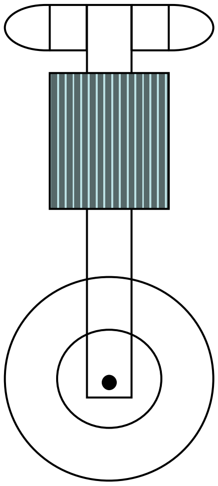
iSTAND – I can Stand

A Self Balancing Platform
to demonstrate the concept of Inverted Pendulum



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For

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Table of Content

1.0 Abstract 3
2.0 Executive Summary 4
3.0 Introduction 5
4.0 Integrated System 6
5.0 Mobile Platform 8
6.0 Actuation 9
7.0 Sensors 10
7.1 Obstacle detection and ranging sensors: 10
7.1.1 SONAR – Ultrasonic Range Finder 10
7.1.2 Infra Red Distance sensors 11
7.1.3 Bump switches 11
7.2 Encoders 11
7.3 Special Sensor to measure Tilt Data – Inertial Reference Sensor 11
7.3.1 Accelerometer and Gyro Sensor 11
8.0 Behaviors 13
9.0 Experimental Layout and Results 14
10.0 Conclusion 15
11.0 Documentation 16
12.0 Appendices 17

1.0 Abstract

iSTAND is a two wheeled self balancing robot. As we know a body cannot normally stand on two wheels. The analysis goes like this - the two point of contact of the body with ground can be seen as a straight line. For a body to remain standing and not tip over the vertical line of gravity passing through the body's CG should pass through it self. Now for a line to intersect another line is always difficult in real time scenario. Any slight displacement of the body may cause the line of CG to miss the straight line formed by the point of contacts with the ground. This will cause it to tilt more and more, so it can never make up and finally falls. Now the challenge in this case is that whenever the line of CG misses the line of contact, we need to do some thing so as to ensure that it comes back to position of stability. For this the robot must move on its two wheels in the direction of the fall. But then how much to move and at what speed should it move is the challenge and the key objective of this project. Some parameters of the system that will come handy and needs to be sensed at any instant are the directions of tilt, tilt angle or the amount of tilt and rate of fall. These data are being sensed in iSTAND using an accelerometer and a gyroscope. On basis of the tilt data, the processor unit takes decisions and commands the motor controller to let the motors move in desired direction by specific amount in a closed loop control system and thus balancing is ensured.

2.0 Executive Summary

iSTAND is a self balancing robot that's stand as well as move on just 2 wheels. This is ensured by the balancing algorithm driven on a ATmega128 microcontroller based on tilt data inputs from a inertial reference sensor made by combining an accelerometer and a gyroscope chip based sensor that directly provide electrical signals proportional to the tilt data. The balancing algorithm uses a PID controller to send control signals to the motor driver in order to move the body in direction of the fall by a particular distance at a particular speed. This will again be reinforced by a closed loop control system that takes feed back from shaft encoders on the motor/wheel.

I aim to build a robust body made up of high torque motors with big sized wheels. The body of the robot will be made tall and efforts will be made to raise the CG as high as possible. To ensure this, I may also need to put heavy metal parts just to shift the CG higher. The Inertial reference sensor and the MCU board will be placed at the top and away from the high current circuitry that includes battery, motor controller and motors. This will ensure least interference onto the sensitive circuitry by the magnetic field produced by the high current circuit and stray voltages that may get induced due to the frequent switching of this current at the motor driver. I am yet to decide the right motor and form the mobile platform. They key area where I need to work on are interfacing the inertial reference sensor and designing the balancing algorithm based on a PID controller to control the motors. iSTAND will also have obstacle avoidance sensors to protect itself from collisions and find path during runs. If time permits, I will also make a mechanism suing which iSTAND will be able to rest safely. Either I will make a mechanism that will make it stand and then make it sleep in horizontal stable condition without human effort or I will make a mechanism that will provide a third support to the system when not trying to do balancing. I am going through the reports on similar robots made by past IMDL students and will ensure to take care of lessons learnt by them from experience and the valuable suggestions given by them.

