Self-standing Monopod

Xin Chen

Diyu Yang

Jianan Gao

TA: Luke

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Contents

1. Introduction

1.1 Objectives and Background

This project intends to build an auto-balancing monopod for cameras that can replace most of the functionalities of a tripod. The concentration of this project is mainly in control systems.

The inspiration of our project comes from the problems with the existing tripods photographers use: it is heavy to carry, difficult to set up, and it has only one shooting angle.

Therefore, we would like to build a monopod that can balance itself on rugged surfaces and under various disturbances like wind. Furthermore, better than a tripod, our monopod is lighter and easier to setup: what the user need to do is to turn on the power switch and put the monopod at the vertical balanced position. Furthermore, the user can always manually change the shooting angle of the monopod by holding it at a different angle. The monopod would automatically go back to balancing position once the user releases the monopod.

1.2 High level Requirement list

1) When no disturbance is present, the monopod can balance itself with less than +/- 5 degree oscillation at the vertical position.
2) The monopod can balance itself on a non-slippery surface with an incline of at most 15 degrees.
3) The monopod can restore to vertical balancing position from at most 30 degree leaning angle resulted from either disturbance of wind or shooting angle adjustment by the user.
4) The length is adjustable from 1.4m to 2m. Monopod will be able to meet requirement (1)-(3) for any length satisfying the condition above.

