Bridge Inspection Robot

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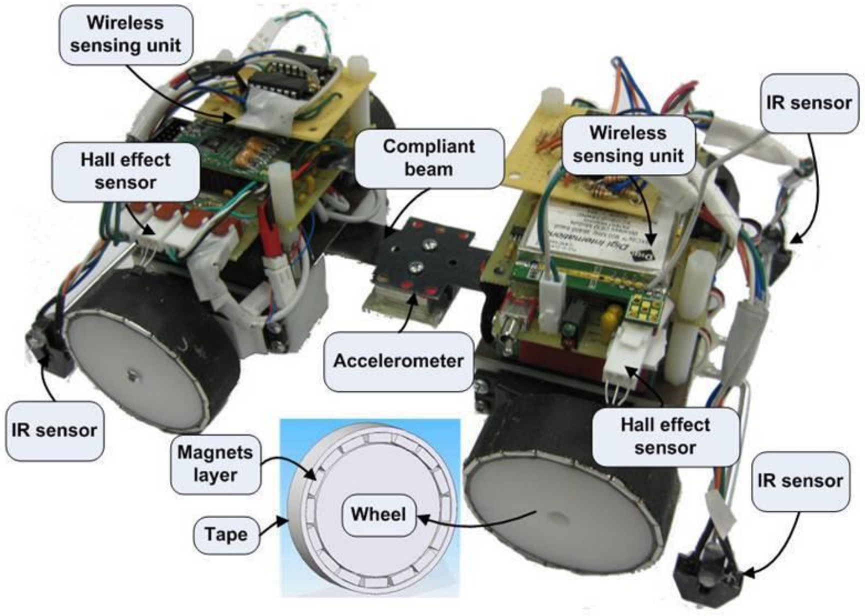
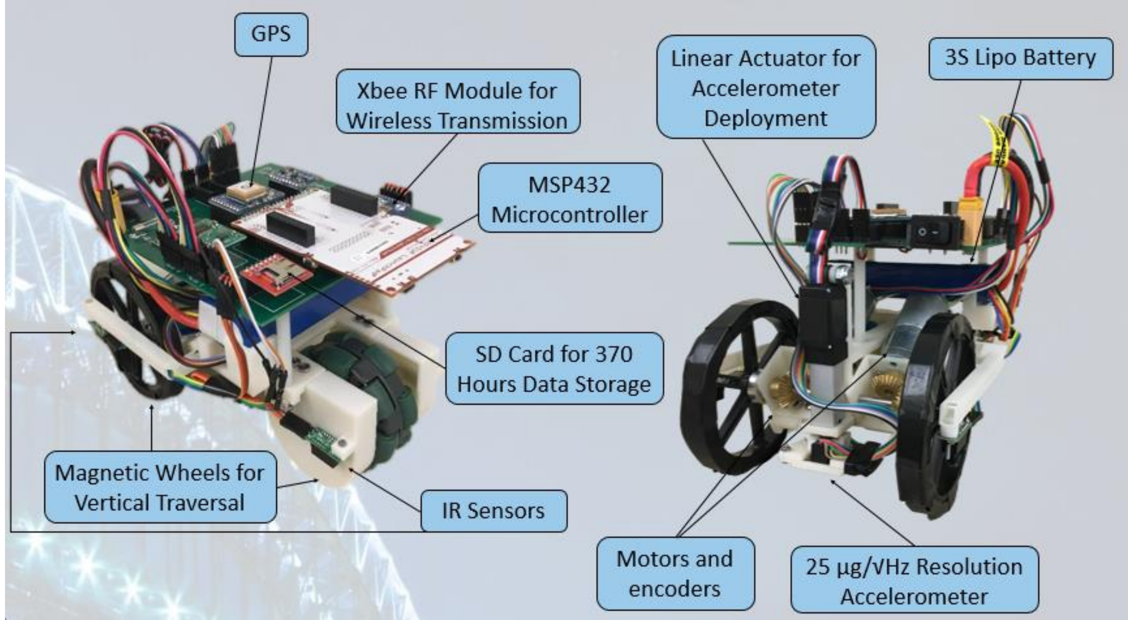
Introduction

- The team designed a wireless sensing robot for structural health monitoring of steel structures
- Replaced the old flexure-based, four-wheeled robot with a design that features upgraded electrical and mechanical components along with increased mobility

Previous Design by Dr. Wang's Team



Current Design



Problem Background

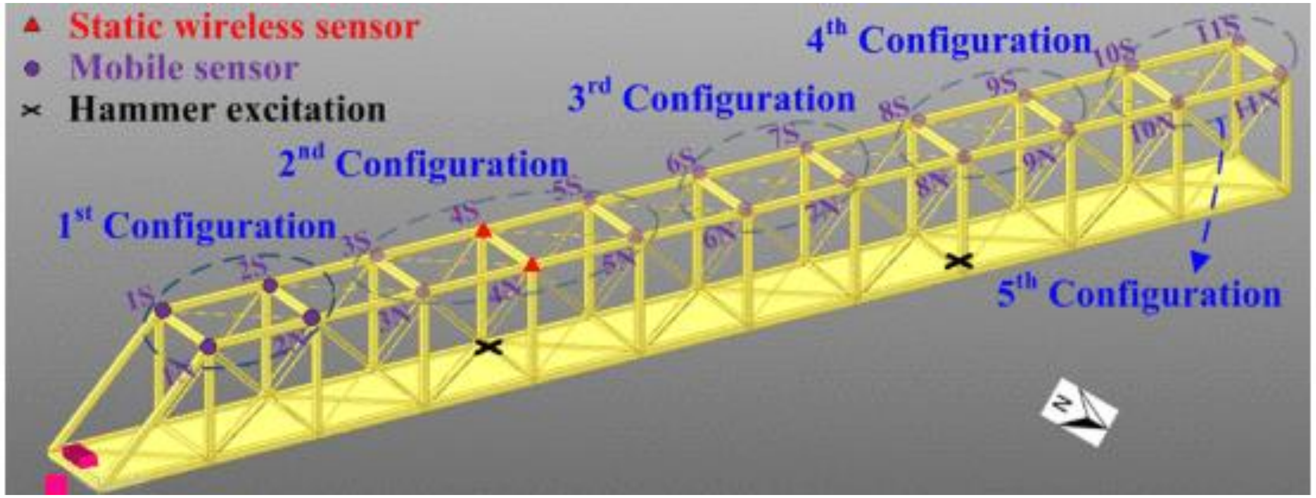
- The repair and maintenance of civil infrastructure systems is a constant challenge
    - 50+% of U.S. bridges built before 1940's
    - **1 in 9 structurally deficient**
    - Maintenance costs **~$20.5 billion annually**; only $12.8 billion available
    - American Society of Civil Engineers (ASCE) gave C+ grade for bridge infrastructure in 2017 Report Card on America's Infrastructure
- Visual inspection subjective and leaves damage below surface undetectable

Solution: Structural Health Monitoring (SHM) System

- Utilizes accelerometer and other sensor data
- Current Solutions - Stationary sensors
  - Cons
    - Cable installation between sensors is high cost
    - Hard and time consuming to place and maintain
    - A lot of sensors needed
  - Resensys Senspot Sensors
    - For average-sized highway bridge, would need ~500 sensors * $20 = $10,000, not including installation costs
    - Human installation required roughly every 20 years

New Solution: Network of Wireless, Sensing Robots

- Network of robots capable of synchronized, autonomous traversal and structural health measurement
- Benefits
  - Only small number of robots needed to cover whole bridge
  - Low-cost and no installation
- Challenges
  - No similar existing solution
  - Drastically more complex



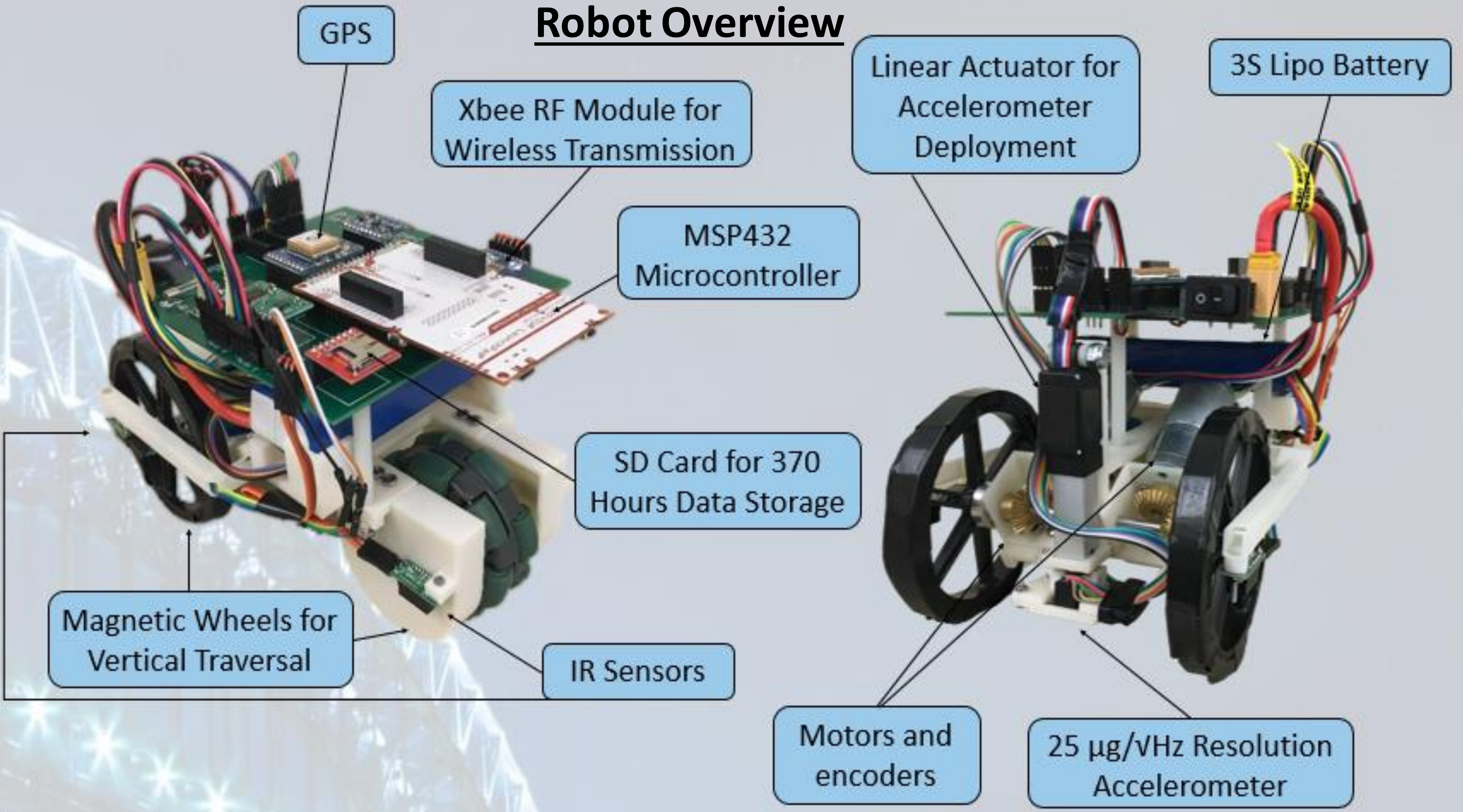
Goals

- Design and build one robot to compose the new network
- The robot must be able to do the following:
    - Horizontally and vertically traverse steel bridges
    - Measure bridge vibrations at low frequencies
    - Wirelessly transmit vibration data to a PC
    - Lightweight for deployment and retrieval by drone

Outline

- Robot Overview
- Mobility Design
    - Motor Choice and Implementation
    - Magnets
- Accelerometer Measurements
    - Accelerometer Choice
    - Data Filtering
    - Accelerometer Deployment
- Motion Tracking
- Microcontroller
- Wireless Data Transmission
- Power
- Robot Structure
- Verification
- Final Demonstration Results

Robot Overview



GPS

Xbee RF Module for Wireless Transmission

MSP432 Microcontroller

SD Card for 370 Hours Data Storage

Magnetic Wheels for Vertical Traversal

IR Sensors

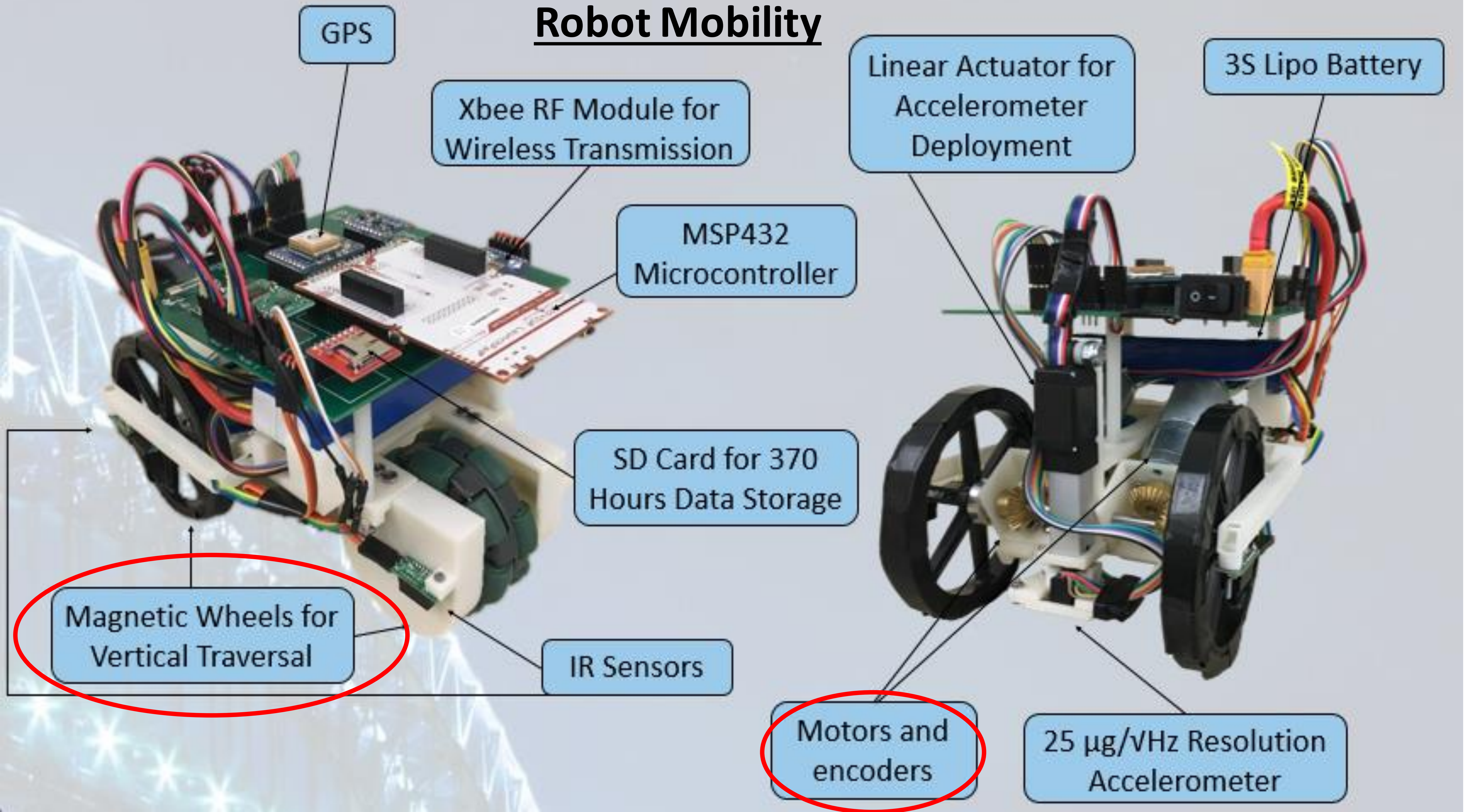
Linear Actuator for Accelerometer Deployment

3S Lipo Battery

Motors and encoders

25 µg/√Hz Resolution Accelerometer

Robot Mobility



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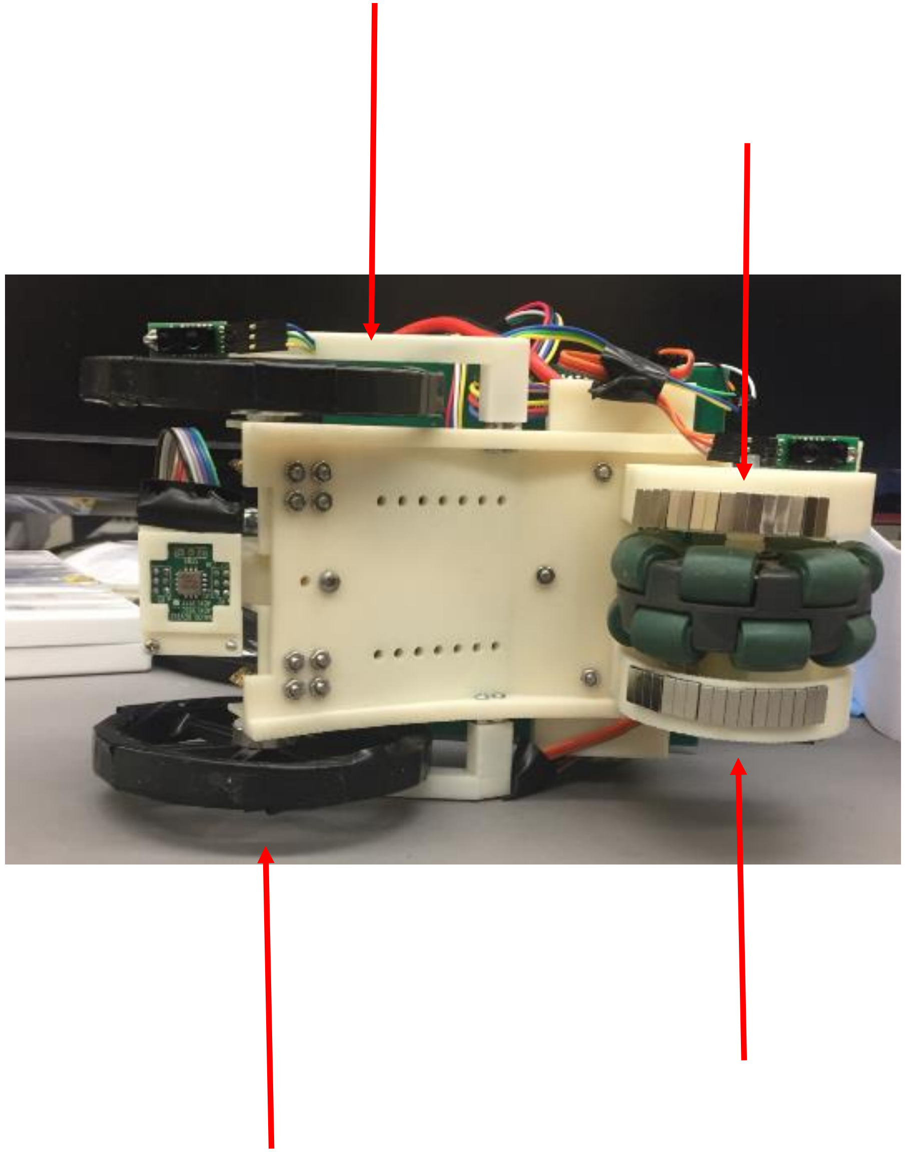
Three-Wheeled Design

