Inverted Pendulum BalanceBot

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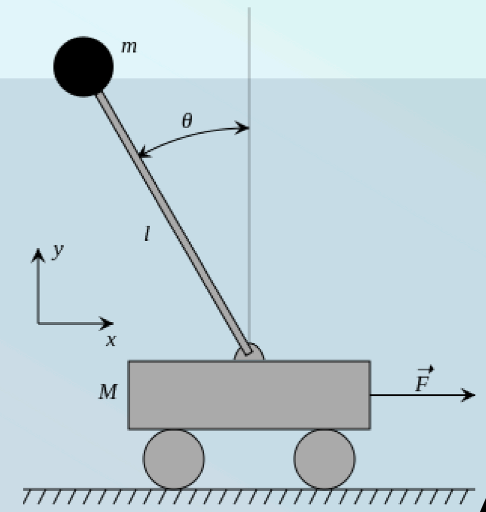
CHALLENGE

The goal is to build a robot that can self-balance on a single set of wheels. It should be able to withstand any outside forces and balance itself out while maintaining its original position. Furthermore, the robot should be able to balance a load of roughly 2kg, and continue to maintain balance. Finally, the robot will be paired with a receiver and transmitter allowing the user to operate the robot remotely.

BACKROUND & THEORY

The inverted pendulum is a dynamically unstable system. Assuming the angle is small, the system can be modeled by the second-order differential equation below:

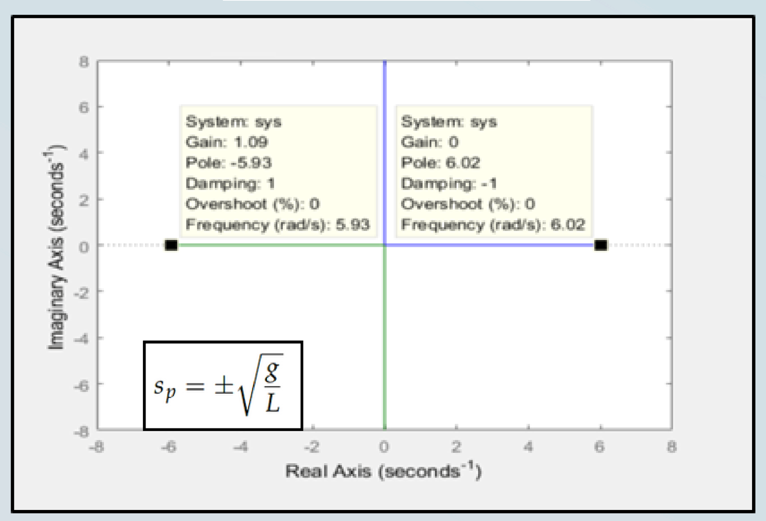
$$L\frac{d^2\theta(t)}{dt^2} = g\sin[\theta(t)] - a(t)\cos[\theta(t)] + Lx(t) \longrightarrow L\frac{d^2\theta(t)}{dt^2} = g\theta(t) + Lx(t)$$



Solving the differential equation using Laplace Transform, we see a pole located on the positive real axis - rendering the system unstable.

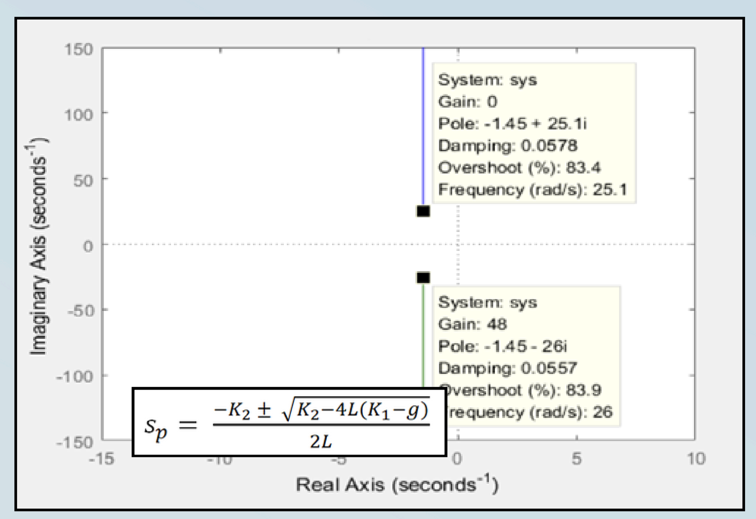
$$H(s) = \frac{\theta(s)}{X(s)} = \frac{1}{s^2 - \frac{g}{L}}$$