2. Design

2.1 Block diagram & Physical diagram

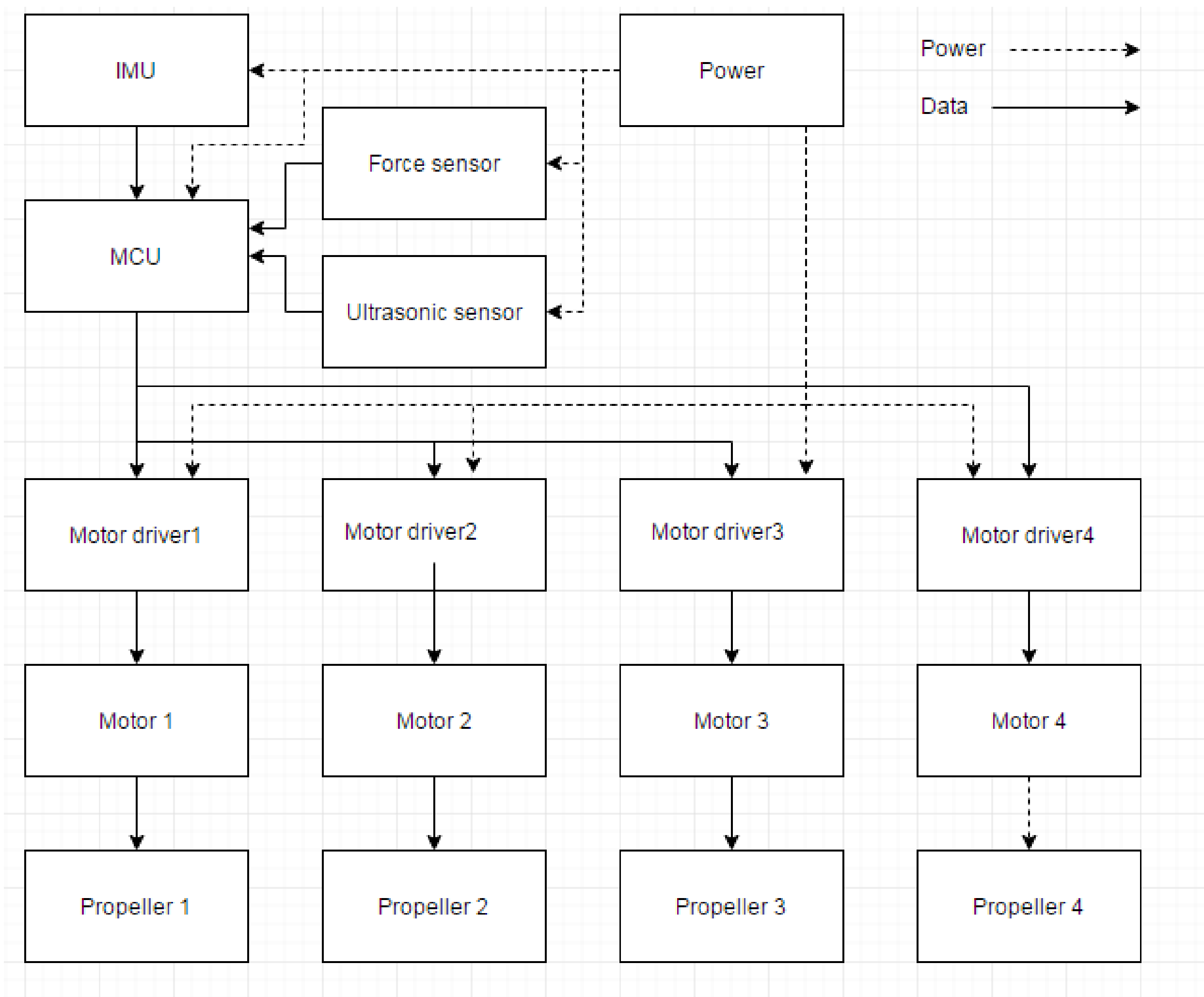

Figure 1. Block diagram

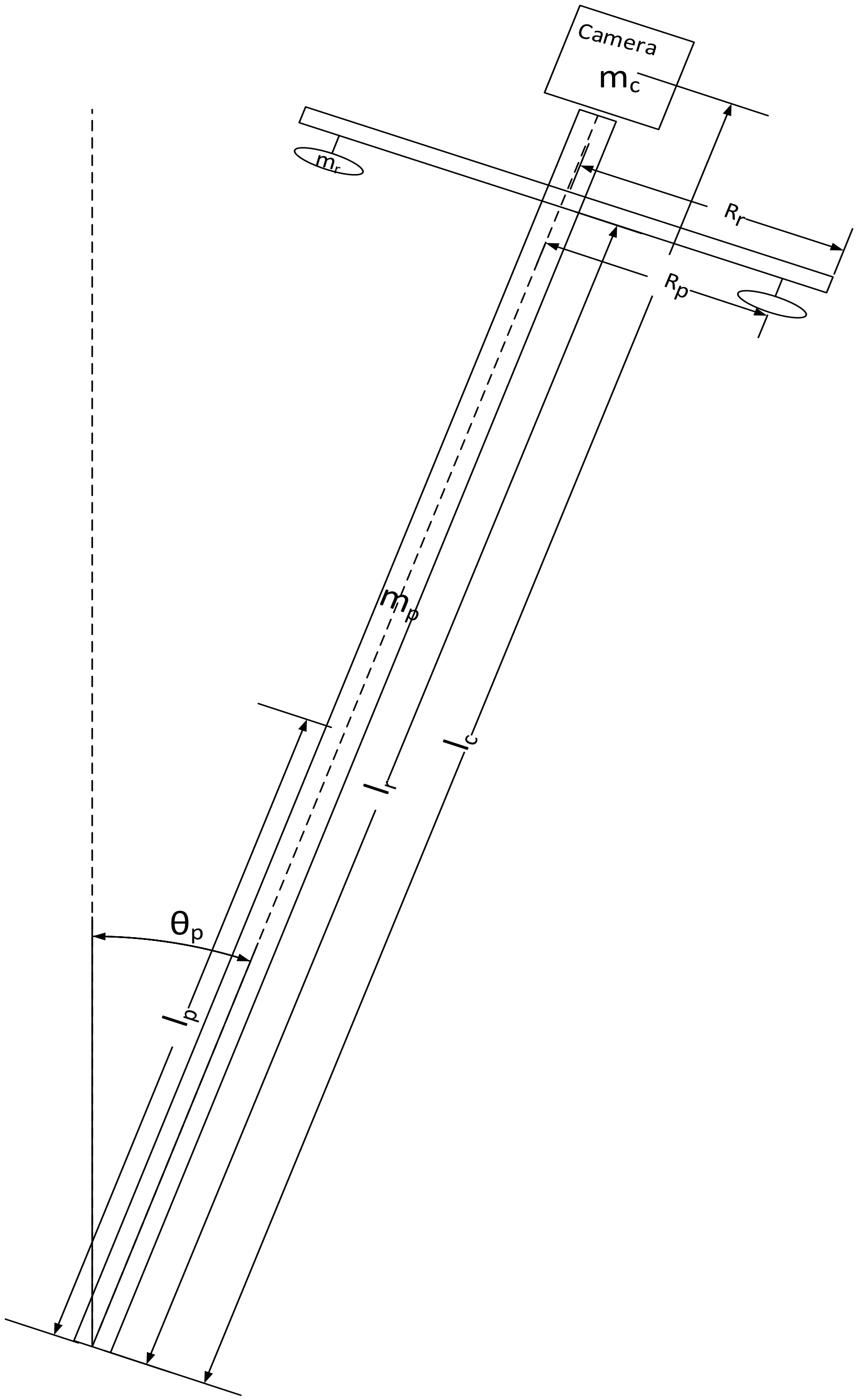

Figure 2: Physical Diagram[3]