- Two motorized wheels in the front and passive omni-wheel at the back

- Permanent magnets
  - Surround motorized wheels
  - Adjacent rear omni-wheel

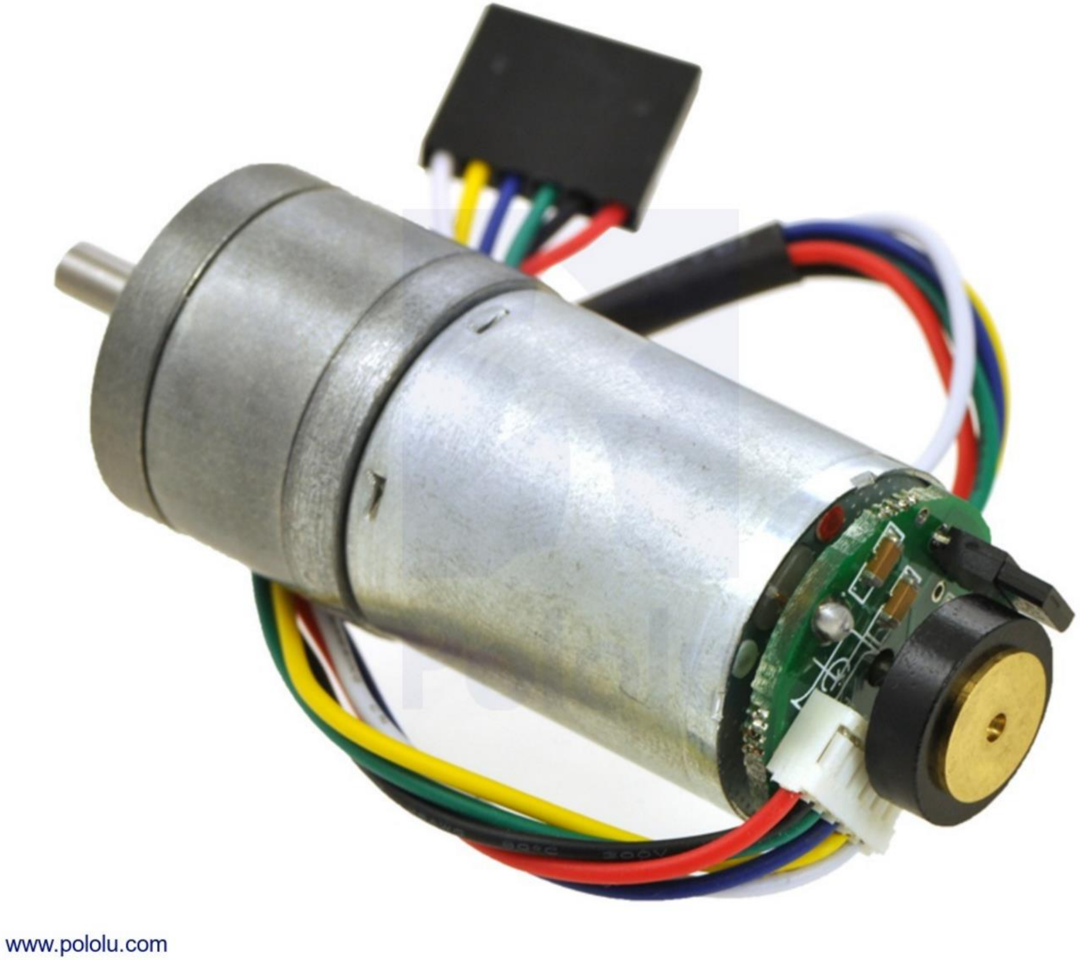


Mobility Choice: Three-Wheeled Design

- Pros
  - Retains capabilities of old flexure-based design
  - Turn in place capability
  - Less weight and power consumption compared to original design
- Cons
  - Omni-wheel provides less stability
  - Currently lacks ability to traverse 90° angle
  - Potential Solution:
    - Leverage Arm
    - Motorize back wheel

Motors - Pololu 25D Metal Gearmotor

- Motor includes encoder with 1200 counts per revolution
- Includes low power option at 12V
  - Free-Run Speed: 55 rpm
  - Free-Run Current: 100 mA
- Provides high torque needed for vertical traversal
  - Stall Torque: 115 oz·in
  - Stall Current: 1110 mA



25D mm metal gearmotor with 48 CPR encoder.

Motors - Implementation

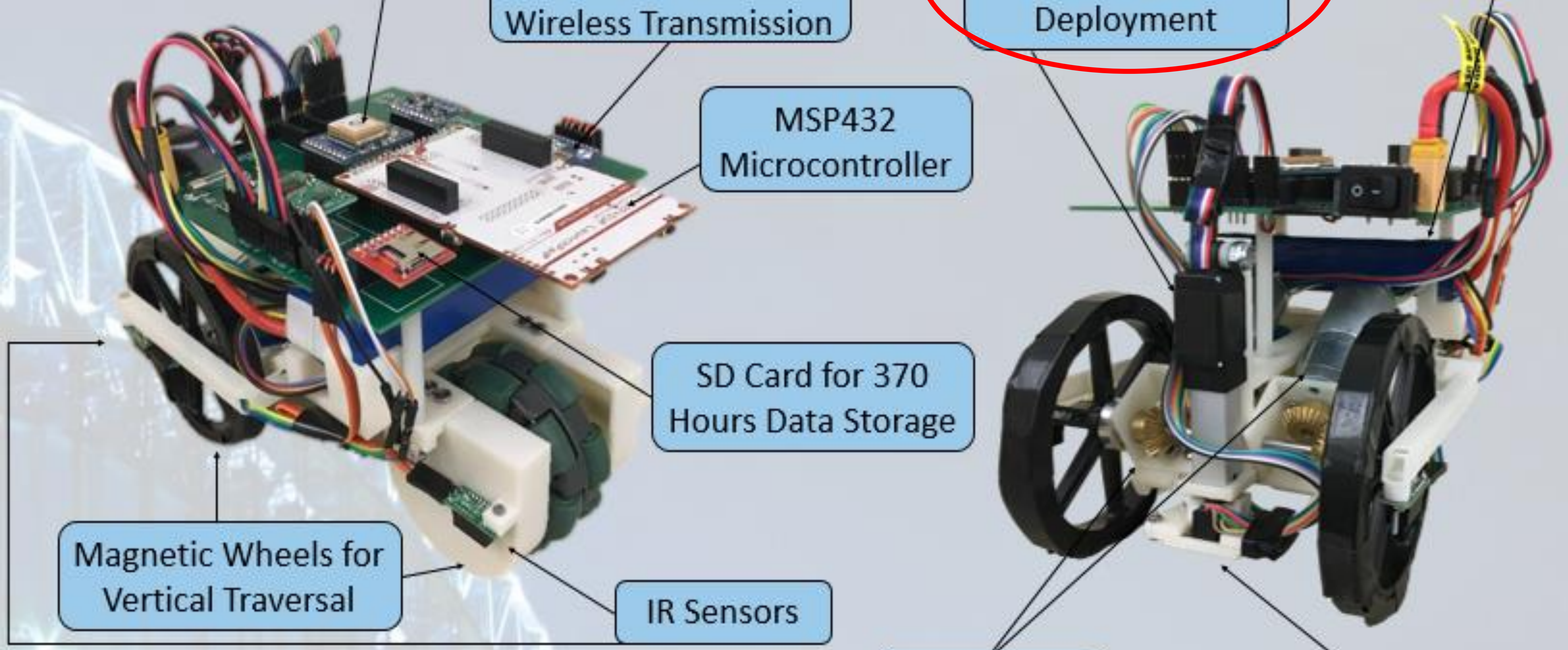
- Motors placed in line with length of robot in order to minimize width
  - Two beveled gears used to transfer motion 90° to wheels
- Encoders provide 1,200 counts per rotation of the wheel
  - Travelling one meter returns 4000 counts per wheel
- Magnets are placed along the surface of the wheel
  - Keeps robot attached to bridge on any surface

Magnets - B621 Grade N42 Neodymium Magnet

- Material: NdFeB, Grade N42
- Weight: 0.36 g/magnet
- Dimensions: 3/8” x 1/8” x 1/16” thick
- Holding Force: 1.15 lbs.

- Initial magnet choice was too large and too strong
  - Motors had trouble producing enough torque to overcome holding force
  - Due to size, initial magnets surrounding the wheel circumference turned the wheel into a polygon
  - Chosen magnet was half the width to form a more uniform circle

Accelerometer



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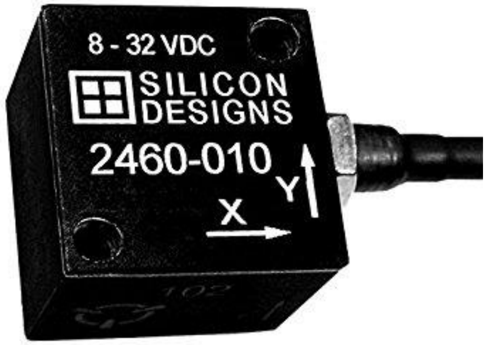
Accelerometer Design Choices

Parameters	**Initial Accelerometer: Silicon Designs 2460-002**	**Final Accelerometer: Analog Devices ADXL355**
Acceleration range	±2g	±2.048 g
Frequency Range	0-300Hz	0-10,000Hz
Resolution:	38 ng/bit (with 2000x gain)	3.8ug/bit
Noise Specification:	10 µg/√Hz (before signal conditioning and A/D)	25 µg/√Hz
Operating Power:	276 mW (without A/D)	495 µW
Mass	21 g (without cabling and A/D)	~5 g

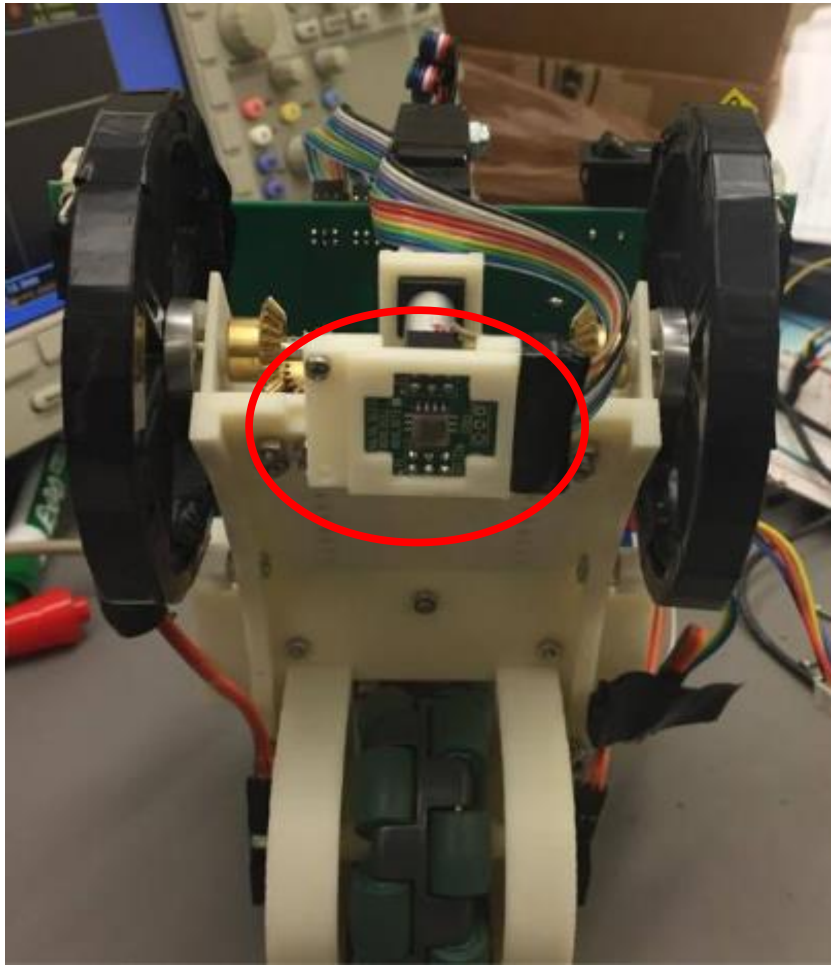


Reason for Accelerometer Change

- Noise Floor Requirements relaxed upon further conversations
  - MRDC Bridge very small in comparison to other bridges
  - Higher sensitivity needed for small structures
- Digital over Analog
  - Initial trepidation due to unfamiliarity
  - Much less noise than analog
    - Controlled environment within one module
    - I2C bus hard to create noise in
  - Can easily change digital filter parameters
- No PCB for signal conditioning module needed
  - Faster prototyping

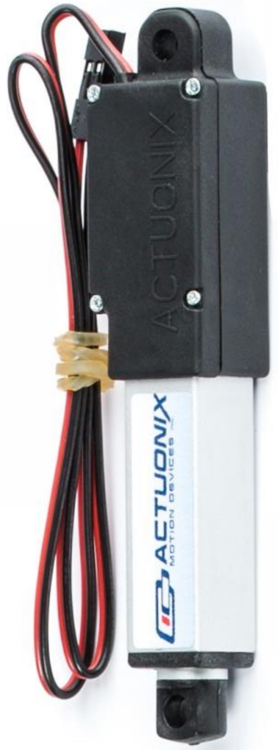
Accelerometer Deployment Method

- Requirements
  - Accelerometer shall mount directly onto bridge
  - Accelerometer shall be flush with bridge to ensure accuracy of measurements
- Design incorporated vertical motion w.r.t. the Bridge Inspection Robot frame



Linear Actuator - Actuonix L12 30mm Linear Actuator

- Prepackaged solution
- Very low mass
- Potentiometer already available for control
- Gear Ratio: 210:1
- Max Force: 80 N
- Stall Current @ 12V: 180 mA
- Control: RC