$$H(s) = \frac{\theta(s)}{X(s)} = L\left(\frac{\left(\frac{1}{Ls^2-g}\right)}{1+\left(\frac{1}{Ls^2-g}\right)\left(\frac{K_1+K_2 s}{1}\right)}\right) = \frac{1}{s^2+\left(\frac{K_2}{L}\right)s+\left(\frac{K_1-g}{L}\right)}$$

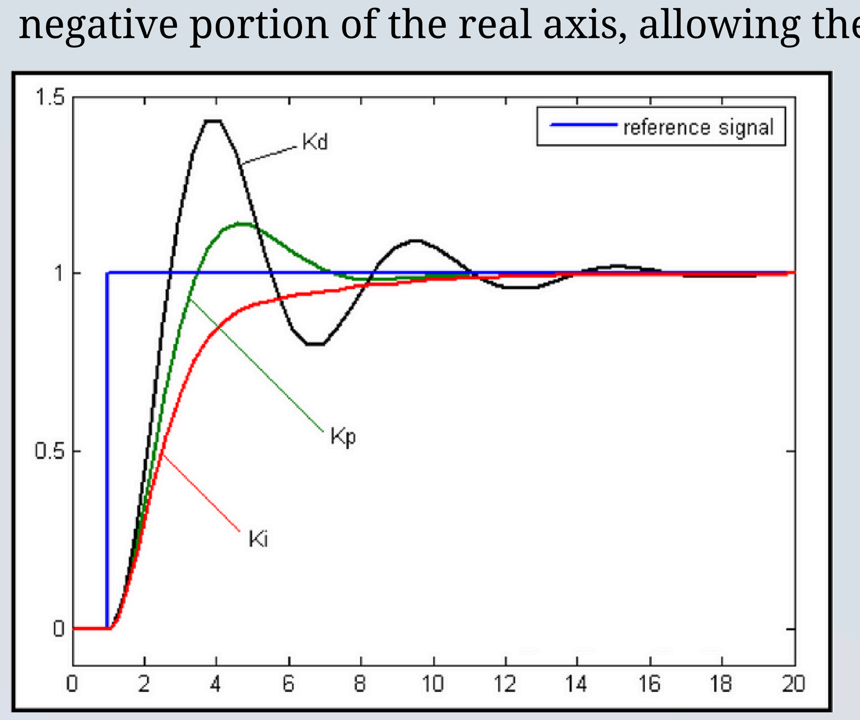


+ Negative Feedback

$(K_1 + K_2 s)$