$m_p = 0.363kg$	Mass of monopod
$m_r \approx 0.02kg$	Mass of each propeller motor package
$m_c \approx 0.5kg$	Mass of the camera
$l_{max} = 2m$	Maximum length of monopod
$l_{min} = 1.4m$	Minimum length of monopod
F_r	Force produced by one propeller
$\square_p$	Distance from bottom to the center of mass of pendulum
l_r	Distance from bottom to the propeller
$l_c \approx l + 0.1m$	Distance from bottom to center of mass of camera
$R_p = 0.15m$	Distance from propeller to the pod

2.2 block description

1. Power Supply: We use 2 Alkaline battery (9V each) for Vdd. We send required voltage to different components using different voltage regulators.

2. Inertial Measurement Unit (IMU): We use IMU’s accelerometer to calculate the angle. The IMU sends (x,y,z) acceleration information to Arduino to calculate the angle when it senses the movement.

3. Microcontroller (MCU): We use a ATmega328 RedBoard AVR® ATmega MCU 8-Bit AVR Embedded Evaluation Board as our MCU. This works as a control unit that will take input as output from IMU, force sensor and height sensor and process to get the duty cycles the PWM signal need for motor to balance the monopod.

4. Motor Driver: Motor driver takes PWM signals from Arduino digital I/O ports as input to control the motors’ speed. It generates current at most 16A, which is enough for our motor.

5. Brushless motors: These motors function as actuators of our system. They are attached to propellers that generate thrust when spinning to stabilize our monopod. The maximum rpm is 11500 rpm. It takes inputs of three phase PWM signals. The reason we use brushless motors over brushed motors is that it can provide more torque under the same power supply. It operates under voltage range from 7V to 11V.

6. Force sensor: We use Interlink Electronics 34-00015 as our force sensor. The sensor will increase resistance with the force increase. Buy measuring the resistance and comparing the resistor and the data sheet given, we can know the weight of our camera.

7. Height sensor: We use Ultrasonic module of Arduino. Ultrasonic contains two round looking component which are ultrasonic speakers.One of it transmitting a 40khz sound wave and let it bounce on a solid surface. The other one will try to detect the echo that is generated when it receives the bounce back. The total time taken for this process to complete will give us the distances between the sensor and the object.

2.3 Requirements and verifications

Requirements	Verifications
Microcontroller (20pts) 1. 1.The microcontroller needs to have at least 4 I/O pins that support PWM with a duty cycle of 50% 2. The MCU can correctly calculate data from IMU to get the theta angle and generate a smooth angular velocity curve after going through a low pass filter. 3. The clock speed of Microcontroller need to be at least bigger than 24HZ which is the minimum sampling frequency for the monopod we use.	1. (a) Connect the output to oscilloscope to check the duty cycle. 2. (a) Collect 1000 data sets from the board and monitor the data in Arduino. (b) Export theta angle to Matlab, use the following function to get the angular velocity: $\frac{(\Theta_{curr}-\Theta_{prev})}{\Delta T}$. (c) fit the curve, we should have less than 10% difference except some extreme high or low points due to instability when measuring.
Control System (20 pts) 1. The rise time for our PID control system should be less than 20.8ms, which corresponds to $\frac{1}{2f_n}$, where $f_n = 24Hz$ is the natural frequency of the system. 2. The steady-state error should be less than 10% of input signal. 3. The overshoot should be less than 5% of input signal.	(a). Tune the PID parameters N_P, N_I, N_D of the system such that the rise time and overshoot requirements are met. (b). Test the result by looking at the step-response of the system.

IMU (15 pts) 1. The IMU needs to be calibrated such that $\sqrt{{G_x}^2 + {G_y}^2 + {G_z}^2} = 9.81\frac{m}{s^2}$ with less than 7% of percentage error in any position, where G_x, G_y, G_z are the projection of gravitational acceleration on each of the x, y, z axis respectively[2]. 2. The IMU is accurate enough to detect +/- 5 degrees angle change in all directions at upright position (with a percentage error less than 30%).	1. (a). Place IMU at a certain position. (b). Look at the output of G_x, G_y, G_z from IMU. (c). Calculate $G = \sqrt{{G_x}^2 + {G_y}^2 + {G_z}^2}$ and calculate the percentage error $e = \frac{G - 9.81\frac{m}{s^2}}{G}$ and see if $e \geq 7\%$ (The answer should be NO). (d). Repeat procedure (a)-(c) for different positions. 2. (a). Place IMU at upright position. (b). Record the two output angles θ_1 and θ_2 from microcontroller and calculate the leaning angle: $\theta = \sqrt{{\theta_1}^2 + {\theta_2}^2}$. (c). Change the position angle by 5 degree along a random direction. (d). Record the two output angles ${\theta_1}'$ and ${\theta_2}'$, and calculate the leaning angle $\theta' = \sqrt{{\theta_1}'^2 + {\theta_2}'^2}$. (e). Calculate angle difference: $\Delta\theta = \sqrt{{\theta_1}'^2 + {\theta_2}'^2} - \sqrt{{\theta_1}^2 + {\theta_2}^2}$ (f). Calculate percentage error: $e = \left\lvert\frac{\Delta\theta - 5^\circ}{5^\circ}\right\rvert$ (g). See if $e \geq 30\%$ (The answer should be No).