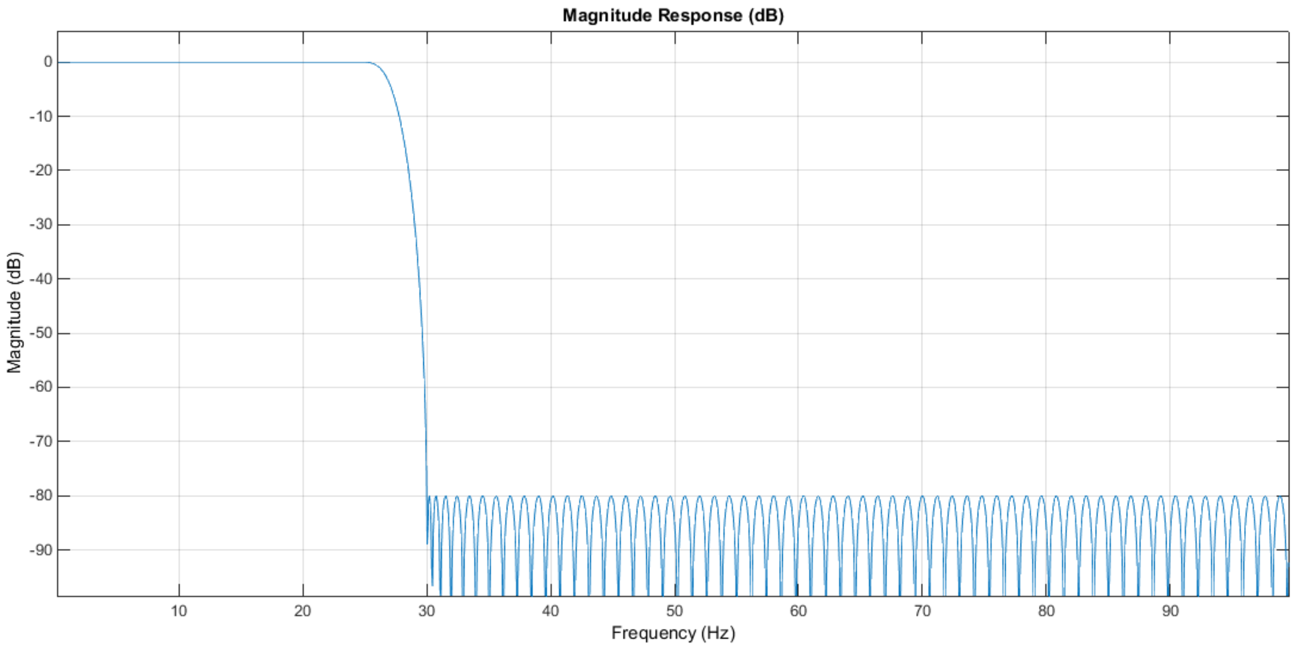
Deployment

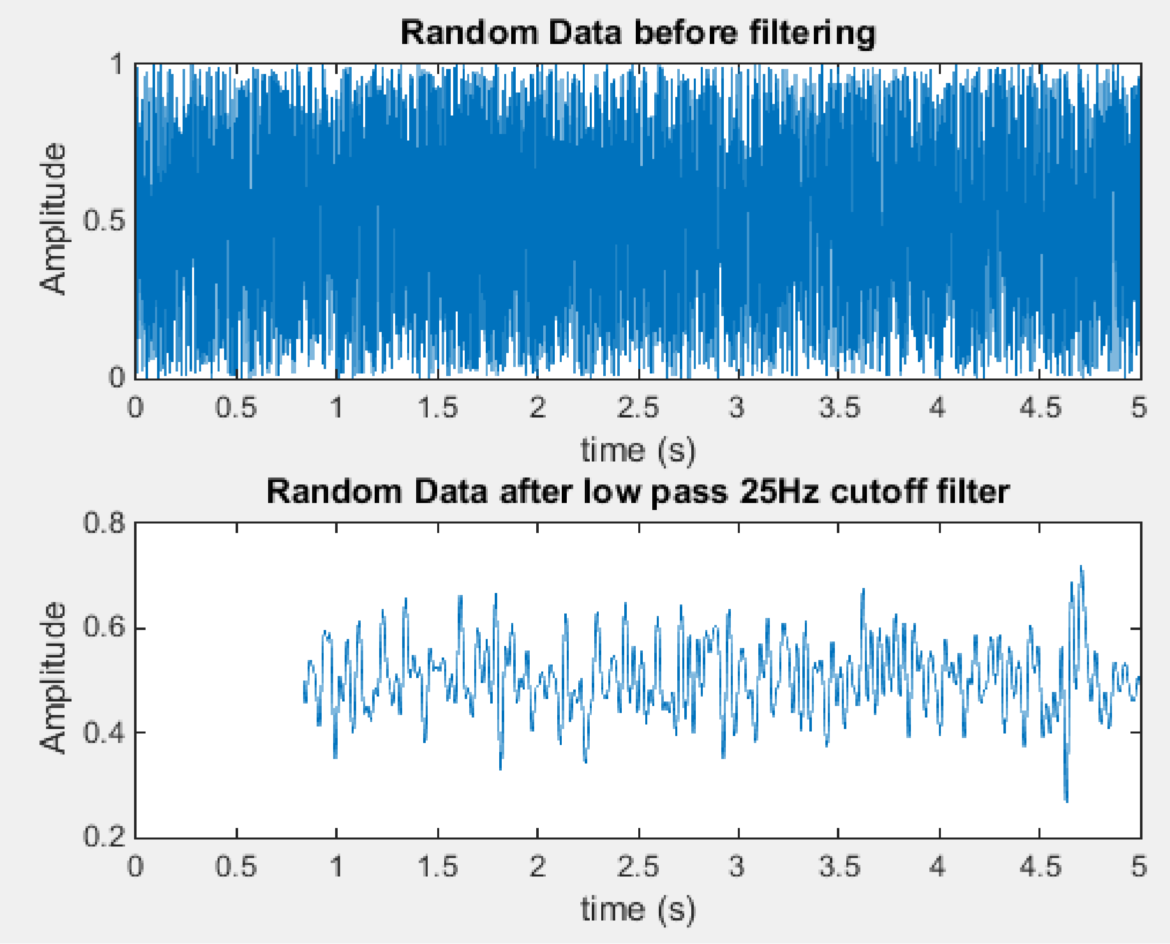
- Feedback not useful for control
  - 210:1 Gear Ratio made Linear Actuator was able to lift robot up off of magnetized surface
  - Solution was to set input value to match the accelerometer position to exactly level with the contact surface of the wheels.

- Accelerometer deployed inverted along the z-axis
  - Allowed for accelerometer on board to be directly in contact with measurement surface
  - Z-Axis Data only needed to be multiplied by -1 in post-processing to resolve

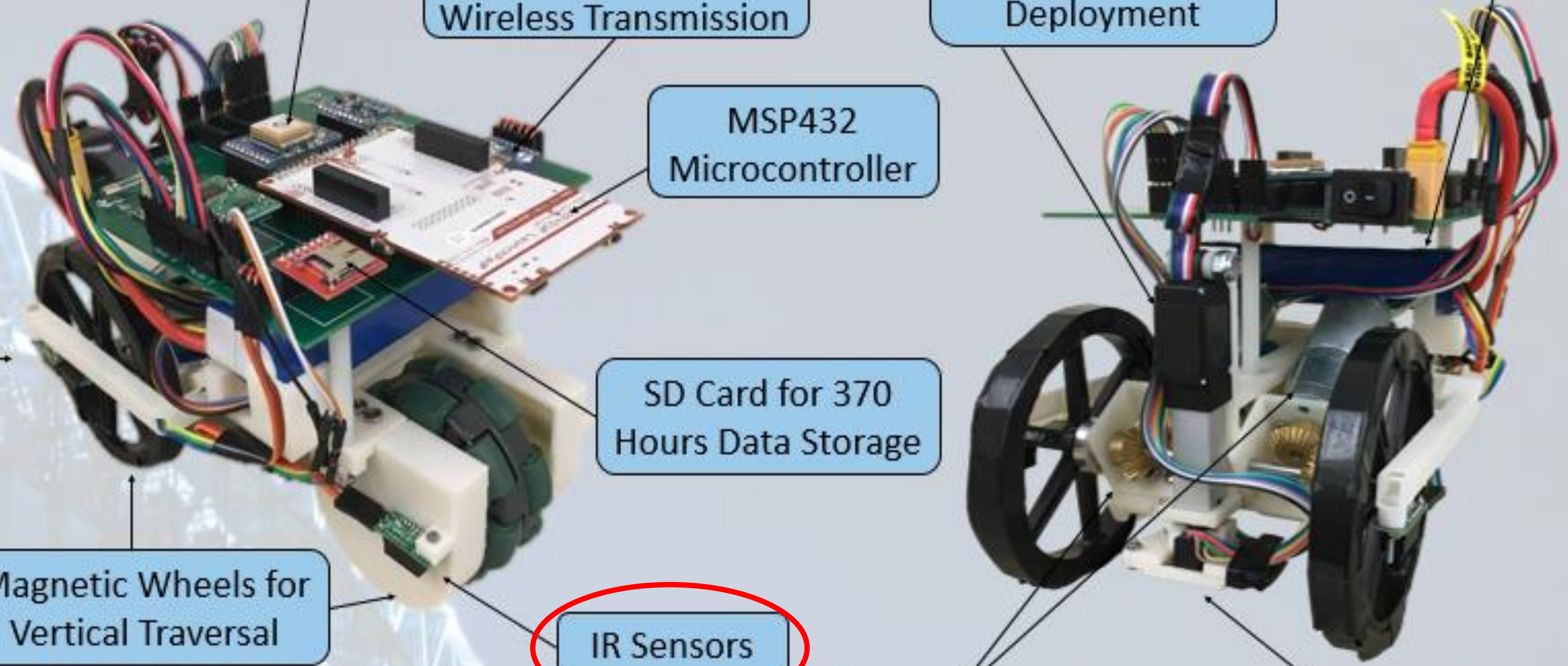
Digital Filter Parameters Option

- Digital Filtering through Matlab
  - firceqrip() or firgr()
- FIR Filter
  - Linear phase delay





Motion Tracking



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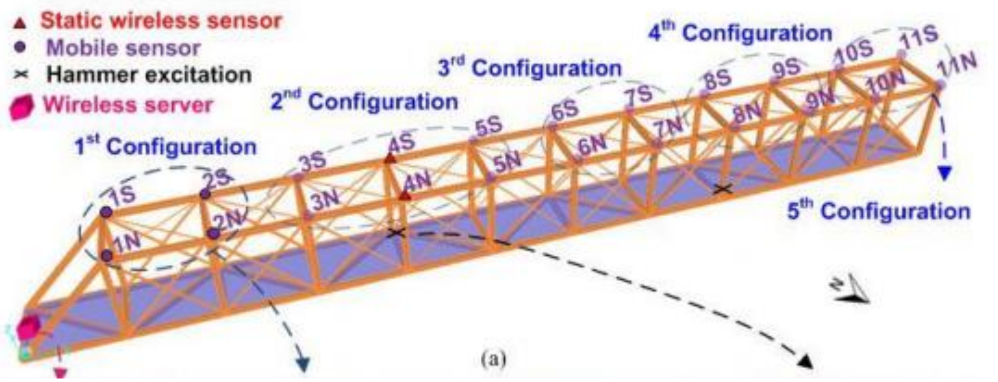
Motion Tracking Requirements

- Assumptions
  - Initial orientation is known
  - Only straight path traversal is required for the most part, with turning used for path corrections



- Requirements
  - Need to go in a roughly straight path so robot won’t need to continuously correct path
  - Need to be able to detect edges so robot won’t fall off
  - Need to be able to identify locations of structural health measurements to around about 2m resolution fairly accurately as in experiment in thesis paper

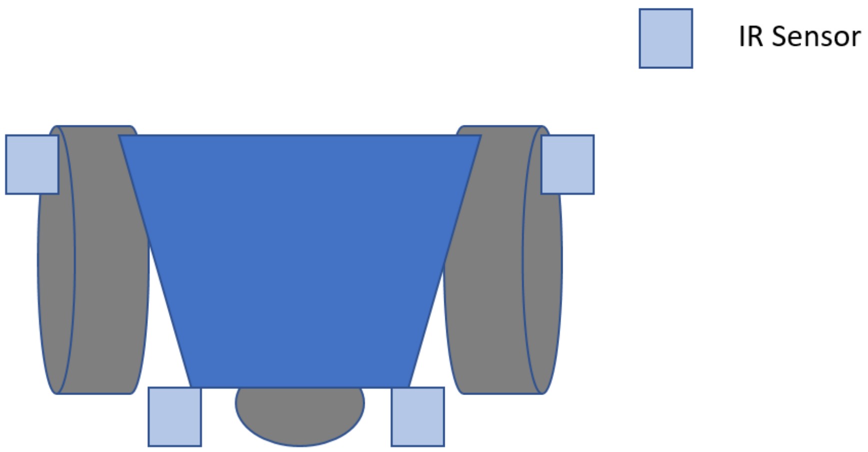
Straight Path Traversal

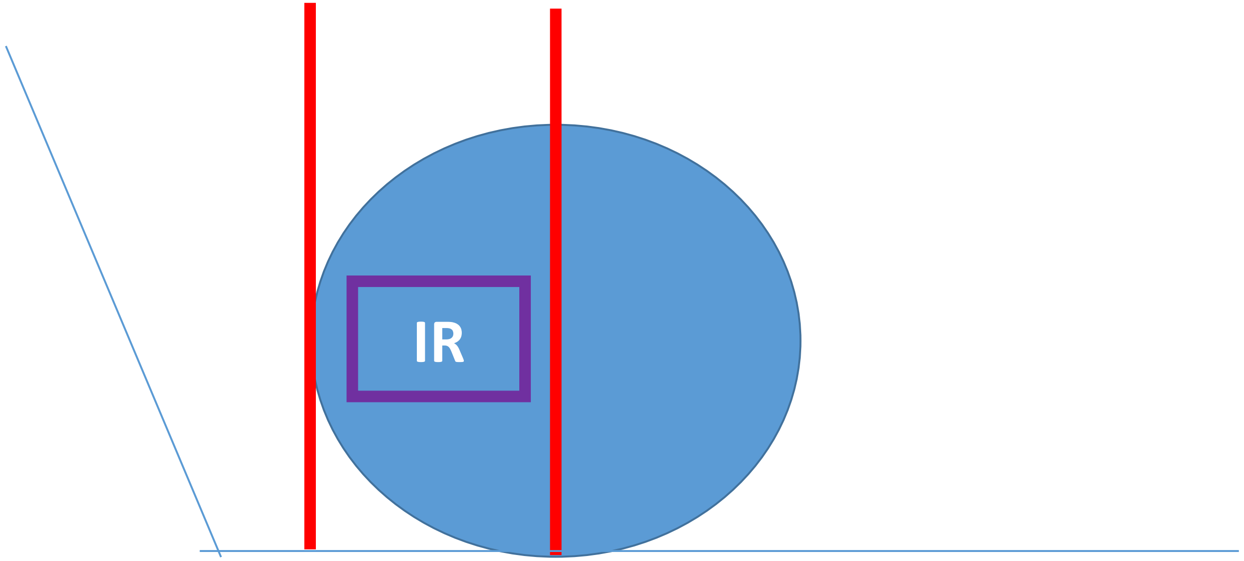
- Encoders alongside proportional control used to maintain straight path
  - Drift likely minimized due to permanent magnets holding wheels and robot body to metal surface
  - Potential drift still a concern
  - No permanent reference point

- Plans to implement gyroscope in design for future use

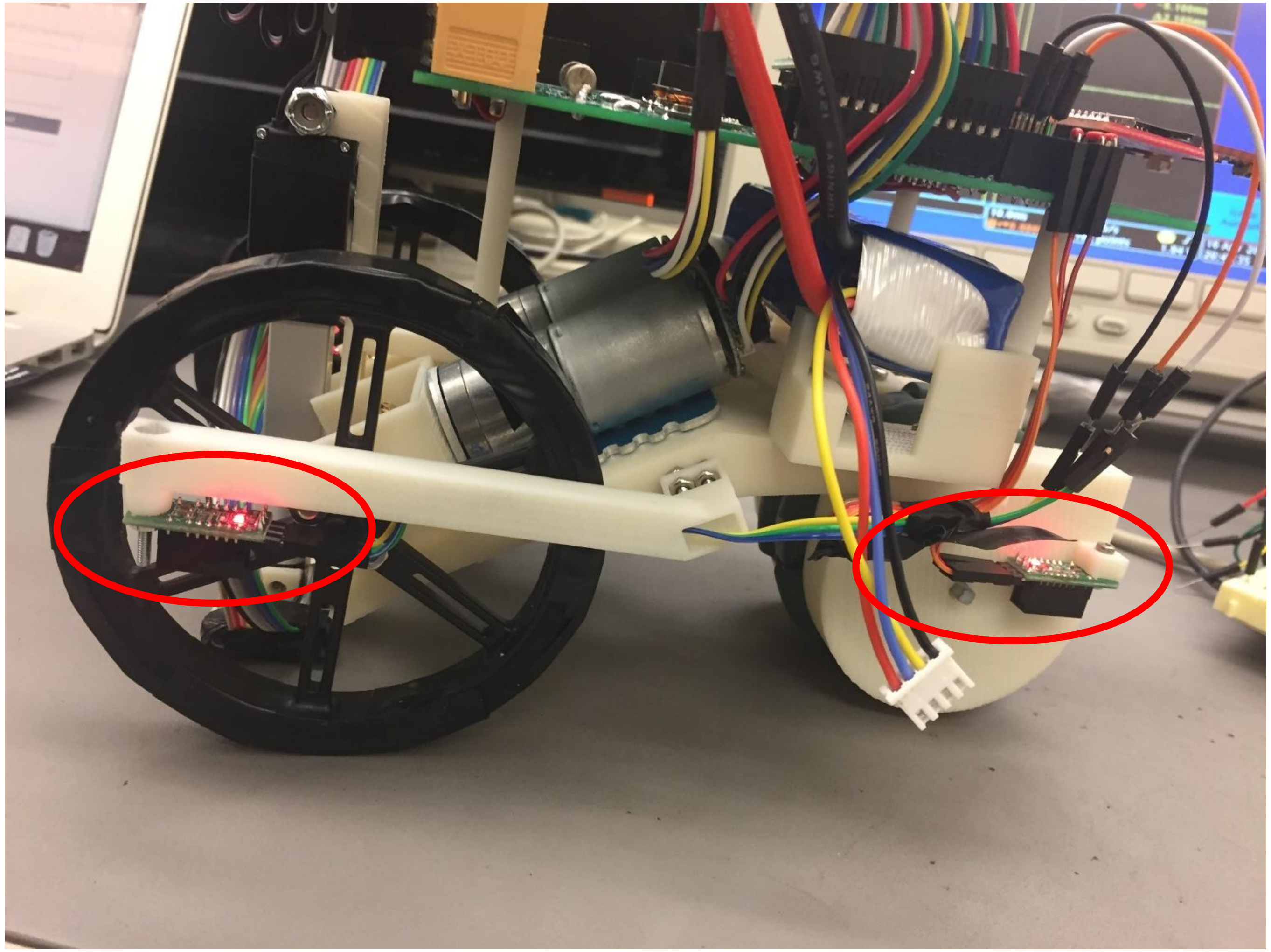
Edge Detection

- IR Sensors
  - Four IR sensors mounted close to wheels and near edge
  - Verified that wheels will hit inclines such that sensors will not scrape against surfaces





IR Sensor Implementation



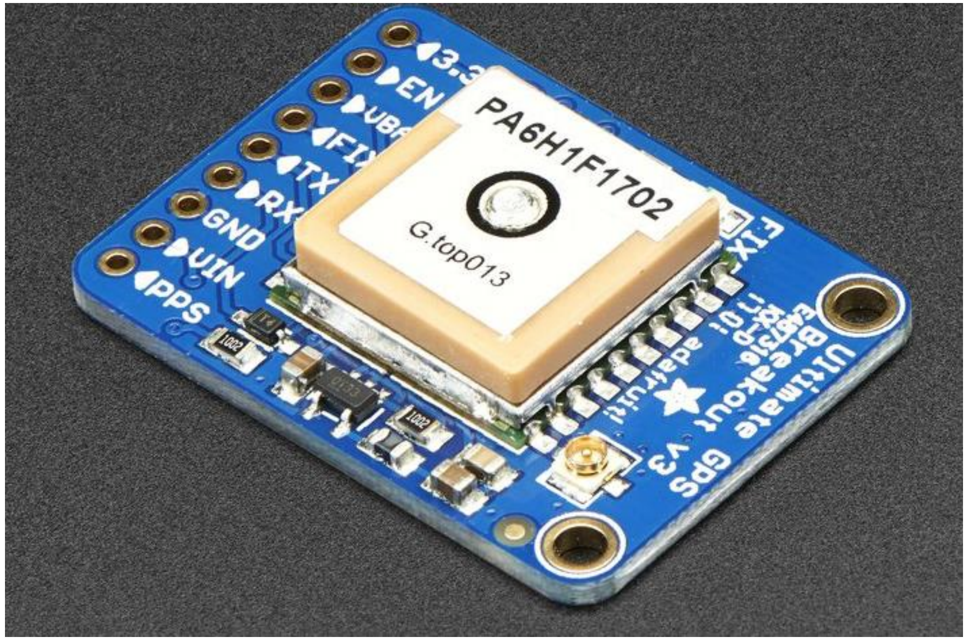
Motion Tracking

- Used encoder movement, combined with GPS for absolute position recalibration every 50m
  - Further minimizes effect of encoder drift
  - Not useful if on underside of bridge without clear line-of-sight of the sky