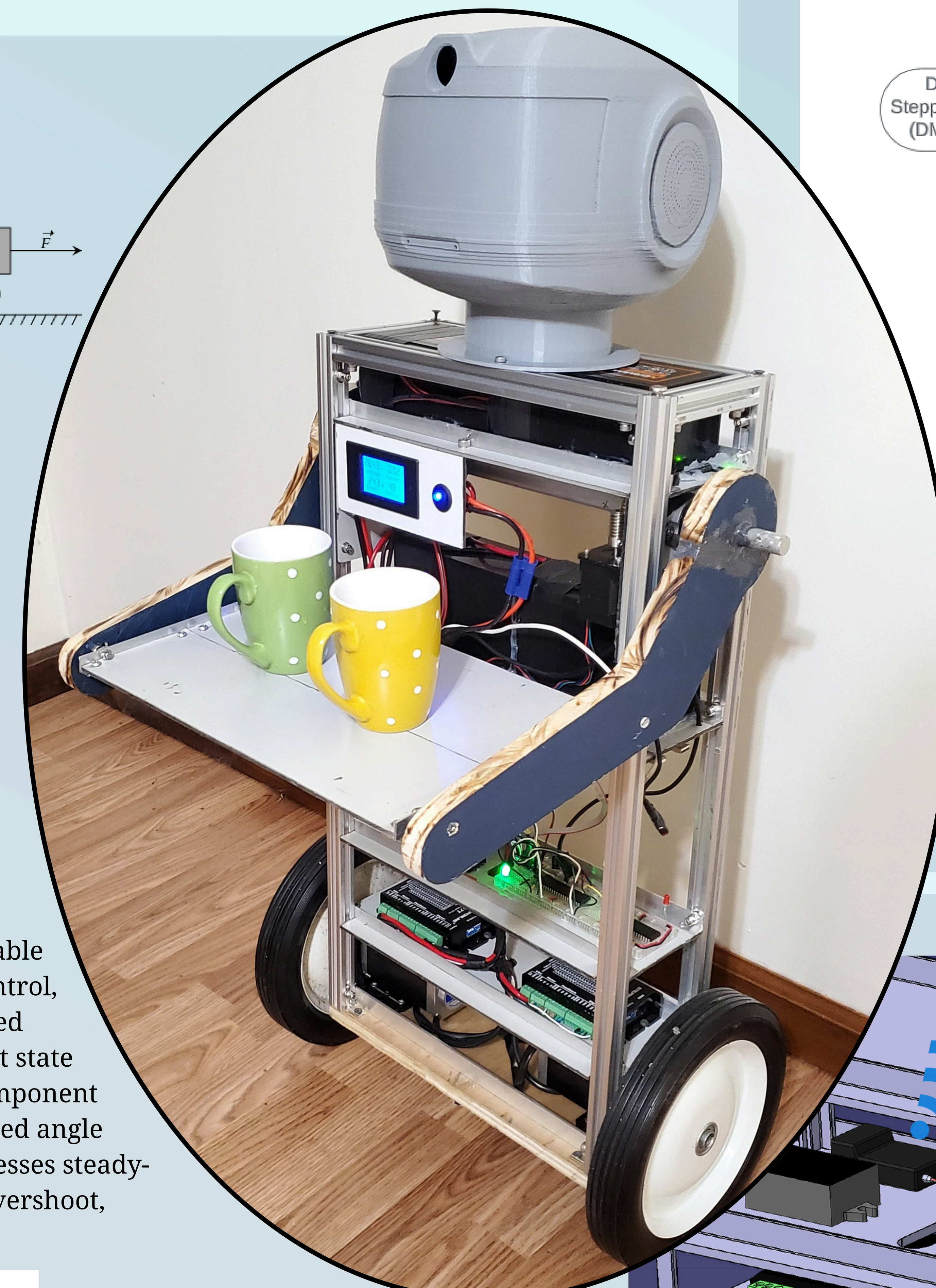


To solve the unstable system, negative feedback was introduced into the original transform function in the form of a proportional and integral gain. As the second plot shows, the poles are on the negative portion of the real axis, allowing the system to stabilize.