3. The output of IMU is stable enough such that the percentage error of detected angle and actual angle is less than 15% for $10^\circ \leq \theta \leq 30^\circ$ along any direction.	3. (a). Place IMU at a position θ, where θ will be incremented from 10° to 30° by 5° each time. (b). Follow procedure 2(b) to record and calculate the angle θ' given by IMU outputs. (c). calculate the percentage error: $e = \left\|\frac{\theta-\theta'}{\theta}\right\|$ and see if $e \geq 15\%$ (the answer should be no). (d). Increment θ by 5° (until $\theta = 30^\circ$). (e). Repeat (b)-(d) for the new θ value.
Motor-Propeller System (15 pts) 1. The system would provide enough thrust to meet high level requirement (3). 2. The output force of the system can be accurately (maximum percentage difference <= 10%) manipulated by changing input power.	1. Set up experiment to messure the relationship between input power and output thrust. Find the best-fit curve for the obtained data. 2. Test the result of our experiment by measuring the percentage error between theoretical output thrust and actual output thrust under various input power level.
Power supply (10 pts) 1. The 2 alkaline battery in series supply 12V DC voltage. 2. The maximum current the battery can supply should be higher than 50mA, which is the required current for 3.3V Pin on Arduino uno.	1. We use digital Multimeter to measure the voltage of two batteries in series. If it displays 18V. Then it is correct. 2. We use digital Multimeter to measure the current that the two battery in series can supply when it is connected to the Arduino uno's 3.3V Pin.
Motor driver (5 spts)	1. We can write a test program that takes duty cycle input from 0 to 255 and generate PWM signal to

The motor should be able to change speed and directions according to the PWM signal sent from Microcontroller.	drive motor driver. We also hook up the motor with motor driver. See if the motor speed increase linearly with the increasing PWM signal input.
Voltage Regulator (5pt) 1. 3 voltage regulators can take input voltage up to 18V and output 2.5V, 5V, 10V as output.	1. We connect 3 voltage regulators to 18V voltage, use digital multimeter to check if the open circuit output is 2.5V, 5V, 10V.
Force Sensor (5 pts) 1. The force sensor's range need to be larger than 500g, which is our theoretical load weight. 2. The force sensor's sensitivity need to be small than 1mg/LSB	1. We check the datasheet of the force sensor to see if the range is larger than 500g and the sensitivity is smaller than 1mg/LSB
Geometric Model (5 pts) 1. The minimum reachable distance from user's body to the pod needs to be less than 15cm for the convenience of photographer. 2. The distance from the top of the pod to the center of the propeller-rod system (l-l_r) needs to be larger than 10cm to give convenience for attaching camera. 3. The length of the rod (R_r) needs to be larger than the distance from propeller to	1. Build up our mechanical system such that 2. Calculate the maximum force (F_r) required for the propeller such that the maximum torque produced bys propeller: $\tau = F_r \cdot R_r$ will be enough to meet our high level requirement

the pod (R_p) for safety.	