3.0 Introduction

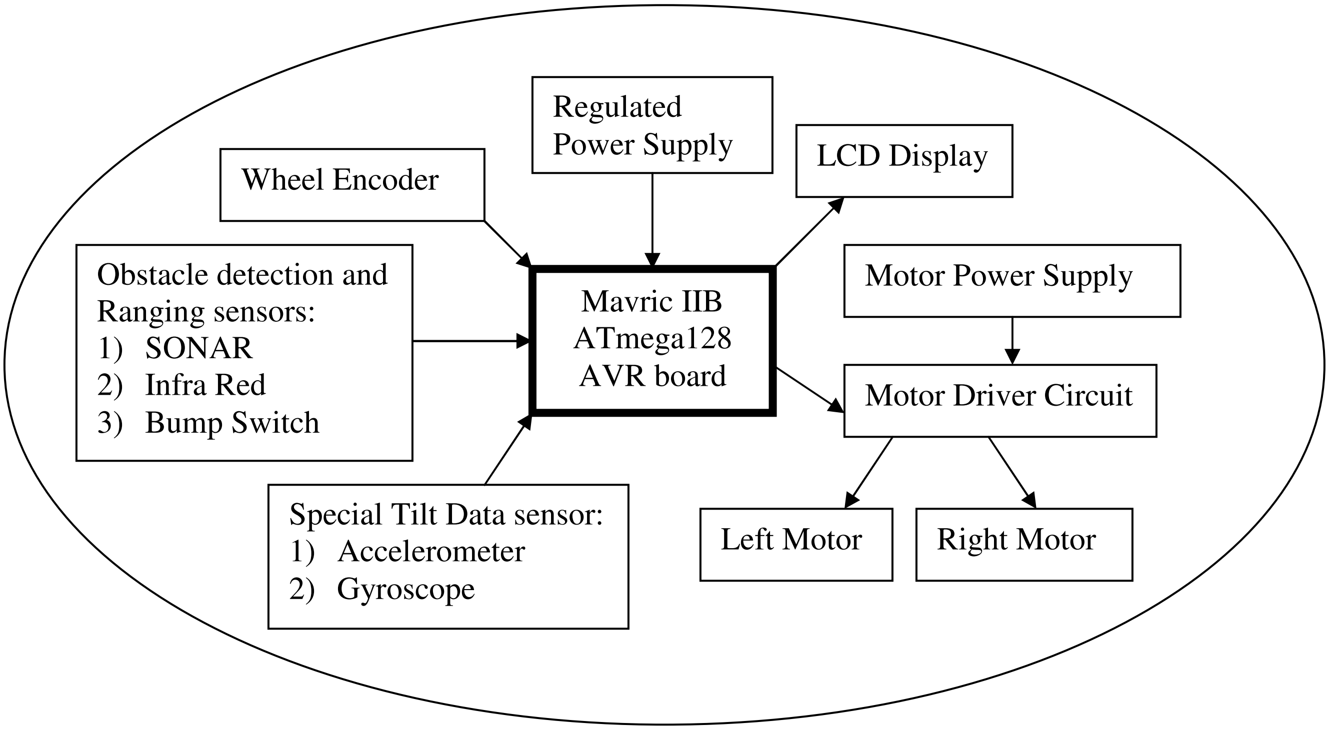
iSTAND is based on the famous control system problem called as the Inverted Pendulum. As the name suggests, this is a case where the major weight (equivalent to the bob of a simple pendulum) is at the top while the pivot is at the bottom. But when the CG goes higher a body becomes unstable and cannot exist in such a state. Thanks to closed loop feedback control system that adds intelligence and actuation systems that adds mobility to such a system and thus prove that an inverted pendulum can me more stable than a normal pendulum that's is considered to be in stable equilibrium.