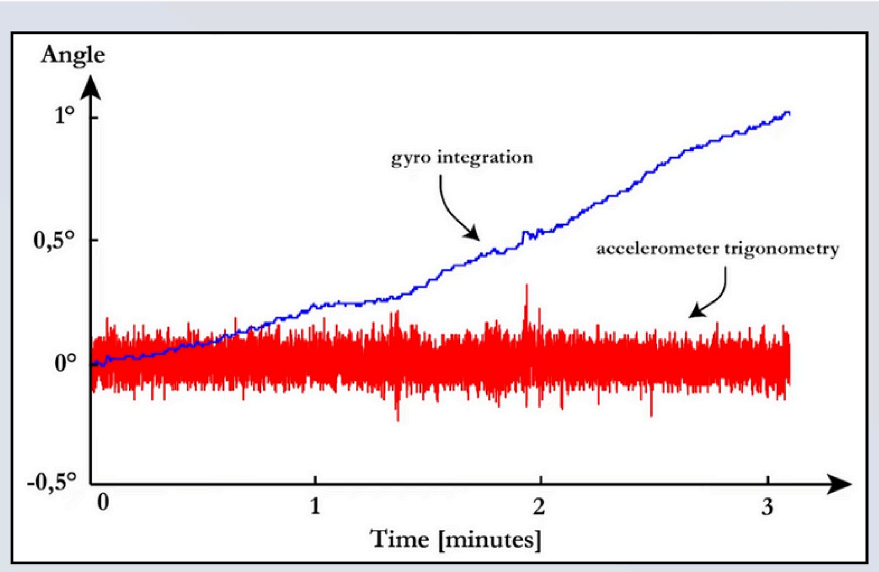


In general, negative feedback can be introduced to an unstable system in the form of a proportional-integral-derivative control, or PID control. PID continuously adjusts output based on the difference between the desired state and the current state of the system, the "error". In PID, the proportional (Kp) component responds to the current error (difference between the desired angle and the measured angle), the integral (Ki) component addresses steady-state errors, and the derivative (Kd) component counters overshoot, reducing rapid changes in response to sudden errors.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt}e(t)$$