2.4 supporting materials

2.4.1 Circuit Schematics

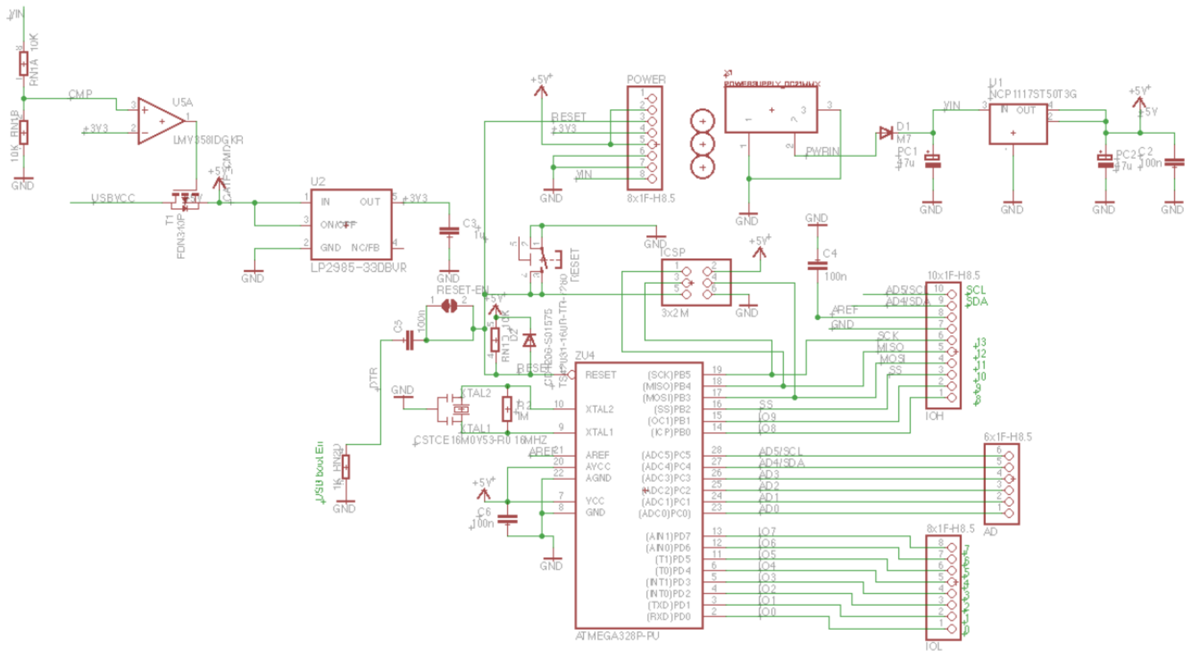

Figure 3： Schematics for Microcontroller Circuit.