- Incorporate gyroscope in a future robot iteration

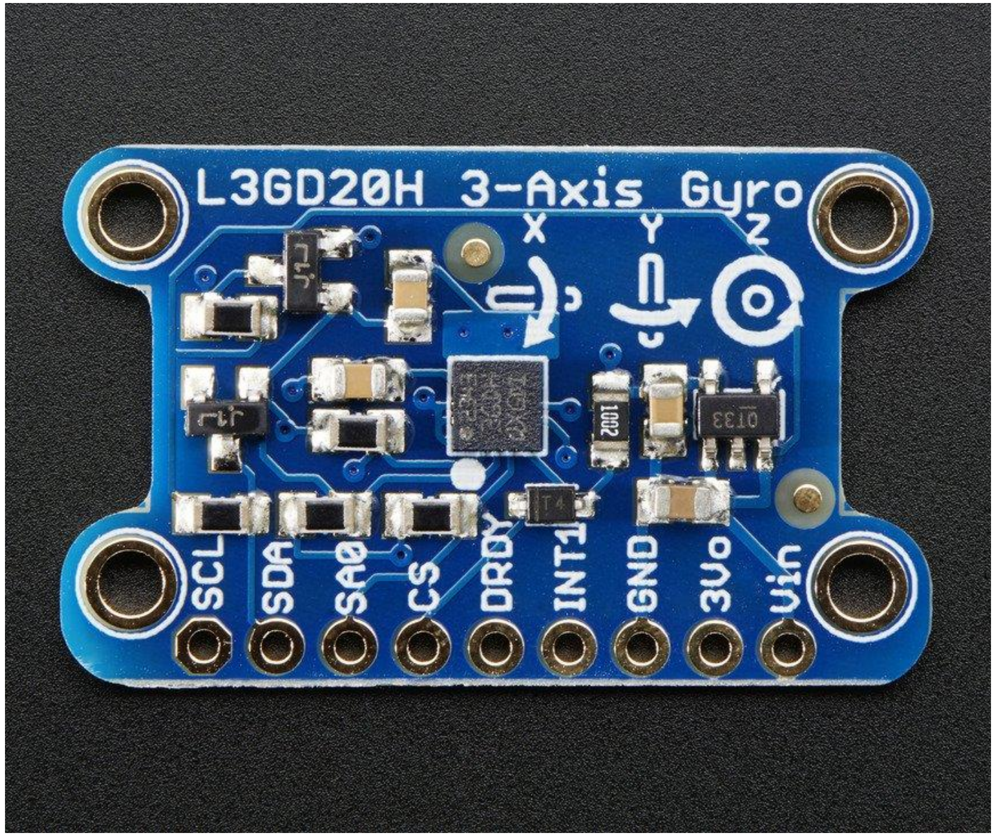
GPS - Adafruit Ultimate GPS Breakout - 66 Channel MTK3339

- Accuracy: 3 m radius
- Update Frequency: 10 Hz
- Sensitivity: 165 dBm
- Power: 100 mW
- Interface: UART
- Other
  - Ships with breakout board
  - Built-in data-logging
  - SMA connector to connect external antenna

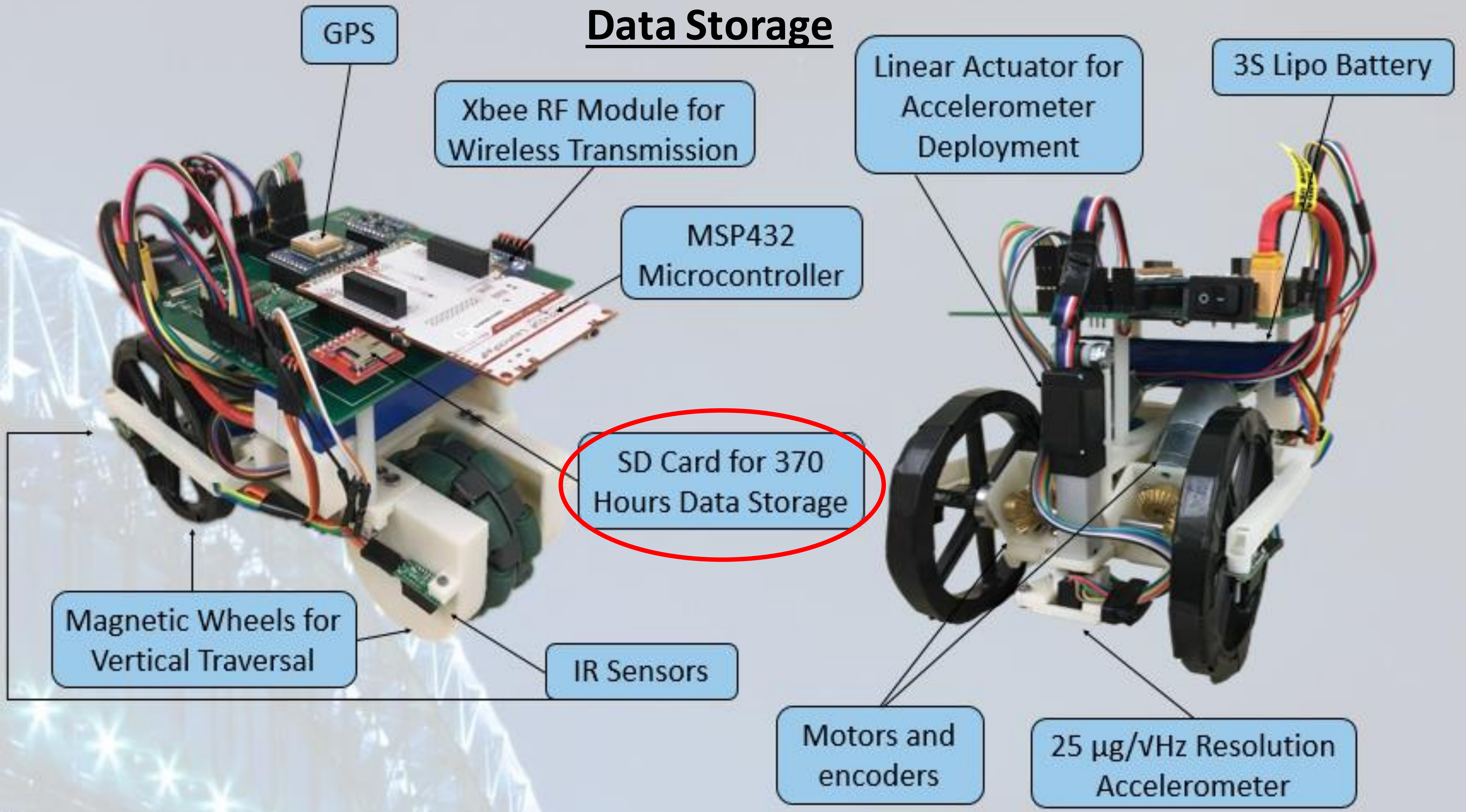


Gyroscope – ST L3GD20H

- X-, Y-, Z-axis data
- Resolution: ±245/±500/±2000°/s with 16 bits
- Accuracy: Zero Bias: ±25°/s
- Power: 15 mW
- Interface: **SPI**/I2C
- Other: User-enabled integrated low-pass and high-pass filters; Temp sensor.

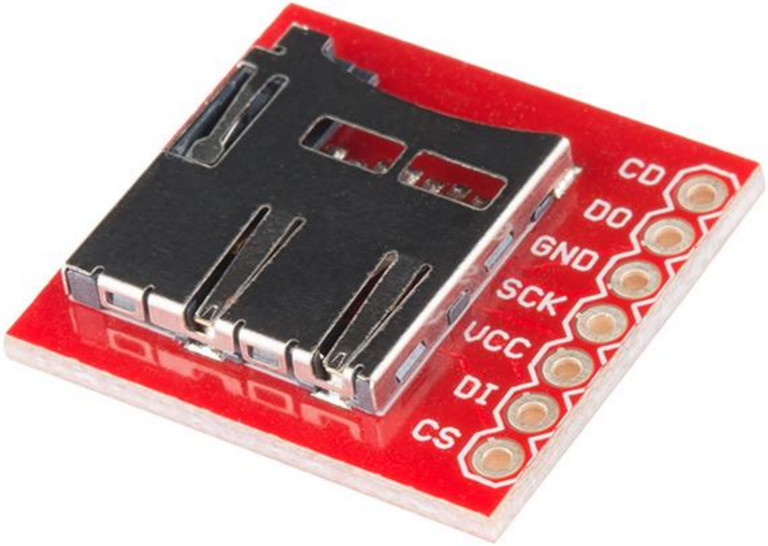


Data Storage

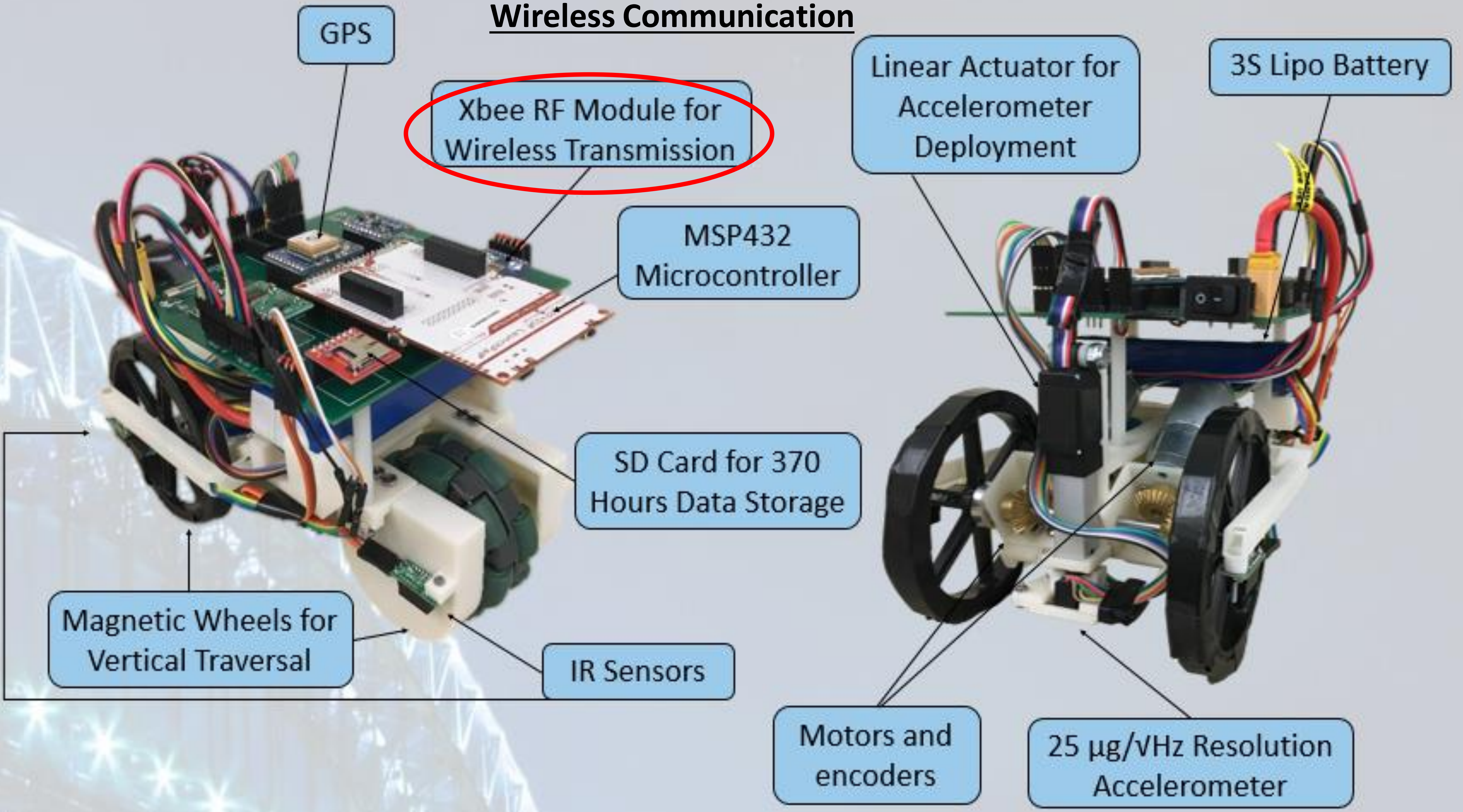


SD Card – Sparkfun microSD Breakout

- Connects SanDisk Class 4 16 GB microSD card to MSP432
  - Capable of storing over 370 hours of accelerometer data at a sample rate of 1000 Hz
- Interfaced via SPI
  - R/W Speed: 1 MHz



Wireless Communication



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Motors and encoders

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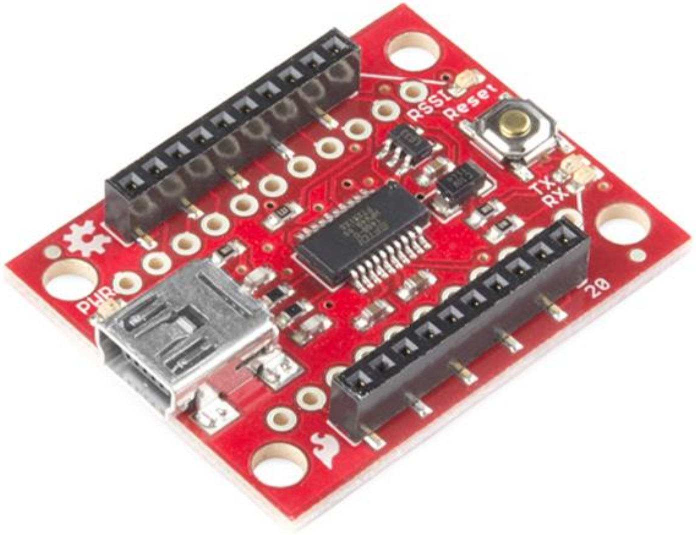
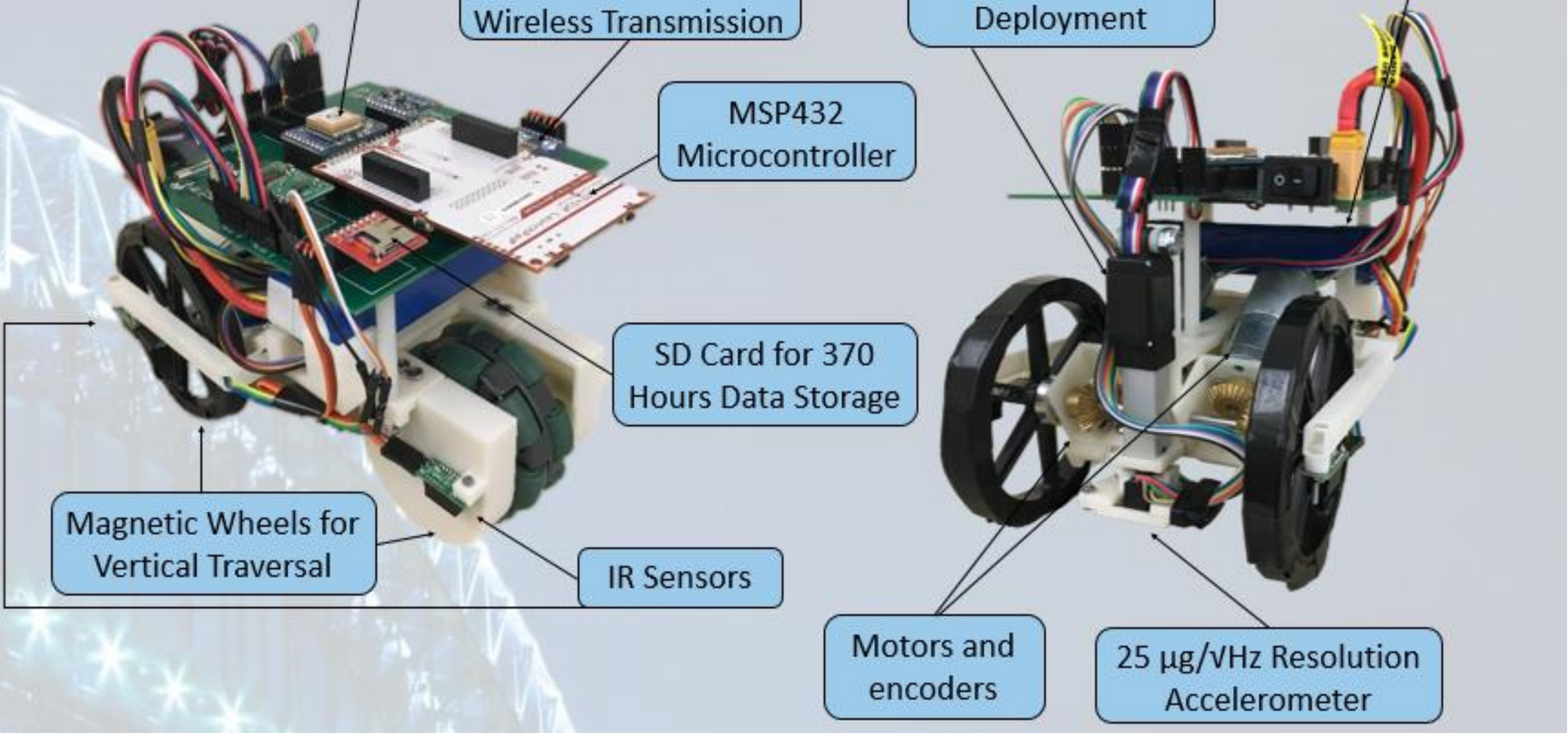
Wireless Module - XBee S2C 802.15.4

- Specifications
  - Max outdoor range: 1200 m
  - Throughput: up to 250 Kbps
  - Interface: UART
  - Current draw (typical): 28-33 mA
  - Wireless Protocol: IEEE 802.15.4
    - Switched from Digimesh

- Communicates with PC through a Sparkfun XBee Explorer USB



Power



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Power Requirements

- Power requirements were mainly dependent on the following:
  - Motors
  - Wireless Communication
  - Accelerometer
  - Accelerometer Deployment