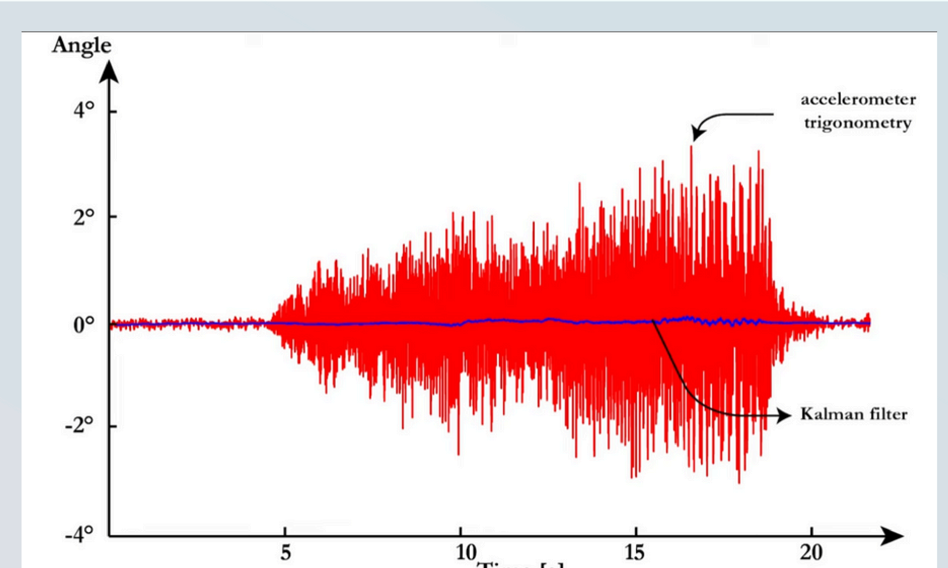


Sensors & Filters



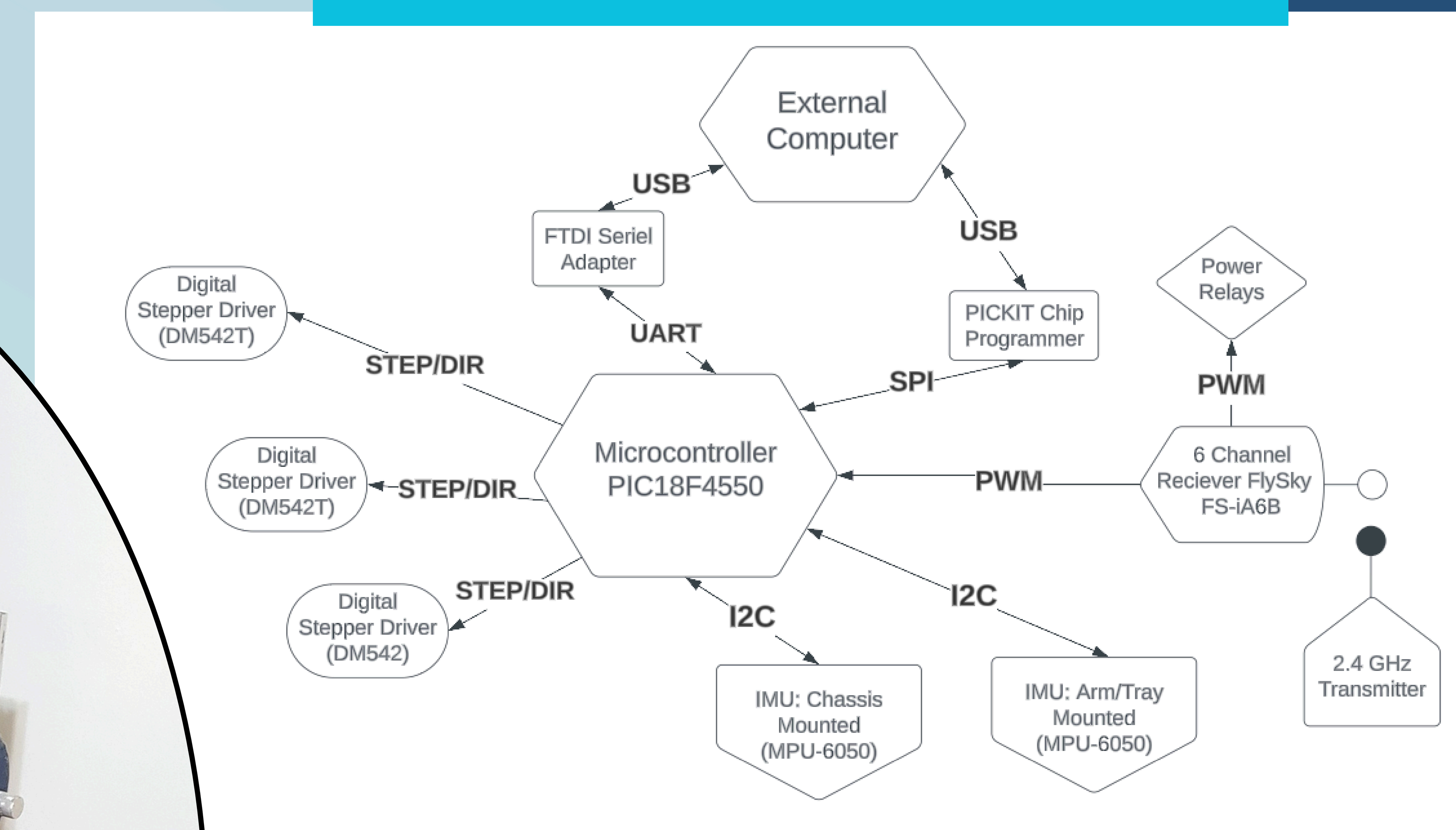
The plot shows the resulting angle measurement from the gyro in "blue", and the angle measurement calculated using the acceleration in "red"

When integrating the gyroscope from the MPU6050 to calculate the angle, we find that the angle measurement drifts over time which is not ideal, By using trigonometry, we can calculate the angle using the XYZ accelerations. This resulting angle measure does not drift, but is extremely noisy. We can combine the two measurements using a Kalman Filter to achieve more consistent and accurate angle measurements without any side effects of the individual sensors.