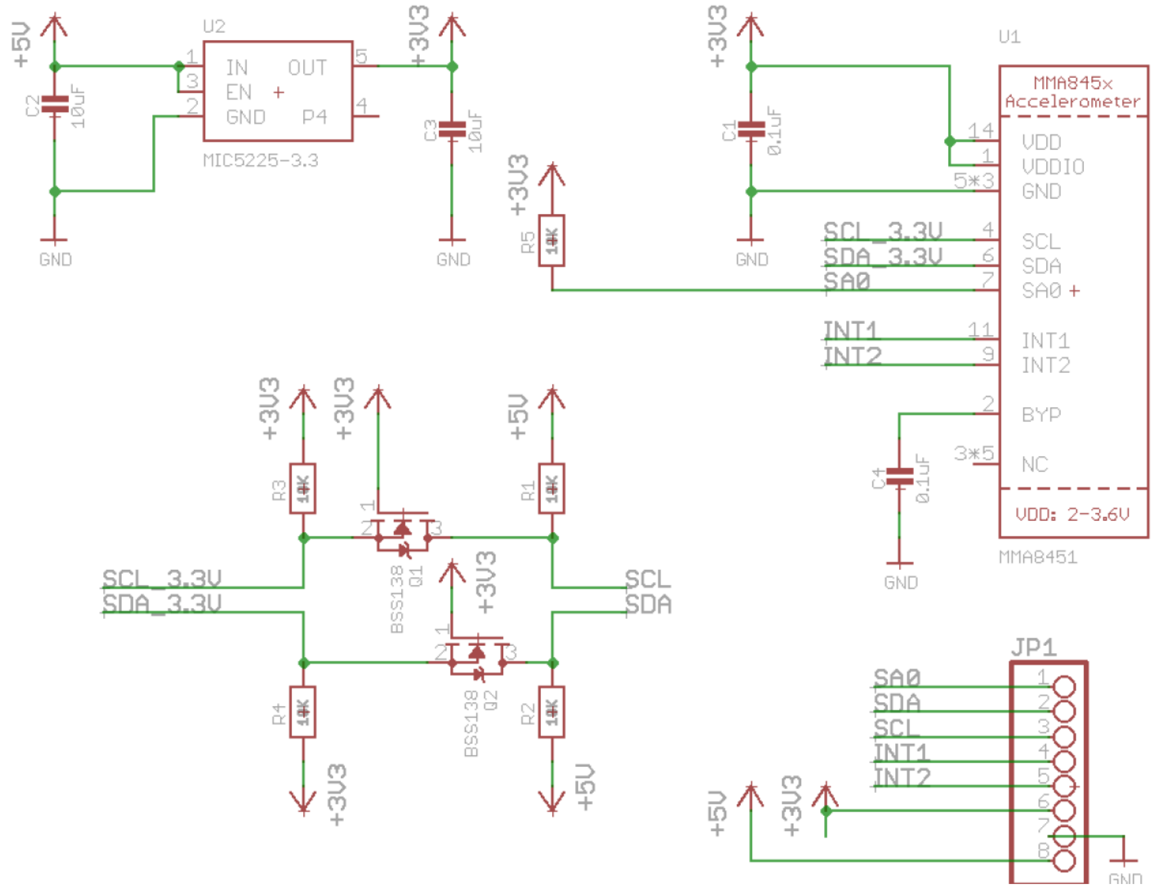

Figure 4: Schematics for IMU

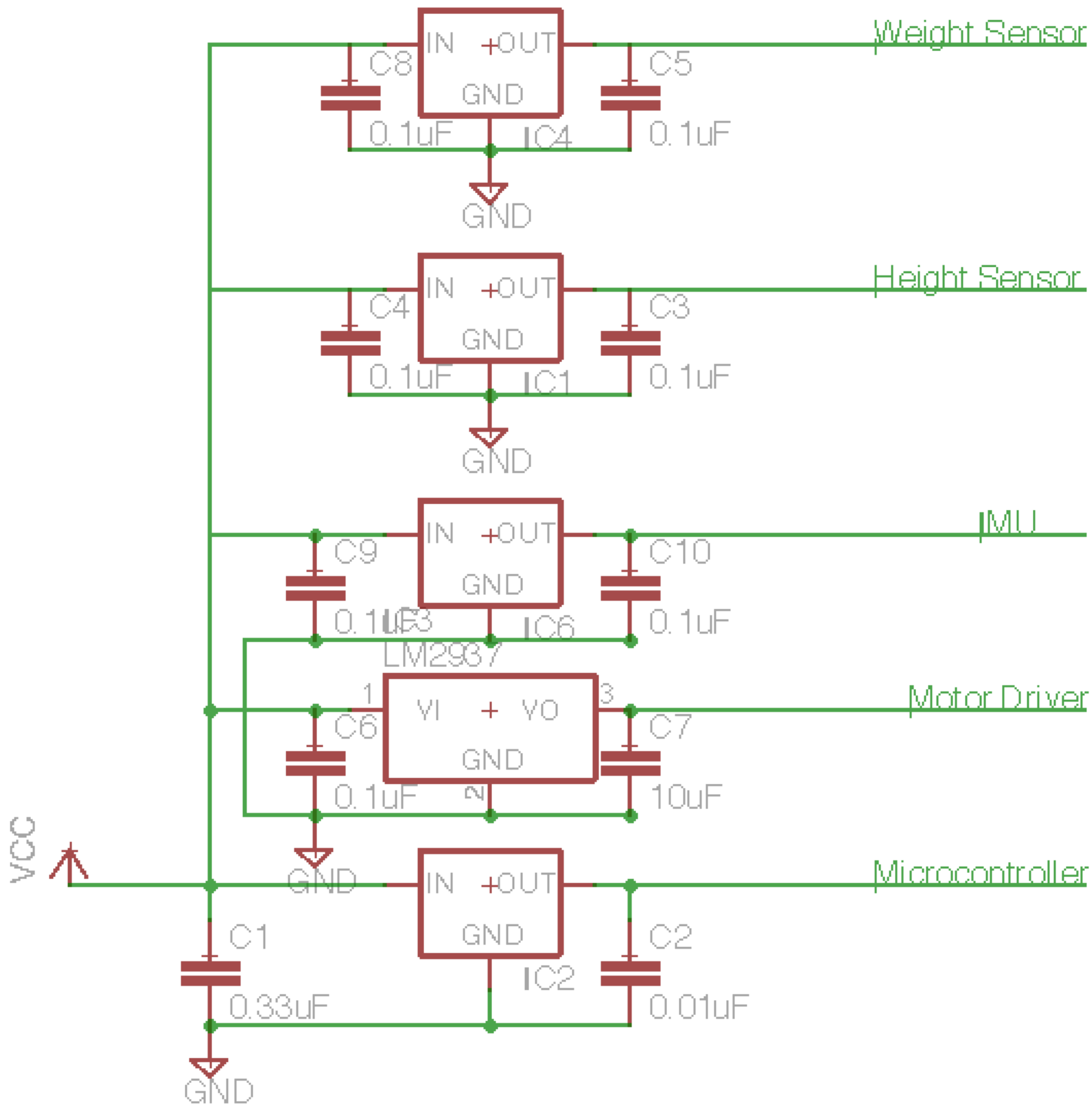

Figure 5: Schematics for Power Module

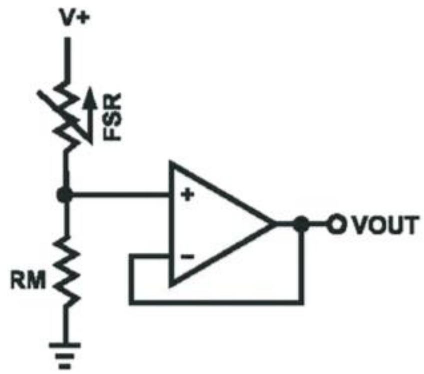

Figure 6:Schematics for pressure Sensor

2.4.2. Mathematics Model

Our PID control system takes pendulum angle θ_p as input, and output the force needed to produce for each propeller in each direction.