This concept has been with us for ever, this is the very concept which the human body uses to stand erect. This concept and the control system have been very widely in use to maintain stability. A simple application is the Pole Balancing robot which has a cart that can translate in 1-D and has a long rod/inverted pendulum mounted on it via a hinge. This cart moves forward or backward to ensure that the inverted pendulum on it remains erect/vertical. In such a case, the cart remains horizontal and hence used as a frame of reference to measure the tilt angle of the pole wrt vertical with simple linear angular sensors like Potentiometers or optical encoders. The case of a 2 wheeled self balancing robot is an advanced version of the above. Here the pivot of the inverted pendulum is the axis of the wheels and so, the measurement of tilt angle becomes difficult. There are different ways to measure the tilt angle like using IR/Sonar sensors to measure the distance from the floor on both sides and using a simple pendulum inside the body. But the best and most universal way to measure the tilt angle irrespective of the working environment is to use inertial reference sensors. An inertial reference sensor comprises of an accelerometer and a gyroscope. Both of them being mechanical devices used to be inaccurate but with the advent of MEMS technology, light weight and small solid state IC based versions of accelerometer and a gyroscope came into existence. This proves to be the best possible way to measure the attitude (tilt angle and rate of fall) of an inverted pendulum.

The actuation system that can move the robot body forward or backward to avoid a fall also needs to be accurate in order to solve this complex problem. For this the concept of PID controller along with feedback from the shaft encoders will be utilized to provide appropriate signal to the actuation system in iSTAND. The following report will cover details about the design, algorithm, steps/precautions taken and the implementation of the iSTAND.

4.0 Integrated System

The iSTAND system can be outlined by the block diagram below.

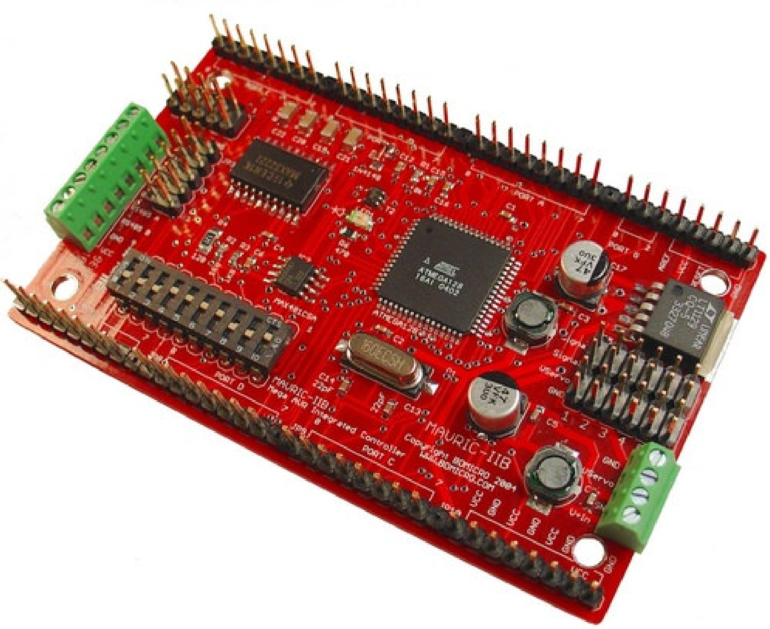


The Input devices form as the window of the system to the external world. The SONAR and IR sensors will combine to provide data about presence and position of obstacles around the robot system. In case these two sensors fail, the bump switches will be the last line of defense to detect any obstacle lying very near and touching the robot body. The wheel encoders will provide input about the angular displacement and the rotational speed of the wheels. While the Special sensor formed by combination of solid-state chip-based Accelerometer and Gyroscope will provide the data about the tilt angle with respect to vertical and the speed at which the body is falling/tilting in one direction.