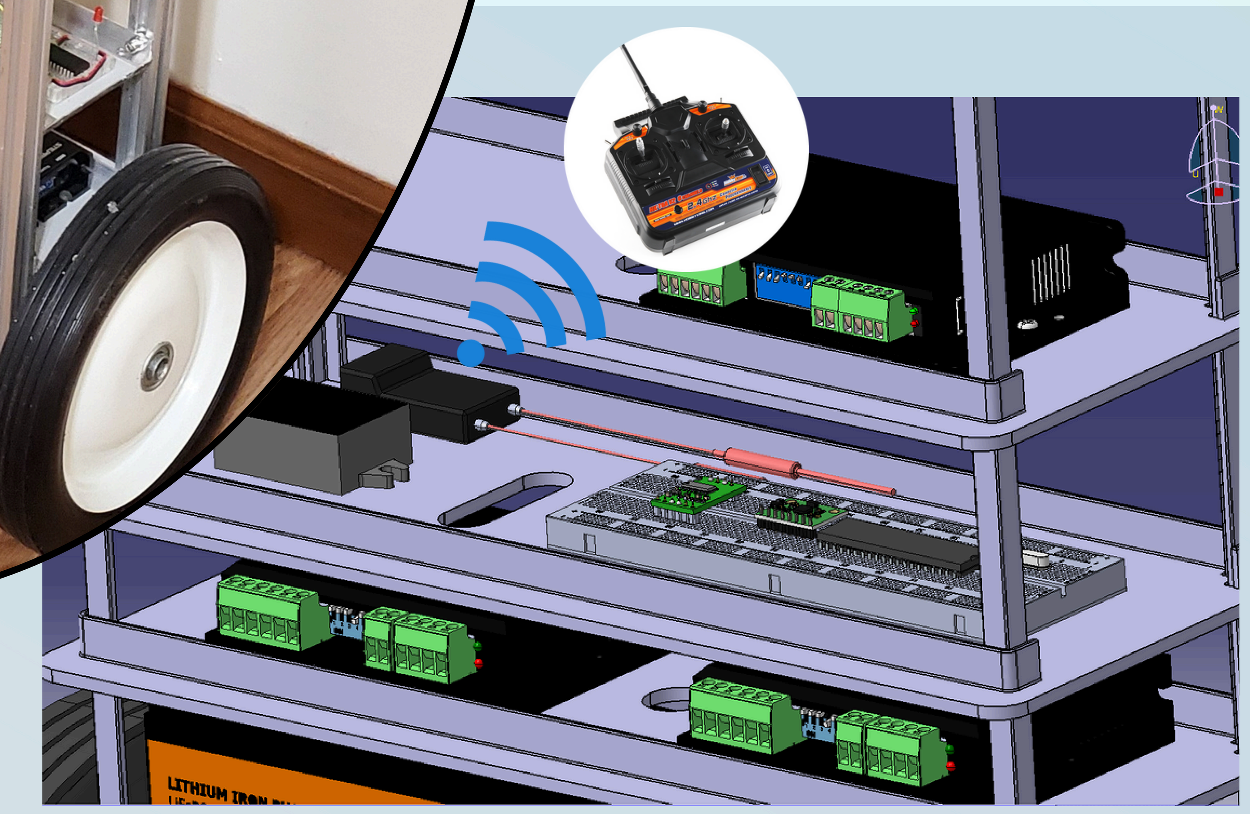


The plot shows the resulting angle measurment after passing through the Kalman Filter