Net Torque added onto the system:

$$\Delta\tau = (m_p l_p + 4m_r l_r + m_c l_c) g \sin\theta_p - F_r R_p$$

$$\Delta\tau = -\dot{L}$$

Where L is the angular momentum of the pendulum-propeller system, and can be expressed as follows:

$$L = J\dot{\theta}_p$$

The moment of inertia of the system can be expressed as follows:

$$J = J_c + J_p + 4J_r$$

$$J_c = m_c {l_c}^2$$

$$J_r = m_r {l_r}^2$$

$$J_p = \frac{1}{3} m_p l^2$$

As a result, the feedback control system can be expressed as follows:

$$F_r R_p - (m_p l_p + 4m_r l_r + m_c l_c) g \sin\theta_p = \left(m_c {l_c}^2 + \frac{1}{3} m_p l^2 + 4m_r {l_r}^2\right) \ddot{\theta_p}$$

Using first order approximation for sine function, we get the following control system:

$$\ddot{\theta_p} = -\frac{(m_p l_p + 4m_r l_r + m_c l_c) g}{m_c {l_c}^2 + \frac{1}{3} m_p l^2 + 4m_r {l_r}^2} \theta_p + \frac{F_r R_p}{m_c {l_c}^2 + \frac{1}{3} m_p l^2 + 4m_r {l_r}^2}$$

2.4.3 Requirement Calculation

Requirements for IMU:

Sampling frequency:

The natural frequency ω of our monopod can be calculated as follows:

$$\frac{1}{2} J \omega^2 = (m_p l_p + 4m_r l_r + m_c l_c) g$$

Where J, the total moment of inertia can be calculated as follows:

$$J = m_c {l_c}^2 + \frac{1}{3} m_p l^2 + 4m_r {l_r}^2$$

The natural frequency can be expressed as follows:

$$\omega = \sqrt{\frac{2(1/2 m_p l + 4m_r l_r + m_c l_c) g}{m_c {l_c}^2 + \frac{1}{3} m_p l^2 + 4m_r {l_r}^2}}$$

For the maximum ω, we take $l = l_{min}$, $l_r = l - 0.1m$, and we get $\omega_{max} = 23.9417Hz$

As a result, the sampling frequency of IMU needs to be larger than $\omega_{max} = 24Hz$.

Accuracy

According to our design requirement, we need the monopod to oscillate within +/-5 degrees around balancing position when no disturbance is present. So the minimum accuracy requirement is as follows:

$\Delta a = sin(5^{\circ})\, g = 0.0872\text{g} = 87.2\text{m}g$, where g is the gravitational acceleration.

Requirement for Propeller:

According to our design requirement, the maximum leaning angle of the monopod can be tolerated by the system is $\theta_p = \pm 30^{\circ}$. We can assume that $\ddot{\theta_p} = 0$ when $\theta_{pmax} = 30^{\circ}$, which leads to the following equation:

$$F_{rmax}R_p - (m_p l_p + 4m_r l_r + m_c l_c) g \sin\theta_{pmax} = 0$$

So the maximum force needed for each propeller can be expressed as follows:

$$F_{rmax} = \frac{(m_p l_p + 4m_r l_r + m_c l_c) g}{2R_p}$$

Taking $l_p = \frac{1}{2} l_{max} = 1.0m$, $l_r = l_{max} - 0.1 = 1.9m$, $l_c = l_{max} + 0.1 = 2.1m$, we get the maximum forces needed from each propeller to be $F_{rmax} = 44.3046N$.

2.5 Risk assessment and tolerance evaluation

After evaluating the whole project, we may encounter the following difficulties:

- Math model for the system is fundamental for our project, everything is based on it, and since it is a multi-input and multi-output system, we may use advanced math and physics to solve.
- Microcontroller communication would be difficult if we designed a circuit with large noise and turbulence.
- IMU doesn't have that sensitivity to detect tiny changes in angular velocity and acceleration.