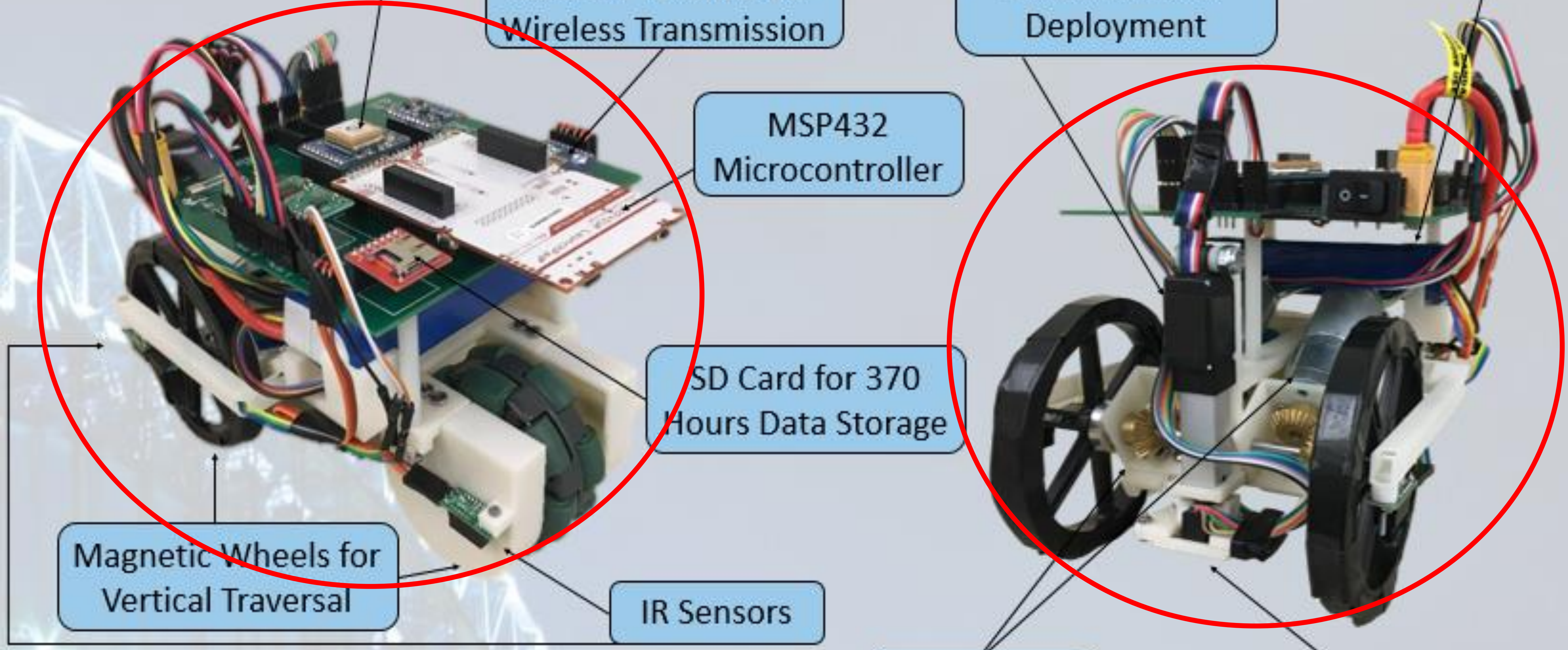
- The robot was expected to run actively for at least one hour and one additional hour while stationary

- The robot required a maximum voltage of 12V to accommodate the accelerometer and motors. Power conversion circuitry used to create lower voltages for other components

Turnigy Lipo Pack

- Minimum Capacity: 2200mAh (True 100% Capacity)
- Configuration: 3S1P / 11.1v / 3Cell
- Weight: 188g
- Provides a high continuous current and long lifetime

Robot Structure



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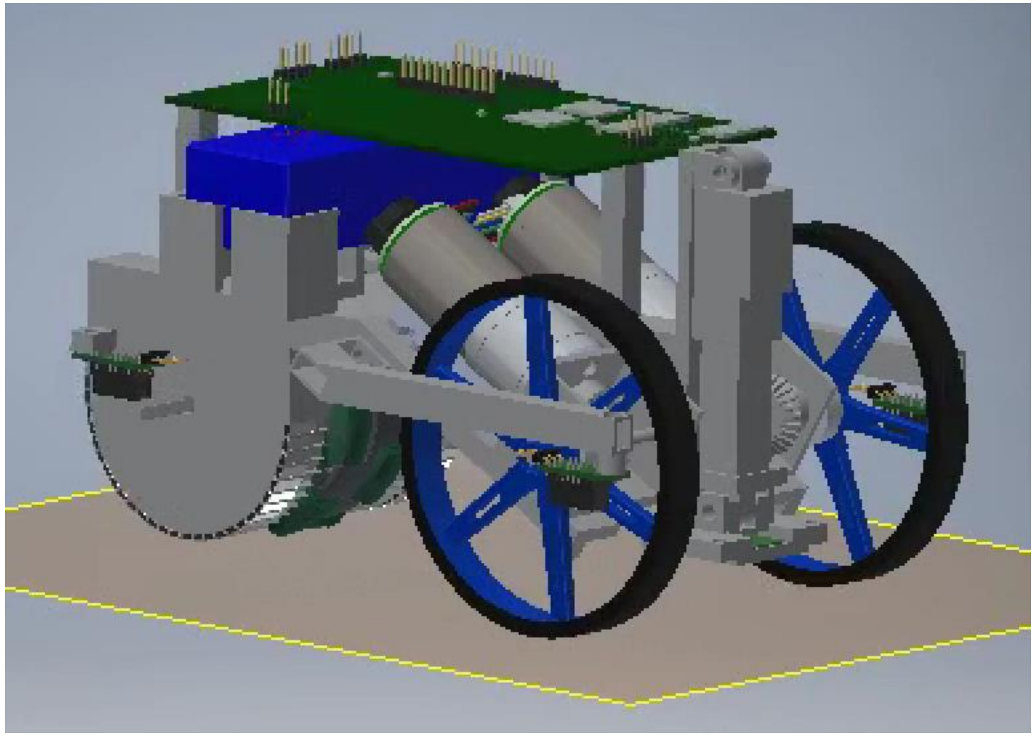
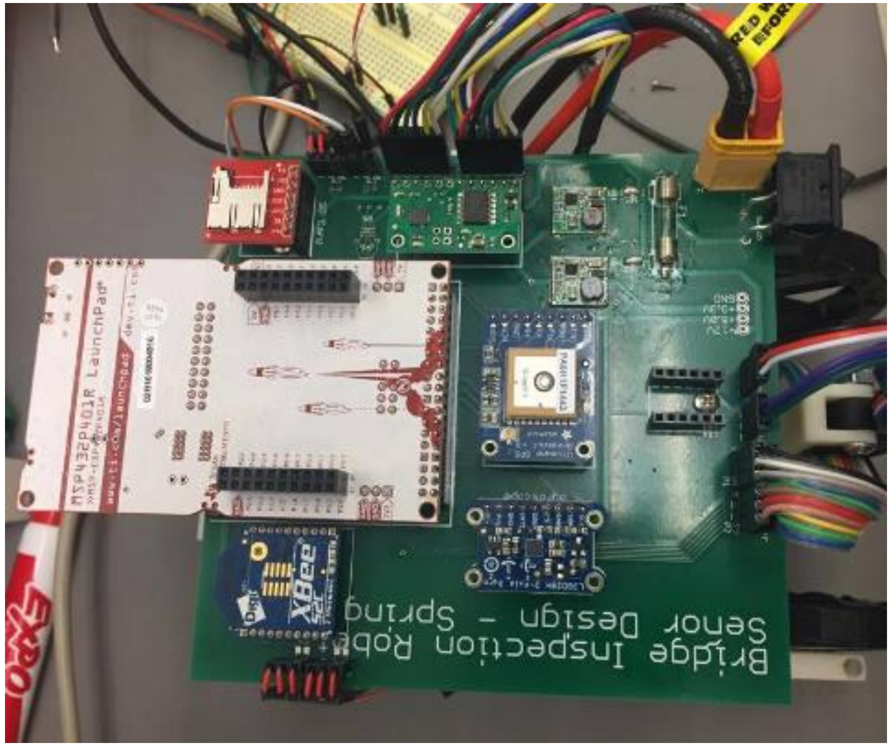
Structure

- A holding structure is needed for battery and circuitry
- Structure was rapidly prototyped using Inventor 2017 and 3D printing with the Senior Design Lab
- Alternate Consideration
  - Aluminum or acrylic sheets are used for a high strength support, designed in Inventor 2017 and machined at the invention studio.

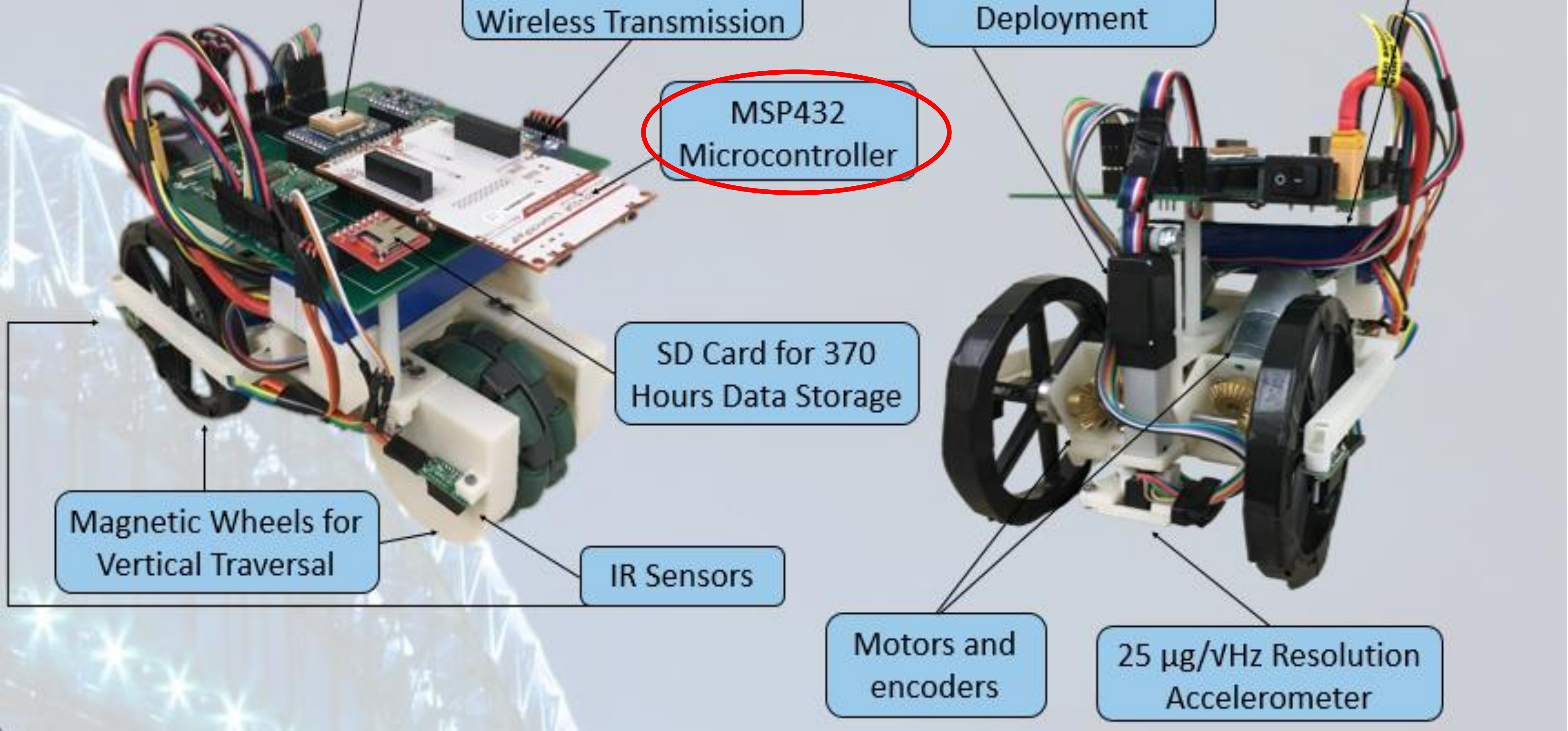


Printed Circuit Board (PCB)

- Designed using the educational license of Autodesk EagleCAD
- Single circuit board for power, data transmission, and motor control
- Used for routing signals between subsystems
- Implements modular design to allow detachment or replacement of major components



Microcontroller



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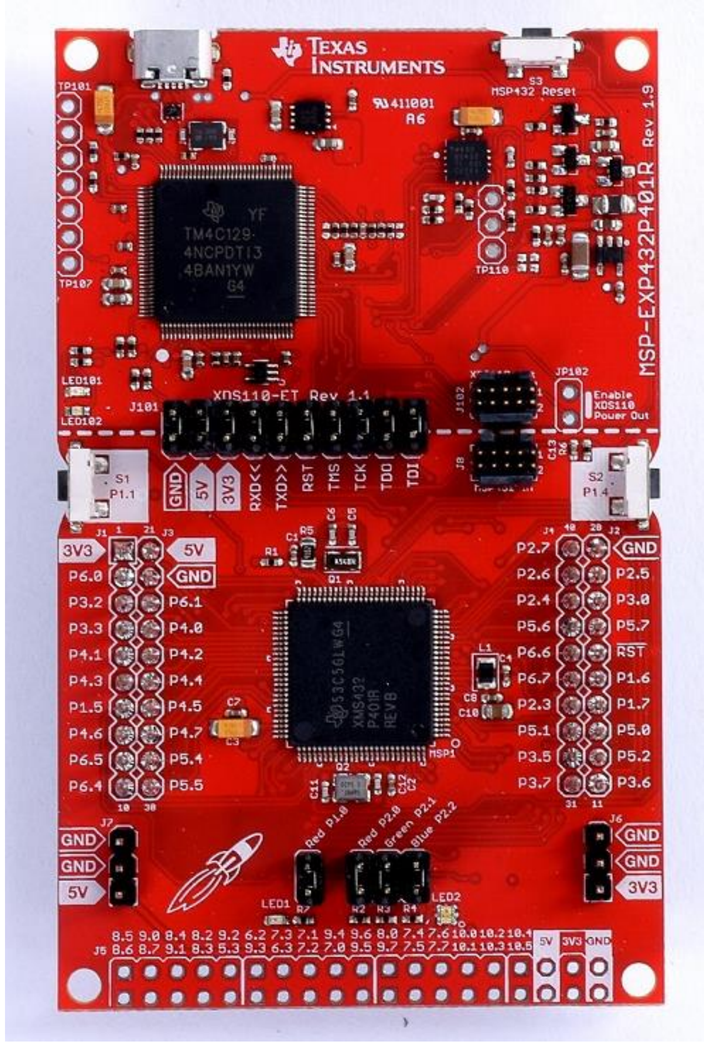
Microcontroller – TI MSP432P401R

- Specifications
  - 48 MHz ARM 32-bit CPU
  - 256 kB of flash memory
  - 64 kB SRAM
  - 14-bit ADC
  - 4 UART channels and 4 SPI channels
  - Current draw (active mode, typical): 7.8 mA

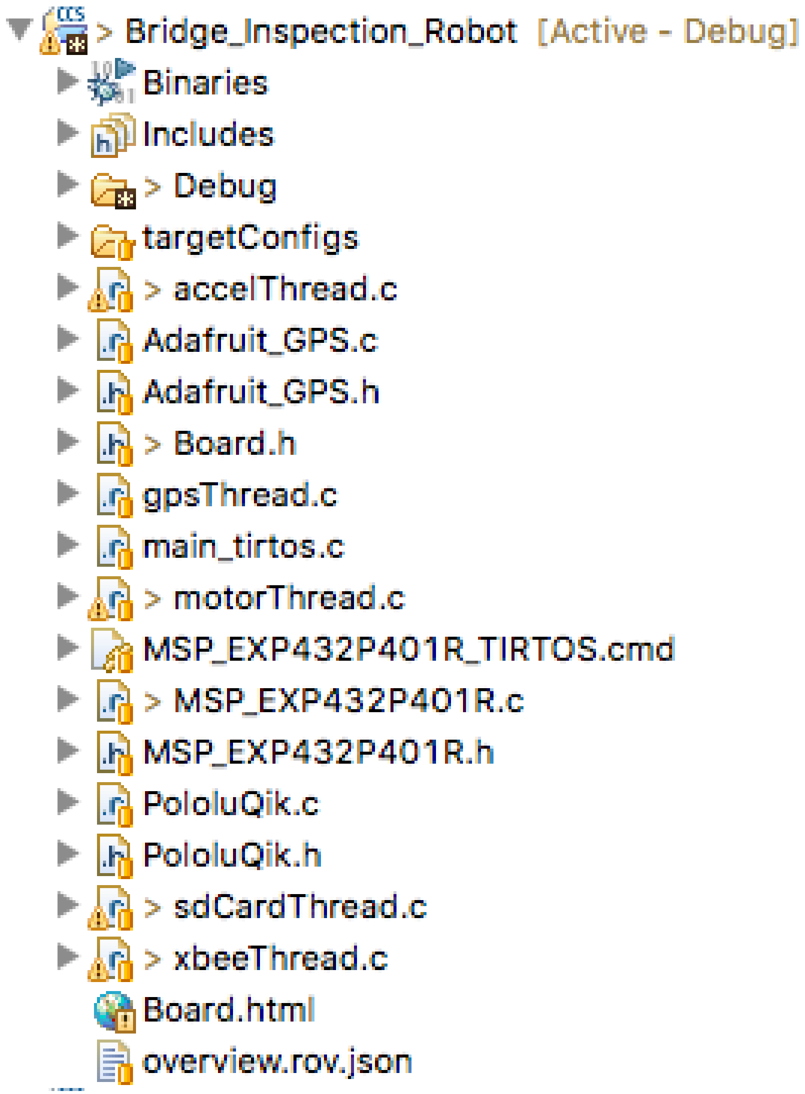
- Programmed via Code Composer Studio IDE

