
\]

Also, the motors were powered by the motor drivers, running at a frequency of 31372.55Hz which made it completely inaudible to humans, as desired. The motor drivers showed to be more than sufficient and do not require heat sinks in order to dissipate the heat from the transistors when using a 12V power source. However, heat sinks were still added as an extra safety precaution or in the case that the power of the motors ever needs to be increased. It is worth to mention that because of the high torque of the motors, the PWM duty cycle never exceeds 50% because of the powerful motors.

5.3 Mechanical Construction

The mechanical arms were successfully built to be set perpendicular to each other and each motor was mounted with screws to the corresponding axes. The mounting platform for the electronics turned out good but large. The entire mechanical build is lightweight and it is possible to control the system with one or two hands.

5.4 The Complete System

Because of the unreliable values in the yaw axis from the IMU, the motor intended to control that axis was left out of the prototype. The complete system worked decently using a basic P-regulator for each axis. However, when using the system for extended periods of time, errors occurred that caused uncontrolled movement. These errors were later avoided when the IMU was re positioned and its cables managed better. The end result of the stabilizer can be seen in Figure 8.
Figure 8: The final version of the stabilizer.
6 Discussion

6.1 Motors

When choosing the motor type for this project, there were a few options and all of them had different advantages and disadvantages to keep in mind when choosing the correct component.

- **Servo Motors**
  Easy to use, has high torque and has a built in regulator system but is slow and the loud noise from the motors makes it unusable.

- **Brushed DC-Motors**
  Very fast but has such a high speed and low torque that in this application, it is unusable because they are hard to control in a smooth and precise way. If the motor was geared down, it would be very similar to a servo motor and have the same problems.

- **Stepper Motors**
  This type of motor can have high torque, high resolution with micro stepping but on a camera, the steps might be visible which is why this motor was not used, even though it would have been a viable choice. The difficulty of controlling these motors with a high precision is also high.

- **Brushless DC Motor**
  This type of motor has a very high torque, a high speed and very high resolution which is all of the attributes in a motor that are needed for a stabilizing arm. However, the theory behind controlling these motors is complex but is manageable with thorough research and the right components. The power electronics required take up a lot of space in comparison to the other motor types but the BLDC motor was still the superior choice in comparison the the other types.

6.2 ECU

The electronic controller unit has taken many forms throughout the project. The first thought was to use several small microcontroller units, one for the position sensor and one for each of the motor drivers. The idea was to isolate the units as much as possible in order to run the different components of the stabilizer in parallel. This would have been viable and very small but the downside to this is that the I2C communication between devices becomes more complex.

Another generation of the ECU was to use a single Arduino Mega (ATMEGA2560) to read the position sensor values, make the calculations as well as drive all motors. While this is also a very easy and compact way to solve the problem, the PWM frequency of the motors must be high enough to be inaudible to humans and when the I2C communication protocol is used for the position sensor, this is not possible. The reason is that when you change the PWM frequency on the pins of an ATMEGA2560 while communicating with the position sensor, there are timing difficulties that arise. This causes the position sensor to occasionally crash and leave the stabilizer in a state that either does nothing or simply makes the movement worse. Because the PWM frequency could not be altered from the standard frequency (about 500Hz) a loud noise is emitted by the motors and the sound is simply not acceptable.

The final version of the ECU simply consists of two separate microcontroller units where one is the master and one is the slave where the slave runs the motors and the master runs and reads the position and finally sends it to the slave. This allows the motors to run at a high frequency of about 32kHz and the I2C protocol between the position sensor and the master works fine.
6.3 Design and Material Choice

From the start, the mechanical parts were designed in Solidworks, a CAD software and were supposed to be 3D-printed as seen in Figure 9. However, the 3D-printed parts would have taken an extremely long time to print and because of the limited access to 3D-printers, the print may have not been up to our standards when considering strength to weight ratio. Instead, straight aluminum bars were bent with the respect to the design in order to match it. The build was successful and the aluminum parts were lightweight, strong and easy to work with when mounting the motors.

![Figure 9: The initial design which was an inspiration for the look of the final product.](image)

6.4 PID Regulation

When designing the regulator that compensates for the movement of the user, there were two different approaches to solving the problem.

The first way is to regulate the numbers of steps to move through the array of values with a fixed short time between steps. This design is very fast and responsive but the movement can be twitchy and sometimes too fast if the angular velocity of the IMU is rapidly changing direction.

The second approach is to always take the smallest step increment but to regulate the time between steps. This creates a very smooth movement of the stabilizer but it is a lot slower than the other option. This is because when the error is small, the time to take steps increases greatly, up to a maximum value and when sudden movements are applied, this long time because of the previous small error has to be waited out before the next value can be calculated, giving the regulator a slower response time.

In the finished product, both of these regulators can be used and are interchangeable through a simple re-upload of the program in the slave microprocessor. Both regulators have their advantages and disadvantages but since they are so distinctly different, they could not be joined into one regulator. This leaves us with two regulators that have different uses for different applications. For example, the first regulator can be used to compensate for vibrations and shaky movement while the other can be used when filming slow and controlled moving shots where vibrations are not as present.

When looking at the combination of these components, the stabilizing arm is functional, and useful. It compensates for the movement of the user and when a camera is used, gives smooth video footage. However, if one wanted to make this product for commercial use, there are a few things to improve upon. Firstly, the
circuit can be shrunk down extremely if one chose to use a printed circuit board but this is too expensive for simple prototype production. Secondly, if the mounting arm was made professionally, it could be balanced better and have better mounting capabilities for different types of cameras. Thirdly, the regulator system could be improved upon and made more responsive.
7 Conclusion

The active stabilizer works as intended and can be used while filming with a camera to get smooth footage and reduce vibrations induced by the user and the environment. However, there are several points to be improved upon if this product would be made for commercial use.

7.1 Acknowledgements

Firstly, we would like to thank the department of electricity at Uppsala university for funding this project and providing the resources and equipment to make this project possible. Secondly, we want to thank Steffi Knorn who has been the supervisor of this project and has influenced the final product greatly with her input and valuable information in automatic control and general project knowledge.
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8 Appendix

Figure 10: The schematic used for the motor driver IC and passive components [9]