- Soldering a PCB can be tricky since there are many connection ports on microcontroller alone. There are also many small electronic components we need to add on the board. It will be challenging to make sure no connection issue occurs.
- Setting up the feedback loop in the system to achieve self-control is challenging since this is a multi-input and multi-output system. And we need to have state feedback control or observer to achieve that. The accuracy of observer is one of the concerns.

3 Cost & schedule

3.1 Cost

Labor cost

Employee	Hourly rate	Total hours	Total cost
Xin Chen	$50	$150	$7500
Diyu Yang	$50	$150	$7500
Jianan Gao	$50	$150	$7500

Device cost

Device	quantity	Model	Total cost
IMU	1	SparkFun 9 DoF Razor IMU	$2.5
Microcontroller	1	Arduino Uno	$25
Motor	4	Uxcell motor	$4
Propellers	4	Carbon Fiber Propeller for Mini Elec- tric	$16
Battery	2	Duracell Coppertop Bulk	$4
Distance sensor	1	HC-SR04Ultra- sonic Distance	$3
Motor driver	2	L298 Motor Driver Module	$2

Grand total: $22556.5

3.2 Schedule

Week	Task and responsibility
1/16-1/30	Group up and think about ideas
2/6	Diyu is primarily responsible for coming up with math model with reaction wheel. Jianan Gao contact machine shop for component detail and Xin write proposal for our projects.
2/13	Our project has another idea toward our project, we replaced wheel with propeller so Diyu make math model with propeller. Xin write documents for mock design review. Jianan Gao searches components we need and purchases some components
2/6	Our group decided which kind of MCU, IMU and other component detail to use in our project and purchase them and write design review together.
2/20	Diyu programmed the MCU, Xin contacts machine shop for details about propeller protection Jianan Gao get ideas about PCB.
2/27	Jianan Gao and Diyu test the functionality of IMU and PWM. Xin wires up the motors and propellers and test with MCU in whiteboard.
3/6	Diyu build communications between MCU and IMU and PWM. Xin build the system on whiteboard. Jianan Gao build PCB diagrams
3/13	Our group test the basic functionality of our project. Record the problems occurred after testing, think about

	why problems happen. Debug the problems we encountered for all of us.
3/20	Jianan Gao solder PCB and Xin and Diyu test basic functionality of the project.
3/27	Diyu test additional functions such as change height and weight. Xin document and debug problems in testing process. Jianan Gao check circuit and power to debug.
4/3-4/10	Jianan Gao revise PCB if problems still occur. Xin and Diyu provide assistant.
4/17	Mock demo and debug
4/24	Final demo

4. Safety statement & Ethics

1. Our monopod will use 4 propellers to generate torque. So one of the potential danger is that the sharp edges of propellers can damage objects or injure a human if they are close to the propellers. To be consistent with IEEE Code of Ethics #4: "To accept responsibility in making decisions consistent with the safety, health, and welfare of the public." [1] We will eliminate this danger by designing and building a cover for each of the propeller that will protect users get in touch with these propellers.

2. Battery safety should also be taken into consideration. Keep the battery away from fire and teenagers. For prevention, we will put batteries into a battery package to protect users. In addition, we will also store batteries separately with metal or other material.

3. Camera damage could also happen sometime, therefore, I will attach a camera holder using the camera and fix the holder on this monopod carefully.

4. Soldering is dangerous so we will take great care when we are soldering something. Fume extractor will be used at all times during the soldering process to ensure clean air. Clamps will be used to hold the boards and components to prevent burns on the hands. All wires will be trimmed down and insulated with electrical tape to be consistent with IEEE Code of Ethics #4: "To accept responsibility in making decisions consistent with the safety, health, and welfare of the public."

5. To be consistent with IEEE Code of Ethics #4: "IEEE Code of Ethics #4: "To accept responsibility in making decisions consistent with the safety, health, and welfare of the public." We will be honest about our design specification and give precise information about our product to customers.

6. To be consistent with IEEE Code of Ethics #9: "to avoid injuring others, their property, reputation, or employment by false or malicious action." We will set the rule that in our development process; any personnel except the person holding the monopod should keep

away from the monopod at least 5 feet. The person holding the monopod should take precaution.

5. Citations

[1] “Improving fan system performance, a sourcebook for industry”. Apr. 2003

[2] Daniel J. Block, Engineering Teaching Lab Specialist, ECE Illinois

[3] Luke Adam Wendt, Graduate Student, ECE Illinois

[4] "IEEE Code of Ethics." IEEE - IEEE Code of Ethics. N.p., n.d. Web. 08 Feb. 2017. https://www.youtube.com/watch?v=_3szGH4j_5E