- MSP432 Launchpad used for rapid prototyping



Software

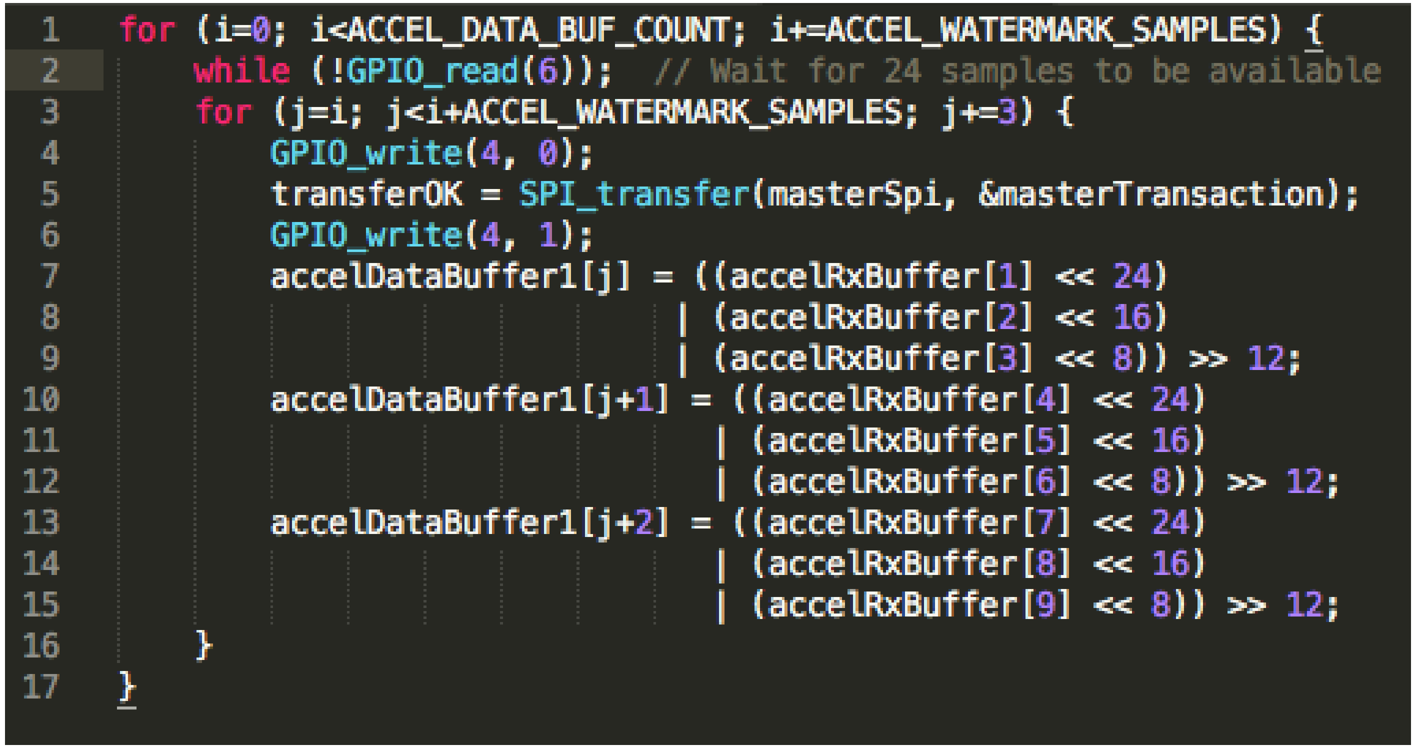
- Written in C
- TI-RTOS: a proprietary RTOS for TI MCUs
  - Libraries for GPIO, ADC, UART, SPI, Timers, etc.
  - Separate threads for different components
    - Mutexes, semaphores, and barriers sync and coordinate actions
- External libraries for motors and GPS ported from Arduino to MSP432



> Bridge_Inspection_Robot [Active - Debug]
Binaries
Includes
> Debug
targetConfigs
> accelThread.c
Adafruit_GPS.c
Adafruit_GPS.h
> Board.h
gpsThread.c
main_tirtos.c
> motorThread.c
MSP_EXP432P401R_TIRTOS.cmd
> MSP_EXP432P401R.c
MSP_EXP432P401R.h
PololuQik.c
PololuQik.h
> sdCardThread.c
> xbeeThread.c
Board.html
overview.rov.json

Datalogging Program

- A "sample" consists of an X-value, Y-value, and Z-value
- Accelerometer provides sequential data in sets of 8 samples
- Double buffer system on MSP432, each holding 1536 samples
    - Accelerometer fills one buffer with data while SD card is filled with the other buffer's data



```
for (i=0; i<ACCEL_DATA_BUF_COUNT; i+=ACCEL_WATERMARK_SAMPLES) {
    while (!GPIO_read(6));  // Wait for 24 samples to be available
    for (j=i; j<i+ACCEL_WATERMARK_SAMPLES; j+=3) {
        GPIO_write(4, 0);
        transferOK = SPI_transfer(masterSpi, &masterTransaction);
        GPIO_write(4, 1);
        accelDataBuffer1[j] = ((accelRxBuffer[1] << 24)
                              | (accelRxBuffer[2] << 16)
                              | (accelRxBuffer[3] << 8)) >> 12;
        accelDataBuffer1[j+1] = ((accelRxBuffer[4] << 24)
                                | (accelRxBuffer[5] << 16)
                                | (accelRxBuffer[6] << 8)) >> 12;
        accelDataBuffer1[j+2] = ((accelRxBuffer[7] << 24)
                                | (accelRxBuffer[8] << 16)
                                | (accelRxBuffer[9] << 8)) >> 12;
    }
}
```

Movement Program

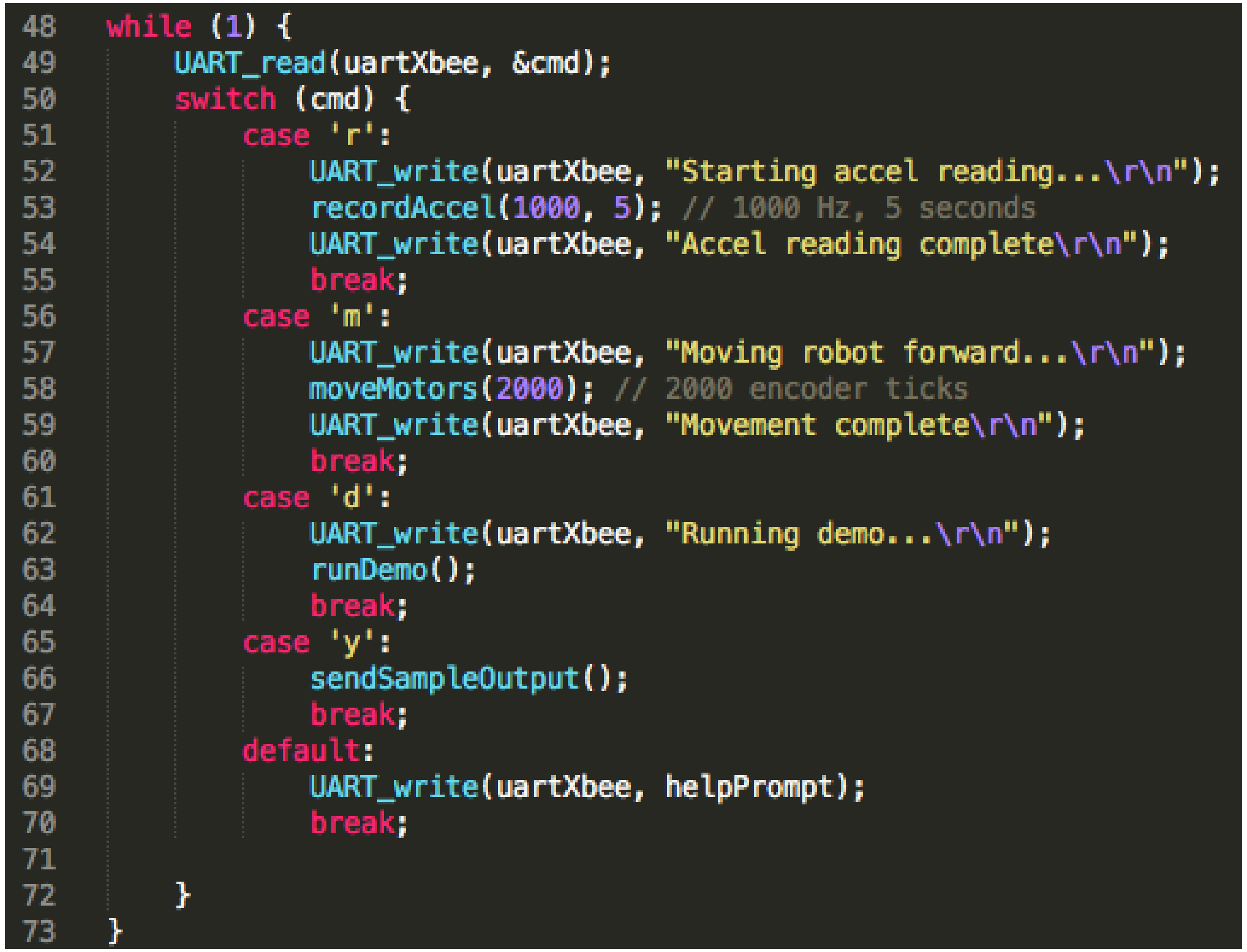
- While motors are running…
  - Encoder counts are incremented/decremented via interrupts
  - Running timer regulates proportional control on the motors
  - IR sensors halt forward progress if edge detected
- Motors stop when the desired encoder count (distance) is reached

```
void edgeDetected(uint_least8_t index) {
    if (!irFlag) {
        irFlag = index; // irFlag indicates where edge is
    }
}
// ...
    while (keepMoving) {
        if (irFlag) {
            correctForEdge(irFlag);
        }
        error = enc1Count - enc0Count;
        if (error > 0) { // increase m0 speed
            m0Speed = 64 + error/3;
            m1speed = 64;
            if (m0Speed > 90) {
                m0Speed = 90;
            }
        } else {        // increase m1 speed
            m0Speed = 64;
            m1speed = 64 - error/3;
            if (m1speed > 90) {
            m1speed = 90;
            }

        }
        PololuQik_setSpeeds(uartMotor, m0Speed, -m1speed);
        sem_wait(&semMoveMotors);   // wait 0.1 seconds
    }
```

User Interface Program

- Commands are sent through a serial port (XBee)
- Accelerometer data is streamed back at 115200 baud
  - Data can be piped to a MATLAB program for automatic plotting



```c
while (1) {
    UART_read(uartXbee, &cmd);
    switch (cmd) {
        case 'r':
            UART_write(uartXbee, "Starting accel reading...\r\n");
            recordAccel(1000, 5); // 1000 Hz, 5 seconds
            UART_write(uartXbee, "Accel reading complete\r\n");
            break;
        case 'm':
            UART_write(uartXbee, "Moving robot forward...\r\n");
            moveMotors(2000); // 2000 encoder ticks
            UART_write(uartXbee, "Movement complete\r\n");
            break;
        case 'd':
            UART_write(uartXbee, "Running demo...\r\n");
            runDemo();
            break;
        case 'y':
            sendSampleOutput();
            break;
        default:
            UART_write(uartXbee, helpPrompt);
            break;

    }
}
```

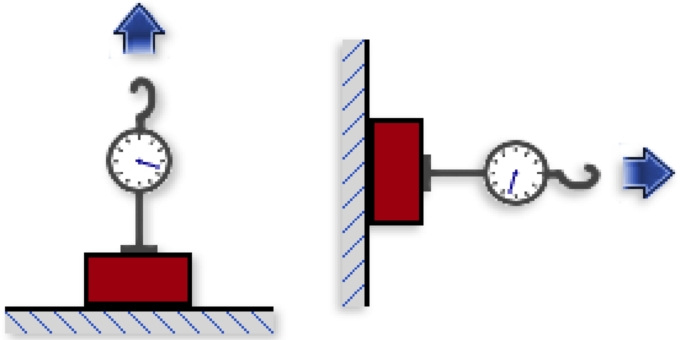
Design Verification

Characteristic	Specification
Magnet Holding Force	Holds robot static indefinitely
Operational Lifetime	Movement Operation Time ≥ 1 hour; Recording Operation ≥ 1 hour
Accelerometer Range and Accuracy	0 – 50 Hz ± 0.5 Hz 50 Hz +/- 0.5 Hz
Robot Size	Greatest side length ≤ 0.25 m
Weight	Total mass ≤ 1 kg
Wireless Communication Distance	Able to send/receive data ≥ 800 m
Path Following	Shall not fall off edge in “sunny day” conditions

Dimension and Mass Properties

	Required Specification	**Actual Specification**	**Requirement Met?**
Dimensions	<= 25cm by 25cm by 25cm	24cm by 14cm by 20cm	**YES**
Weights	1 kg	1.084 kg (5-7% overshoot on scale)	**No**

Test Event: Holding Force



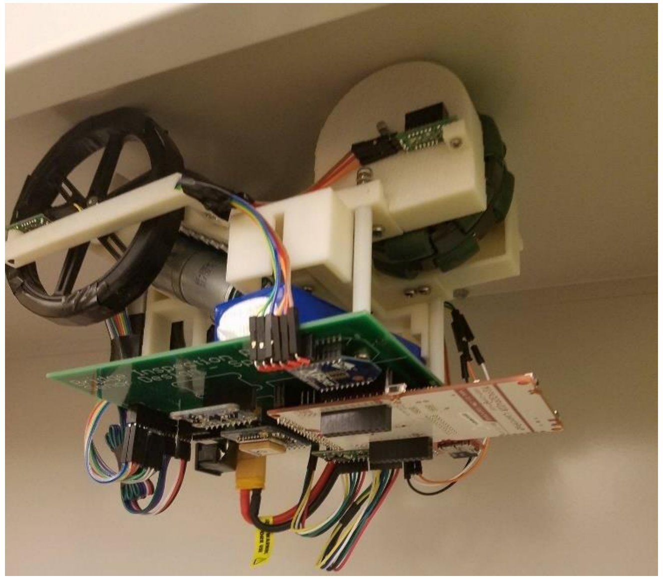
- Initially proposed test was to check if an individual magnet could maintain its position with mass attached to it for at least 2 minutes

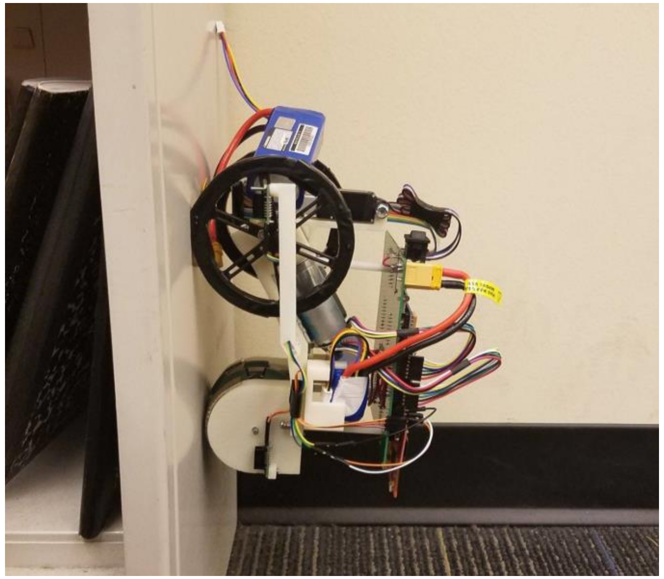
- On further discussion, a more representative test would be testing the fully built robot with some mass attached to it in multiple configurations

- Requirement is verified if robot can maintain its own mass and position in varying positions
  - Stretch goal is the robot being able to maintain its position with extra mass attached

Holding Force Results

- Robot upside down: Maintained position for at least 2 minutes
- Robot on vertical surface: Maintained position for at least 2 minutes
  - Robot is more secure if front wheels are on top
  - If back wheel is on top, increased likelihood of the robot will flip over
  - If robot is sideways, increased likelihood of back wheel slipping



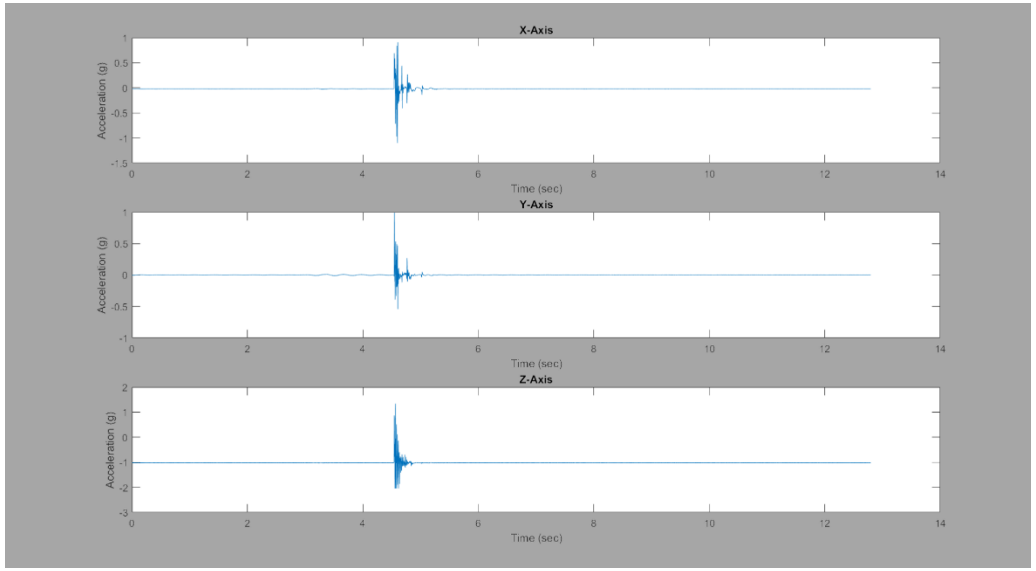


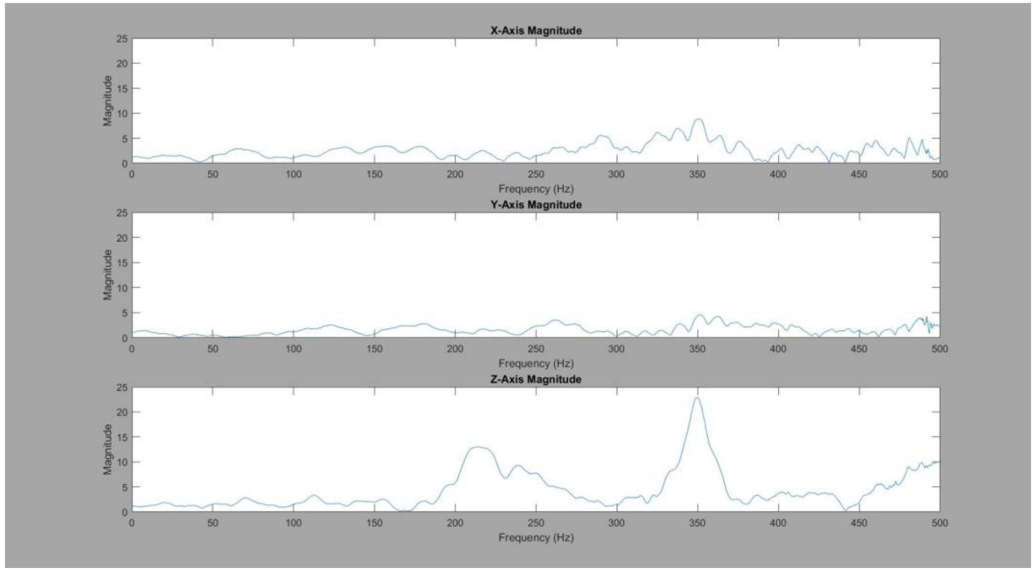
Test Event: Accelerometer Data Accuracy

- Verification of the accelerometer data accuracy required usage of a shaker table
- A vibration profile will be measured by mounting both a statically mounted accelerometer and the robot with its installed accelerometer on to the table