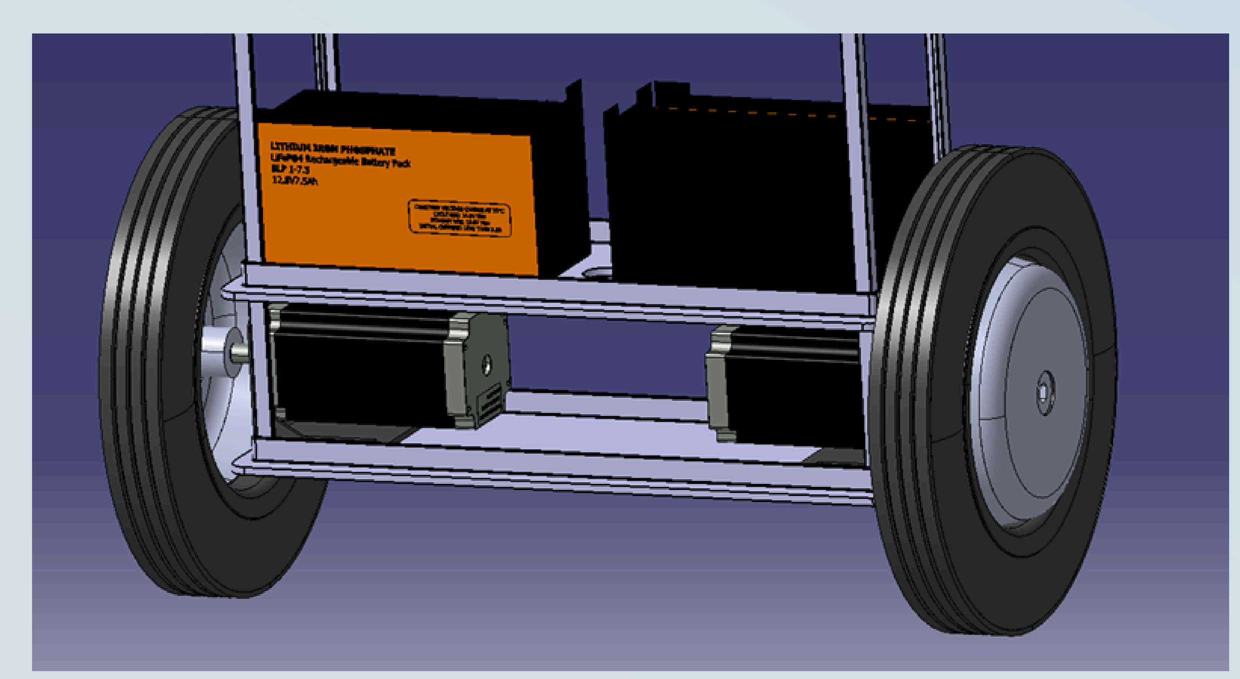
HARDWARE COMMUNICATION



The diagram above depicts various processes and components and how they communicate with each other. The central hub for communication is the Microcontroller which receives sensory data from the IMU, FTDI serial adapter, and receiver. The microcontroller processes the data and outputs pulses of varying frequencies to the stepper motor drivers which power the coils/phase of the corresponding stepper motor, thus stepping the motor. The communication protocols between the microcontroller and peripheral is typically I2C, PWM, or SPI.



ELECTRONICS



- The brain of the robot is a PIC18F4550 Microcontroller. It has 35 I/O Pins and operates at 8MHz. It also can communicate using the I2C Protocol and UART.
- The MPU6050 will act as the inertial measurement unit (IMU), providing a 3-axis gyroscope and a 3-axis accelerometer in a single chip. The device communicates via I2C with a transmission rate of 400KBps
- The FS-iA6B Receiver communicates with any supporting 2.4Ghz transmitter. The receiver outputs 6 channels using PWM.
- 10Amp relays are used to remotely control power to the robot using PWM from the receiver
- The robot is powered by two 12v LIFEPO4 batteries, wired in series that provide a 24Volt supply. They are rated at 13A continuous discharge current with a capacity of 10AH
- 24v Buck Converter steps the voltage down to 5v for low voltage modules like sensors and MCU.
- A Nema17 Stepper Motor with a worm gear controls the pitch of the arms.
- Two Nema23 stepper motors control the left and right wheels.
- Stepper motor drivers rated at 24v and 4.5A RMS