The output devices are the mode through which the robot does actions that can be felt by the external world. The LCD display will be used to display Tilt Data and Wheel Speed, they can be used to keep an eye on various parameters of the system while testing and debugging. The Motor Driver will be commanded to drive the motors in desired direction and to switch the required amount of current from the Motor Power supply to the Motors.

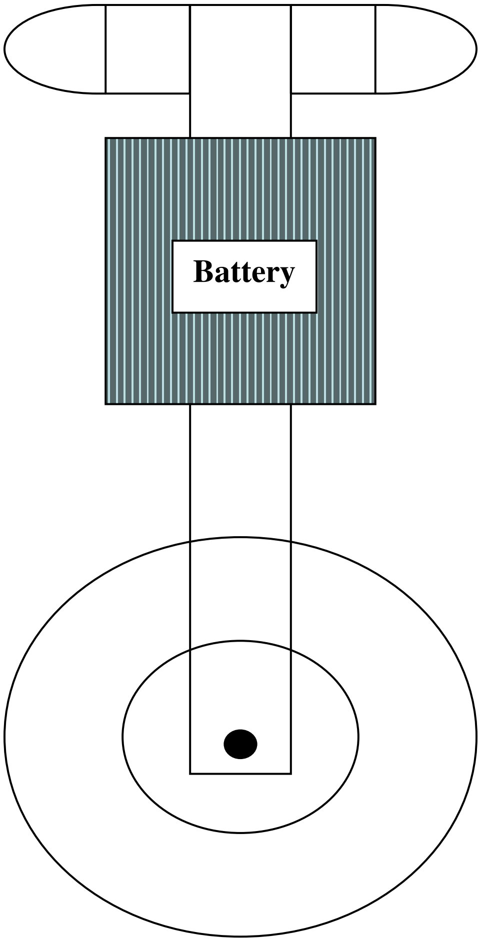
The Brain of the iSTAND will be formed by the MAVRIC IIB board which holds the ATMEL ATmega128 MCU. It has a built in crystal clock with frequency of 14.7456 Mhz which is fast enough to provide quick response needed by iSTAND to keep itself balanced. The MCU is fully programmable using familiar languages such as C and BASIC will hold the balancing algorithm that will keep monitoring the input data sent by the sensors and send drive signals to the motor controller when needed as well as send data to be displayed on the LCD.

Various features of the brain board are as follows.



- PWM generator (In built on the MCU)
- AD converter (In built on the MCU)
- 128K Program FLASH
- 4K Static RAM, 4K EEPROM
- dual level shifted UARTs
- RS485 on-board
- 6 R/C Servo Headers
- I2C ready w/pull-up resistors installed
- up to 51 digital I/O pins
- Selectable clock frequency of 16 MHz or 14.7456 MHz (select at order time)
- Advanced, low drop-out voltage regulator on-board accepts 5.5-15V input with reverse polarity hookup protection
- It can be programmed using an ISP or JTAG programmer.

5.0 Mobile Platform



The mobile platform will be made symmetrical so that it can be easily balanced. It will have two big wheels driven by two bidirectional geared DC motors. The Encoder will be fitted directly onto outer end of the wheel axis. It will have two castor balls one on each side to form the third support needed when it's left resting on the ground. Using this architecture it can even perform in horizontal position with any of the sides facing the ground.

Since one of the key point that helps in balancing is that the CG should be as high as possible so the battery system will be mounted as high as possible on the robot body. Long threaded rods will be used to make the robot tall and move the CG high and at the same time provided rigid structure which doesn't sway or bend while the robot tries to balance itself. This can be felt by comparing the difficulty in balancing a base ball bat about its handle and about the heavy rounded end, it's always easier to balance using the lighter end below. This is simply because the heavier end with higher inertia takes more time to move and fall. While the lower end with lesser inertia can always move faster and try to reach a position in lesser time such that the line of CG remains between the two wheels.

I am yet to do more study on the concept of Inverted Pendulum and control system parameters and equations that need to be analyzed to ensure best possible design to attain stability.