Accelerometer Data Accuracy Results

- No official testing event has occurred yet
- Based on examination of data while integrating accelerometer into robot design, confident in accelerometer functionality
    - Data produced is along the appropriate axes
    - Small perturbations distinct





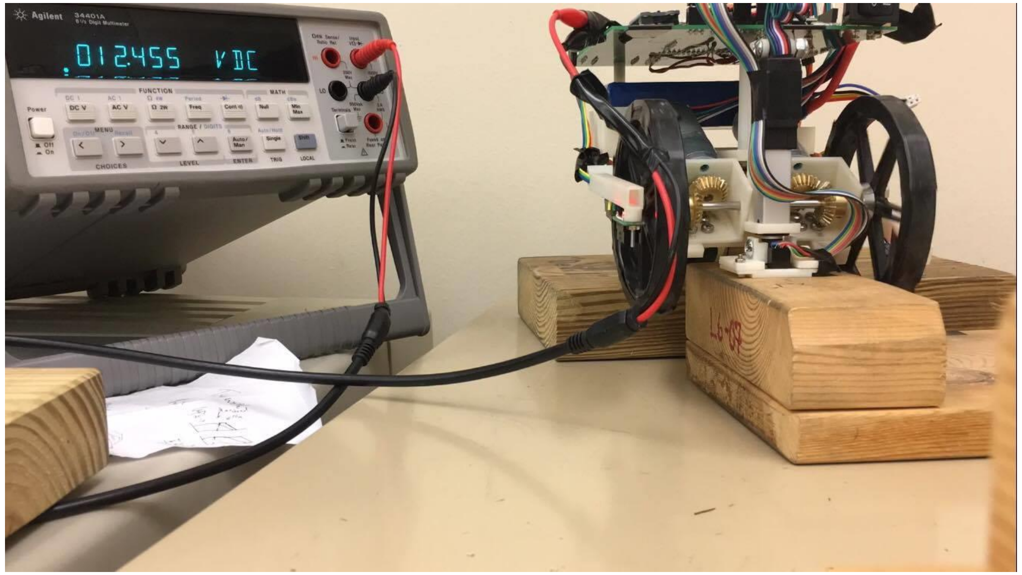
Test Event: Battery Life

- Battery life analysis will be divided into movement operation time and measurement operation time
- Movement operation time will be measured by having the motors drive continuously on metal surface as if it were traversing a bridge
- Measurement operation time will be measured by having the robot collect ambient vibration data
- Requirements will be met if each lifetime surpasses one hour

Battery Life Results

- Upon further discussion, the highest current draw would be during the robot movement as the motors are driven
  - By verifying the movement battery life requirement, the measurement battery life requirement is also verified

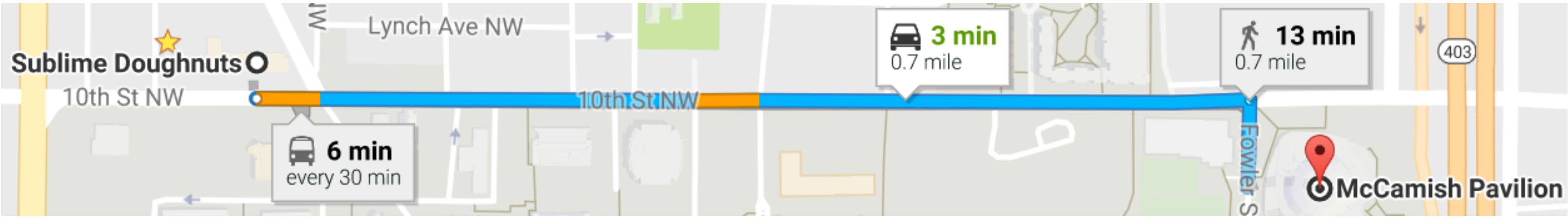
- The robot was set to spin wheels freely while attached to a multimeter
  - 0.25V for 1hr
  - Not completely representative as there is higher current draw when wheels are under load and magnetized to metal surfaces



Test Event: Wireless Communication Distance

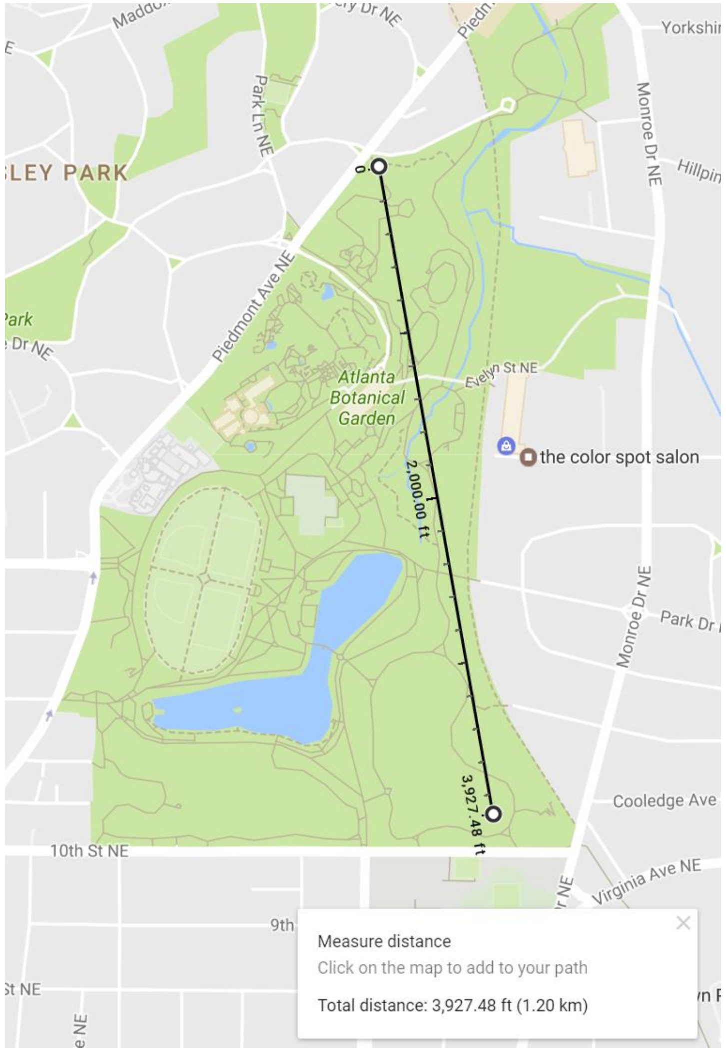
- The robot shall send data at distances varying linearly from 500m to 1000m to a base computer

- Communication distance is verified if it can accurately send data at least 800m away from the computer



Wireless Communication Distance Results

- Initial test sent GPS data back to base computer along 10th Street to the north of Georgia Tech’s main campus
  - GPS data gave out at approximately 500 m
  - Concerns regarding the foliage and passing cars obfuscating the signal
- Retest to take place at Piedmont Park
  - More open space and clearer line-of-sight between robot and PC



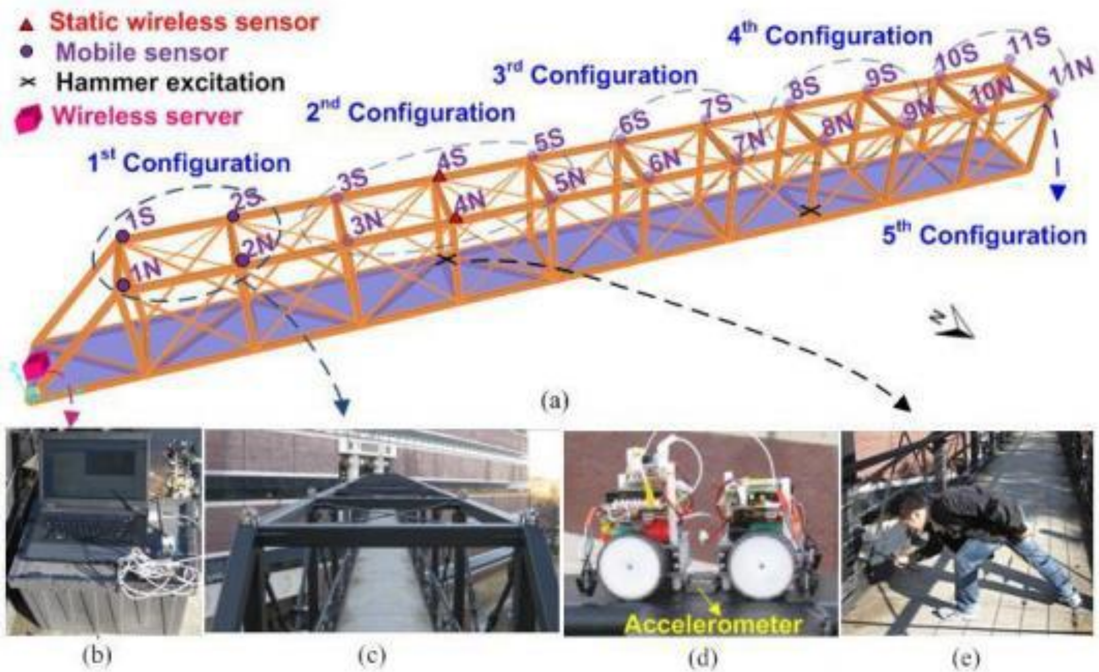
Measure distance

Click on the map to add to your path

Total distance: 3,927.48 ft (1.20 km)

Test Event: Final Demonstration

- The robot will be placed on the MRDC bridge and be expected to traverse to one of the measurement locations in each configuration
- At each configuration, the robot will take measurements at one location simultaneously with stationary sensors at the remaining locations and send the data to the base computer
- Measurement accuracy will be further confirmed by striking the bridge with a hammer during measurements

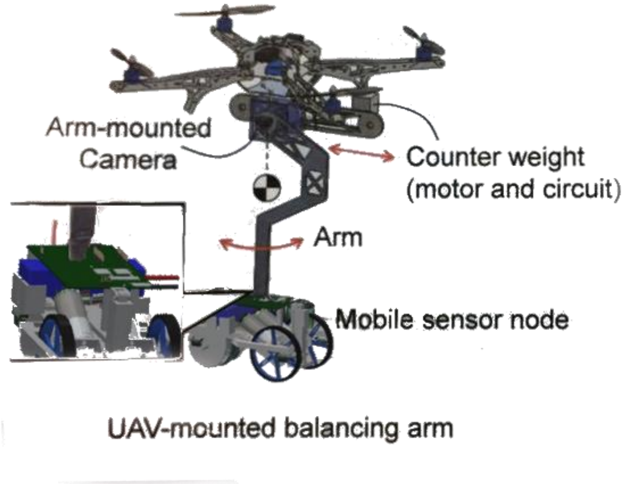


Final Demonstration

- The “bridge” has been brought to the presentation
- The robot shall:
  - Move along the “bridge”
  - Stop after moving for four seconds
    - Robot should not fall off
  - Deploy the accelerometer
  - Measure data
  - Transmit data wirelessly to PC
    - Data shall be plotted in MATLAB
  - Repeat the above procedure in triplicate

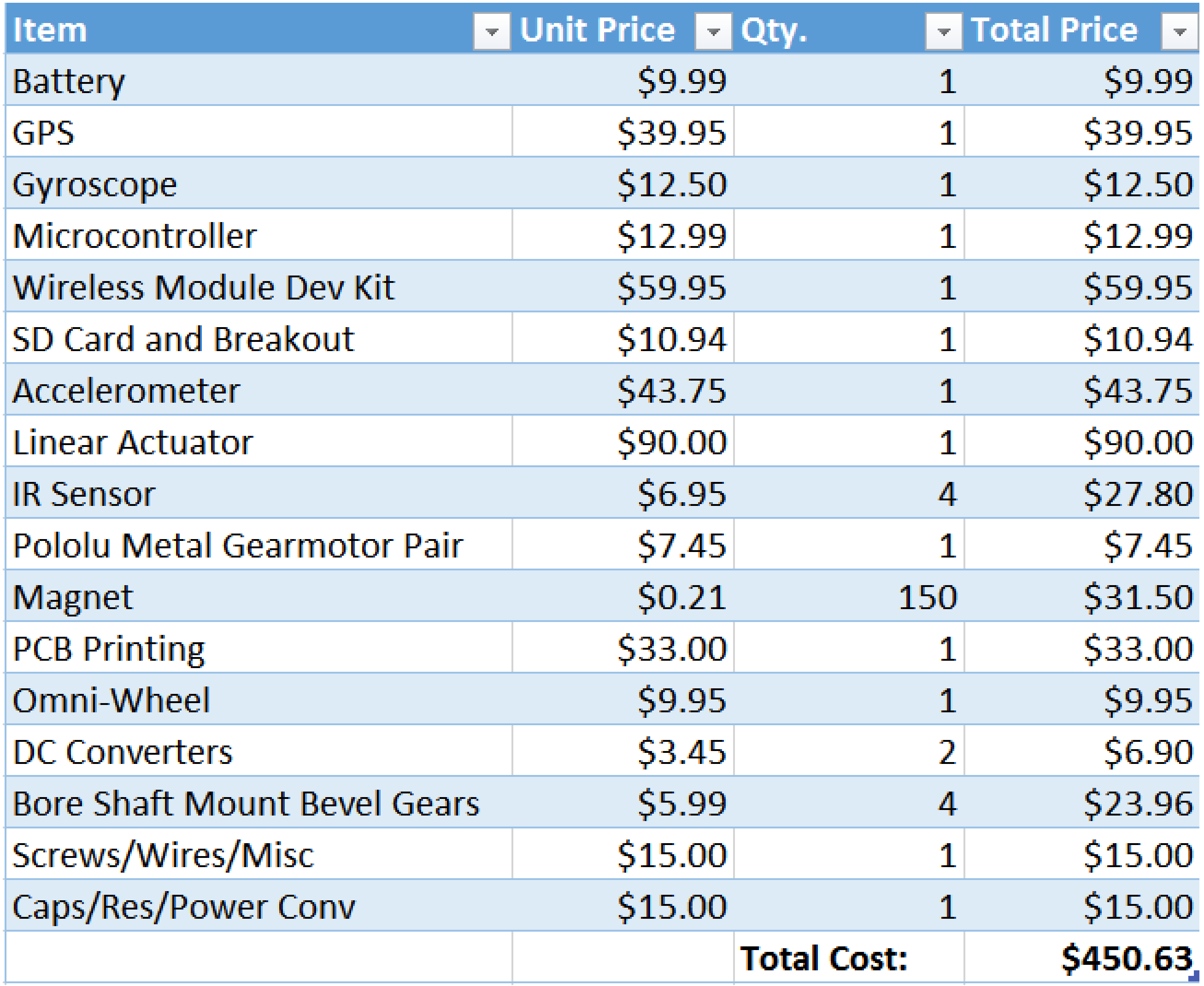
Future Steps

- Integrate gyroscope for complex path following
- Create network of robots for full mobile sensing network
- Modify robot for drone deployment and retrieval
- Incorporate localization