6.0 Actuation

I have not finalized the motors for the actuation system. I plan to buy DC bidirectional geared motors with inbuilt encoders on the back side of the motor. As observed from the conclusions made by past IMDL students, I will go for metal gears so that they do not get damaged and slip due to repeated and frequent forward and backward motion of the motor. I am yet to research and decide over the torque, rpm, dimensions and current rating of the motor that will best server my purpose. I am yet to finalize the H bridge circuit that will be used to drive and control the motors.

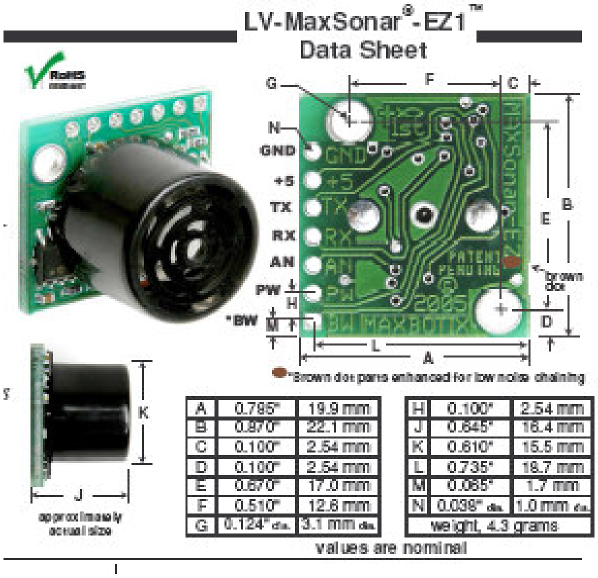
7.0 Sensors

Sensors are the Input devices that form the window of the system to the external world.

7.1 Obstacle detection and ranging sensors:

7.1.1 SONAR – Ultrasonic Range Finder

I plan to use the MAXBOTICS LV-MaxSonar- EZ1 which uses only one Ultrasonic transducer compared to other competitive SONAR Sensors like the Devantech SRF05 and the Parallax PING. Hence the board size is smaller and power consumption is lesser.



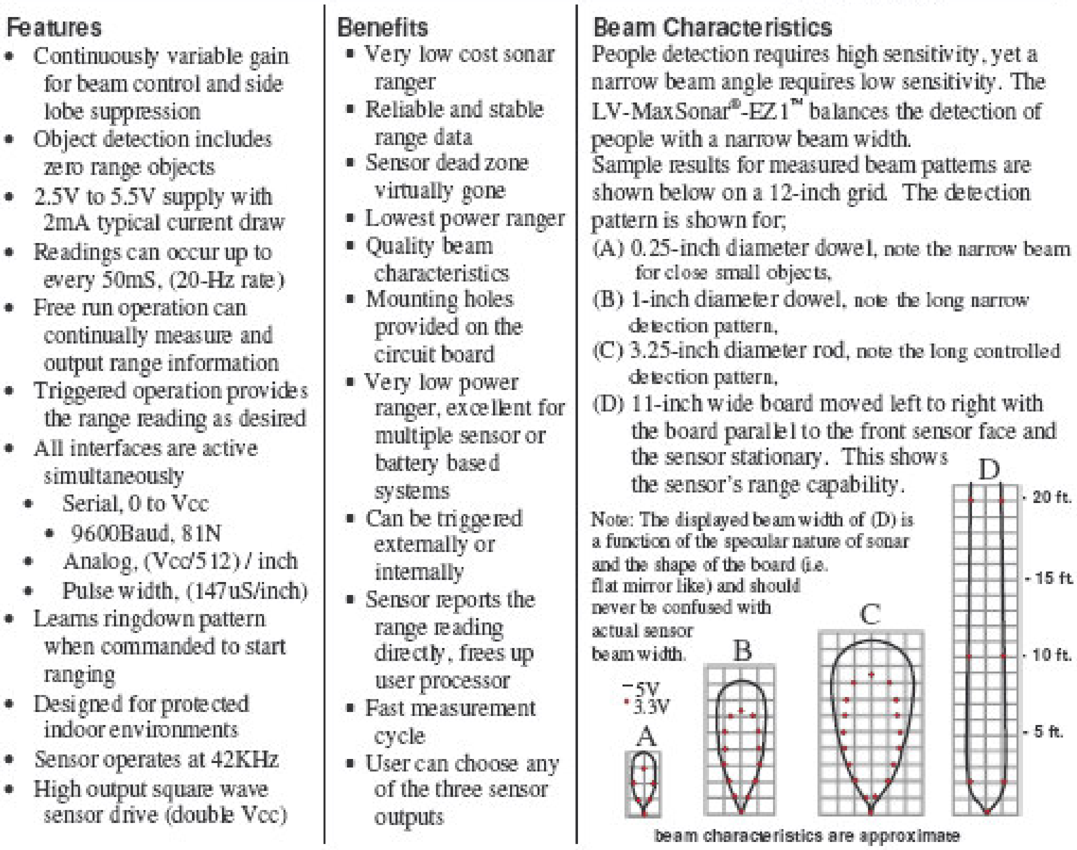
LV-MaxSonar®-EZ1™
Data Sheet

*Brown dot pans enhanced for low noise chaining

A	0.785"	19.9 mm
B	0.870"	22.1 mm
C	0.100"	2.54 mm
D	0.100"	2.54 mm
E	0.670"	17.0 mm
F	0.510"	12.6 mm
G	0.124" dia.	3.1 mm dia.

H	0.100"	2.54 mm
J	0.645"	16.4 mm
K	0.610"	15.5 mm
L	0.735"	18.7 mm
M	0.065"	1.7 mm
N	0.039" dia.	1.0 mm dia.
weight, 4.3 grams		

values are nominal



Features

- Continuously variable gain for beam control and side lobe suppression
- Object detection includes zero range objects
- 2.5V to 5.5V supply with 2mA typical current draw
- Readings can occur up to every 50mS, (20-Hz rate)
- Free run operation can continually measure and output range information
- Triggered operation provides the range reading as desired
- All interfaces are active simultaneously
  - Serial, 0 to Vcc
    - 9600Baud, 81N
  - Analog, (Vcc/512) / inch
  - Pulse width, (147uS/inch)
- Learns ringdown pattern when commanded to start ranging
- Designed for protected indoor environments
- Sensor operates at 42KHz
- High output square wave sensor drive (double Vcc)

Benefits

- Very low cost sonar ranger
- Reliable and stable range data
- Sensor dead zone virtually gone
- Lowest power ranger
- Quality beam characteristics
- Mounting holes provided on the circuit board
- Very low power ranger, excellent for multiple sensor or battery based systems
- Can be triggered externally or internally
- Sensor reports the range reading directly, frees up user processor
- Fast measurement cycle
- User can choose any of the three sensor outputs

Beam Characteristics

People detection requires high sensitivity, yet a narrow beam angle requires low sensitivity. The LV-MaxSonar®-EZ1™ balances the detection of people with a narrow beam width.
Sample results for measured beam patterns are shown below on a 12-inch grid. The detection pattern is shown for;
(A) 0.25-inch diameter dowel, note the narrow beam for close small objects,
(B) 1-inch diameter dowel, note the long narrow detection pattern,
(C) 3.25-inch diameter rod, note the long controlled detection pattern,
(D) 11-inch wide board moved left to right with the board parallel to the front sensor face and the sensor stationary. This shows the sensor's range capability.

Note: The displayed beam width of (D) is a function of the specular nature of sonar and the shape of the board (i.e. flat mirror like) and should never be confused with actual sensor beam width.

beam characteristics are approximate

7.1.2 Infra Red Distance sensors

Since the combination of SONAR and IR proves to be best for Obstacle avoidance as each makes up for the others draw backs in operating environment, distance of obstacle and accuracy of readings, I aim to put suitable IR LEDs modulated at 40Khz and compatible IR sensors.