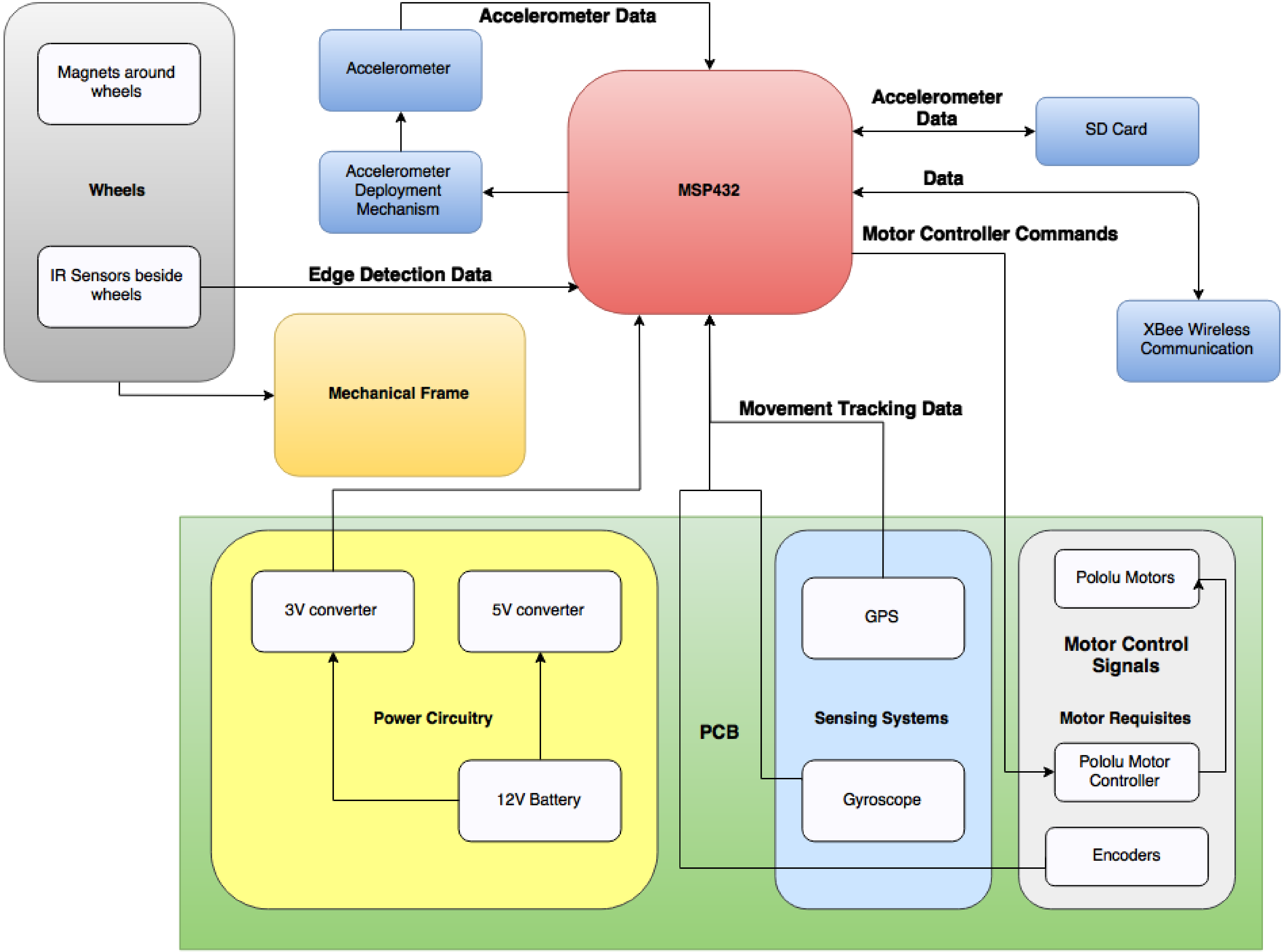
UAV-mounted balancing arm

Cost Analysis

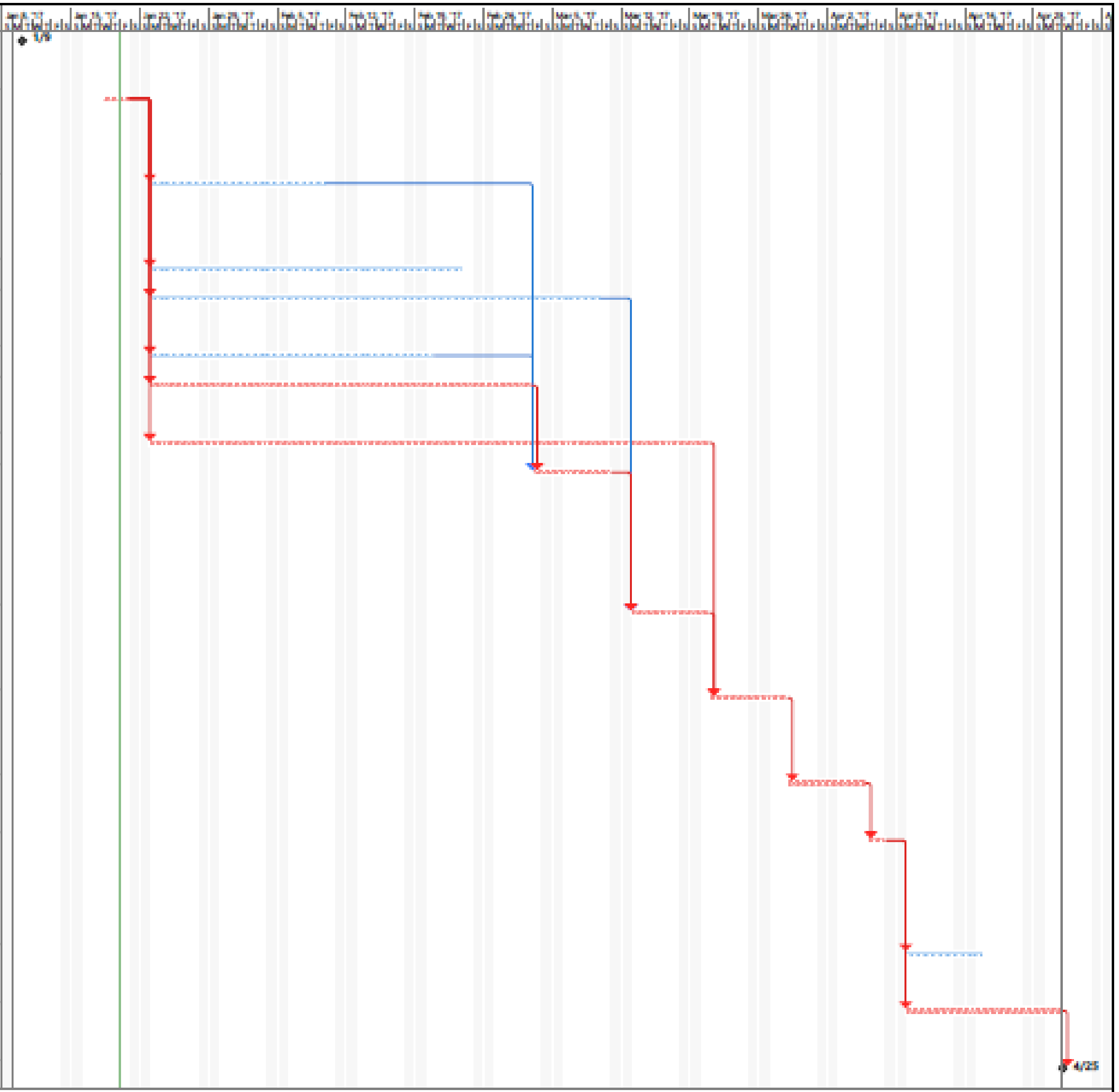


Item	Unit Price	Qty.	Total Price
Battery	$9.99	1	$9.99
GPS	$39.95	1	$39.95
Gyroscope	$12.50	1	$12.50
Microcontroller	$12.99	1	$12.99
Wireless Module Dev Kit	$59.95	1	$59.95
SD Card and Breakout	$10.94	1	$10.94
Accelerometer	$43.75	1	$43.75
Linear Actuator	$90.00	1	$90.00
IR Sensor	$6.95	4	$27.80
Pololu Metal Gearmotor Pair	$7.45	1	$7.45
Magnet	$0.21	150	$31.50
PCB Printing	$33.00	1	$33.00
Omni-Wheel	$9.95	1	$9.95
DC Converters	$3.45	2	$6.90
Bore Shaft Mount Bevel Gears	$5.99	4	$23.96
Screws/Wires/Misc	$15.00	1	$15.00
Caps/Res/Power Conv	$15.00	1	$15.00
		Total Cost:	**$450.63**

Questions?

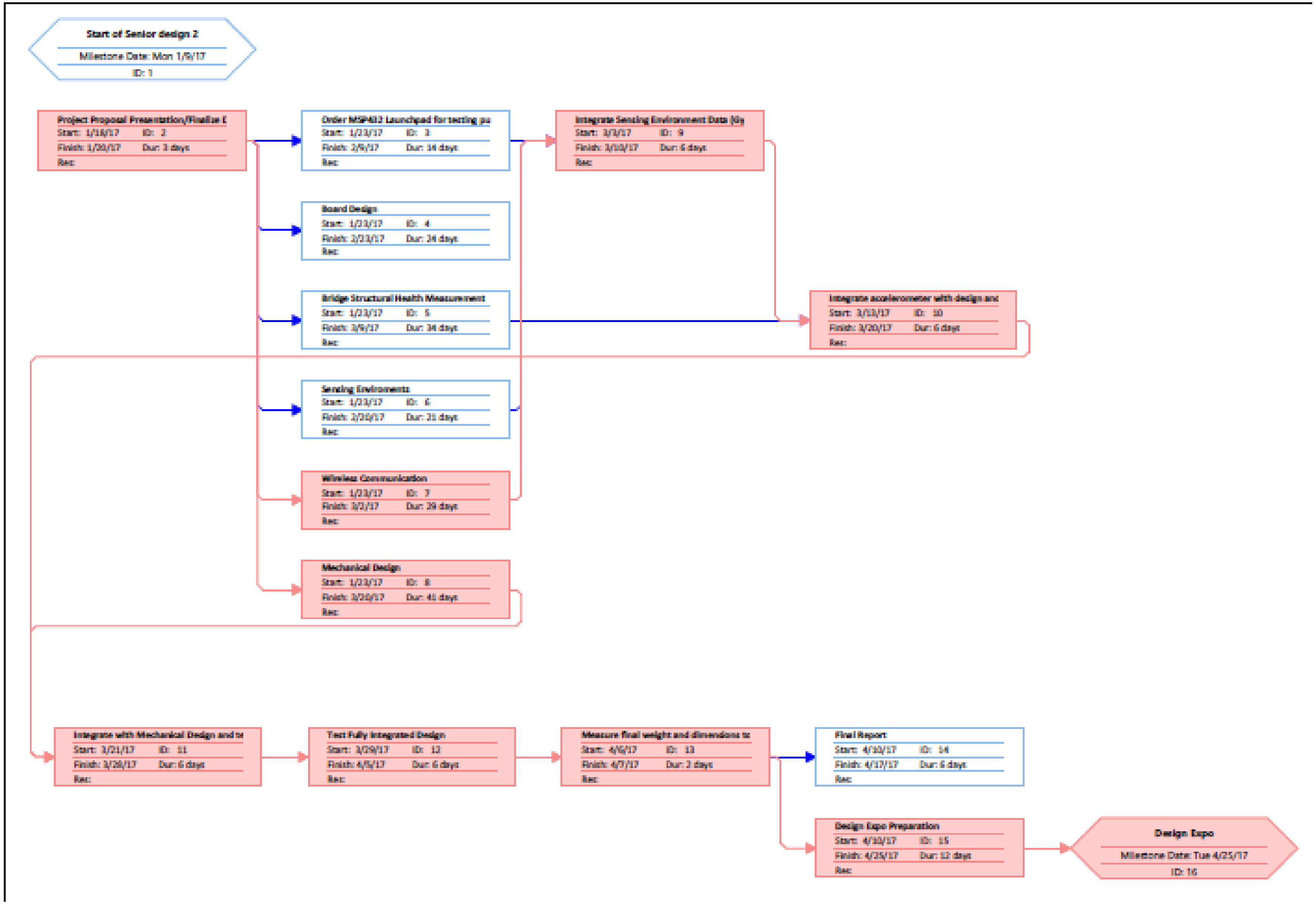

Accelerometer Data
Magnets around wheels
Accelerometer
Accelerometer Data
SD Card
MSP432
Accelerometer Deployment Mechanism
Wheels
Data
Motor Controller Commands
Edge Detection Data
IR Sensors beside wheels
XBee Wireless Communication
Mechanical Frame
Movement Tracking Data
3V converter
5V converter
GPS
Pololu Motors
Motor Control Signals
Power Circuitry
PCB
Sensing Systems
Motor Requisites
Pololu Motor Controller
12V Battery
Gyroscope
Encoders

ID	ℹ	Task Mode	Task Name	Duration	Start	Finish	Start Slack
1			Start of Senior design 2	0 days	Mon 1/9/17	Mon 1/9/17	76 days
2			Project Proposal Presentation/Finalize Design	3 days	Wed 1/18/17	Fri 1/20/17	0 days
3			Order MSP432 Launchpad for testing purposes	14 days	Mon 1/23/17	Thu 2/9/17	15 days
4			Board Design	24 days	Mon 1/23/17	Thu 2/23/17	43 days
5			Bridge Structural Health Measurement	34 days	Mon 1/23/17	Thu 3/9/17	1 day
6			Sensing Enviroments	21 days	Mon 1/23/17	Mon 2/20/17	8 days
7			Wireless Communication	29 days	Mon 1/23/17	Thu 3/2/17	0 days
8			Mechanical Design	41 days	Mon 1/23/17	Mon 3/20/17	0 days
9			Integrate Sensing Environment Data (Gyro, GPS, Encoders, IR) with Wireless Communication	6 days	Fri 3/3/17	Fri 3/10/17	0 days
10			Integrate accelerometer with design and test	6 days	Mon 3/13/17	Mon 3/20/17	0 days
11			Integrate with Mechanical Design and test	6 days	Tue 3/21/17	Tue 3/28/17	0 days
12			Test Fully Integrated Design	6 days	Wed 3/29/17	Wed 4/5/17	0 days
13			Measure final weight and dimensions to verify product specifications	2 days	Thu 4/6/17	Fri 4/7/17	0 days
14			Final Report	6 days	Mon 4/10/17	Mon 4/17/17	6 days
15			Design Expo Preparation	12 days	Mon 4/10/17	Tue 4/25/17	0 days
16			Design Expo	0 days	Tue 4/25/17	Tue 4/25/17	0 days

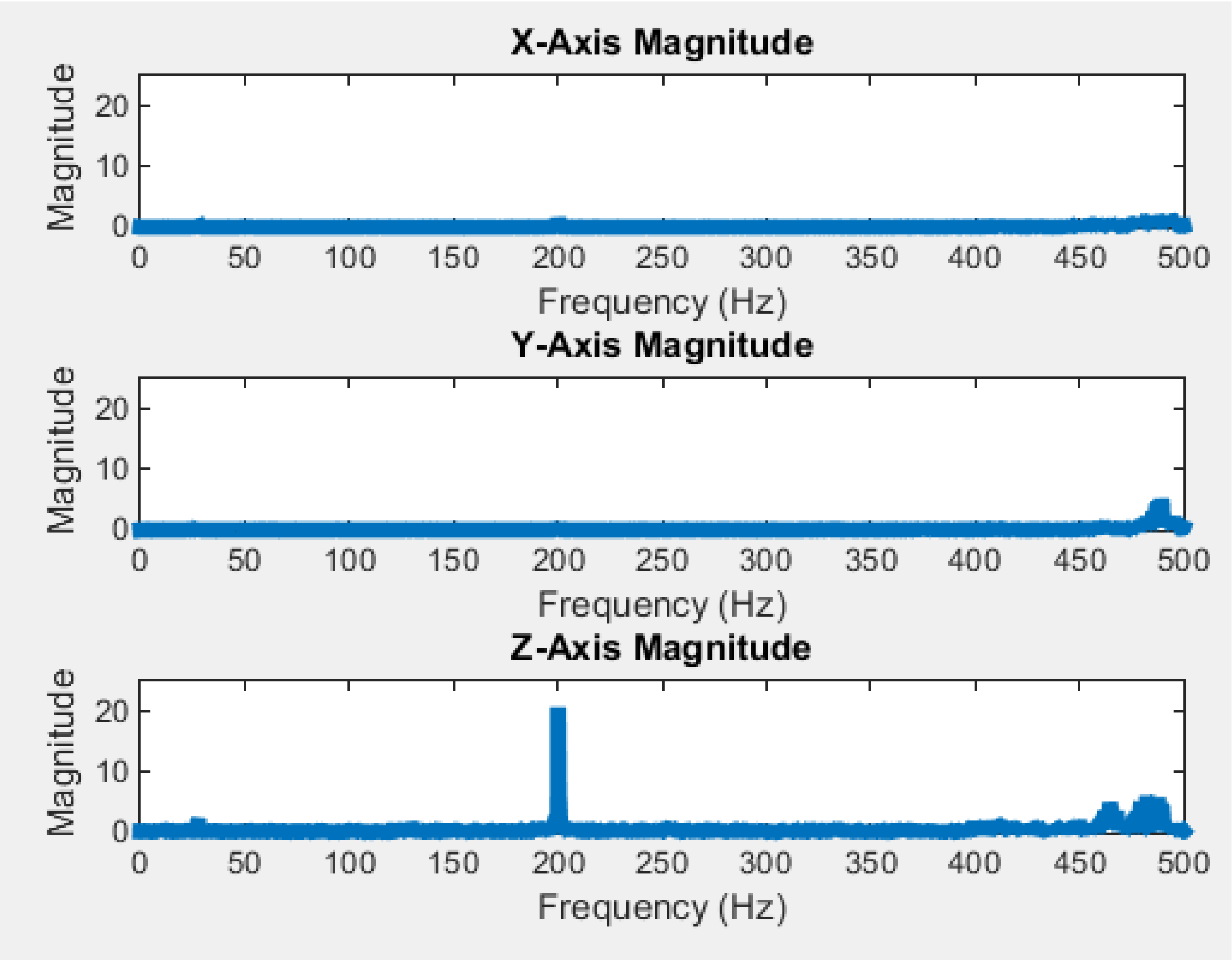


Project: Project1
Date: Fri 1/20/17

Task
Split
Milestone ◆
Summary
Project Summary
Inactive Task
Inactive Milestone
Inactive Summary
Manual Task
Duration-only
Manual Summary Rollup
Manual Summary
Start-only
Finish-only
External Tasks
External Milestone ◆
Deadline
Critical
Critical Split
Progress
Manual Progress


Start of Senior design 2
Milestone Date: Mon 1/9/17
ID: 1
Project Proposal Presentation/Finalize E
Start: 1/18/17 ID: 2
Finish: 1/20/17 Dur: 3 days
Res:
Order MSP432 Launchpad for testing pu
Start: 1/23/17 ID: 3
Finish: 2/9/17 Dur: 14 days
Res:
Integrate Sensing Environment Data (Gy
Start: 3/3/17 ID: 9
Finish: 3/10/17 Dur: 6 days
Res:
Board Design
Start: 1/23/17 ID: 4
Finish: 2/23/17 Dur: 24 days
Res:
Bridge Structural Health Measurement
Start: 1/23/17 ID: 5
Finish: 3/9/17 Dur: 34 days
Res:
Integrate accelerometer with design anc
Start: 3/13/17 ID: 10
Finish: 3/20/17 Dur: 6 days
Res:
Sensing Enviroments
Start: 1/23/17 ID: 6
Finish: 2/20/17 Dur: 21 days
Res:
Wireless Communication
Start: 1/23/17 ID: 7
Finish: 3/2/17 Dur: 29 days
Res:
Mechanical Design
Start: 1/23/17 ID: 8
Finish: 3/20/17 Dur: 41 days
Res:
Integrate with Mechanical Design and te
Start: 3/21/17 ID: 11
Finish: 3/28/17 Dur: 6 days
Res:
Test Fully Integrated Design
Start: 3/29/17 ID: 12
Finish: 4/5/17 Dur: 6 days
Res:
Measure final weight and dimensions to
Start: 4/6/17 ID: 13
Finish: 4/7/17 Dur: 2 days
Res:
Final Report
Start: 4/10/17 ID: 14
Finish: 4/17/17 Dur: 6 days
Res:
Design Expo Preparation
Start: 4/10/17 ID: 15
Finish: 4/25/17 Dur: 12 days
Res:
Design Expo
Milestone Date: Tue 4/25/17
ID: 16

Before Low pass with 0.5 attenuation



After Low pass with 0.5 attenuation