7.1.3 Bump switches

In case the above mentioned two sensors fail, the bump switches will be the last line of defense to detect any obstacle lying very near and touching the robot body and make the motor stop else it may cause the current through the motor to go very high and cause damage to motor, circuitry and battery.

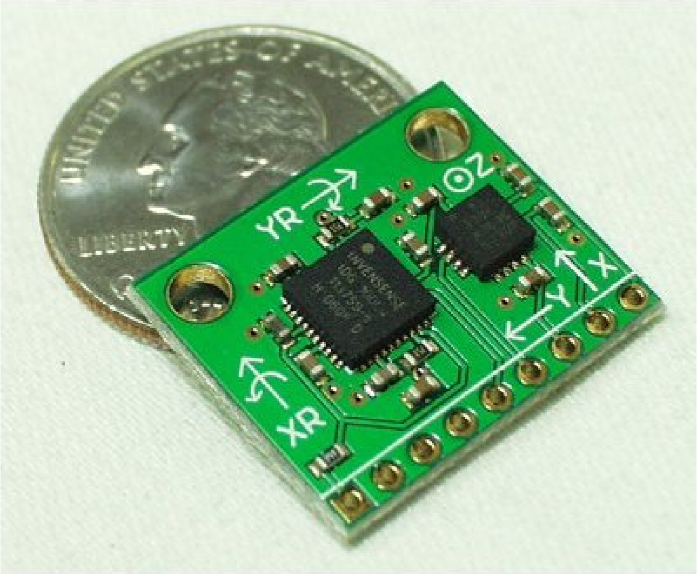
7.2 Encoders

This will be attached to the motor or to the wheel in order to measure the angular displacement and the rpm of the motor/wheel. This data will be used as a feed back to the control system used to achieve balancing.

7.3 Special Sensor to measure Tilt Data – Inertial Reference Sensor

7.3.1 Accelerometer and Gyro Sensor

I am yet to do more study on how they work and how I can interface them to the MCU to get stable accurate tilt data. I aim to use the The Inertia Measurement Unit Combo Board with 5 DOF from Spark Fun Electronics that is a small PCB board incorporating the new IDG300 dual-axis gyroscope and Analog Devices triple axis accelerometer that allows 5 axis of sensing (Roll, Pitch, X, Y, Z) in less than 1 square inch and under 2 grams.



The accelerometer is a device that measures static and dynamic acceleration of gravity with respect to the Earth. Using the static acceleration measurements, the accelerometer can provide an excellent measurement of the platform tilt angle. Unfortunately, there is an undesired result with the dynamic acceleration measurements. If the platform were to be to accelerate towards the ground (e.g. falling), the increase in acceleration appears at the accelerometer output (after all, this is what it is supposed to do!). Because of this, using the accelerometer alone as a tilt sensor is only effective if the platform is not accelerating. In addition, any vibrations that the motors create within the platform are also picked up by the accelerometer. These vibrations tremendously decrease your output resolution since a few of the bits will be lost due to noise. To remedy this problem, another sensor is needed.

A gyroscope is a device that measures angular rate/velocity. If the output of the gyro is integrated, the position of the platform can be determined. Ideally, the gyro can be used as a tilt sensor but there is an error introduced. Gyroscopes tend to drift over time and therefore report inaccurate information and the running integration of the output also introduces small errors. However, if the accelerometer and gyro were combined using a complementary filter, they would be able to help each other. The accelerometer would correct the drift of the gyro when the platform was not falling.

8.0 Behaviors

It will have the two most important behaviors of Static Balancing (stands upright in one place) and Dynamic Balancing (Stays upright while moving on flat and inclined terrain). It will also keep track of obstacle around it and will not only avoid bumping into them but also change its path. If time permits, I will make a mechanism with which it can stand up from horizontal condition on its own.