Bridge Inspection Robot

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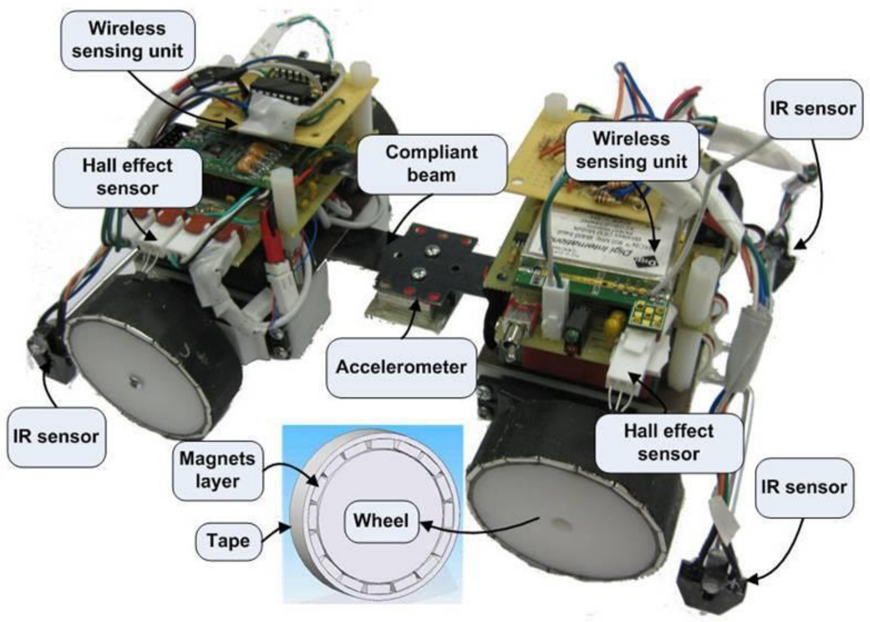
Introduction

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



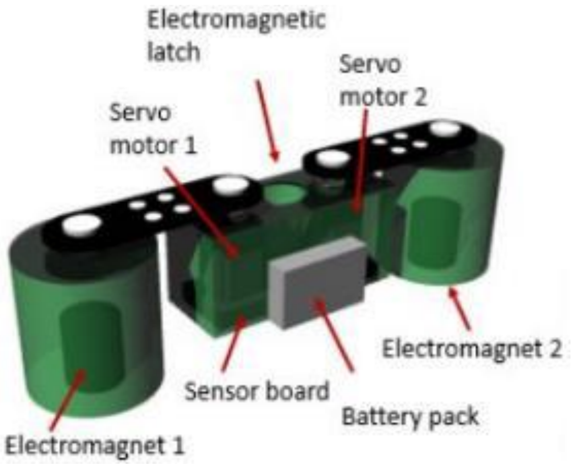
Goals and Stretch Goals

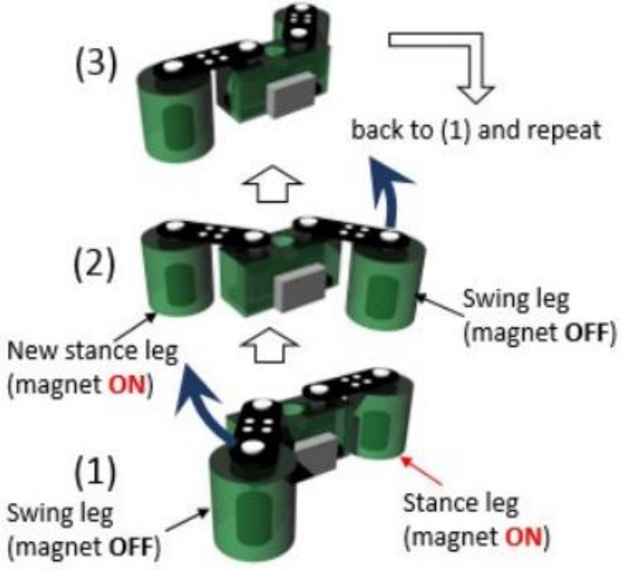
- **Goals**
  - Ability to horizontally and vertically traverse steel bridges
  - Measure bridge vibrations at low frequencies
  - Wirelessly transmit vibration data to a PC
  - Holding weight strong enough for future module attachments
  - Light enough for deployment and retrieval by drone

- **Stretch Goals**
  - Complex Path following

Mobility: Legged Design with Joints

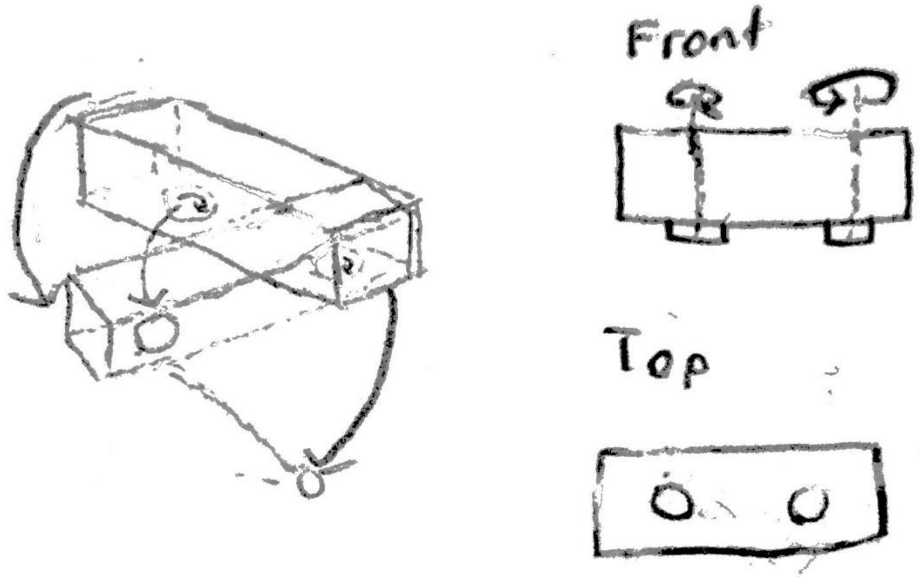
- Two legs attached with joints to a rigid body
- Electromagnets at the "feet"
- Servos placed at the joints move robot through waddling action
- Pros
    - Can turn any angle in one movement
- Cons
    - Cannot traverse inclines or corners
    - Feet will scrape floor during movement
    - Requires more movement controls
    - Mechanical complications





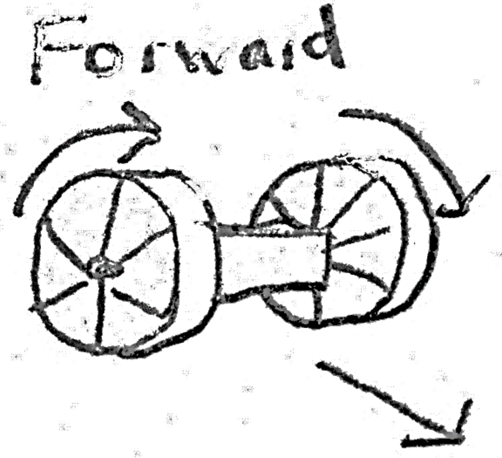
Mobility: Legged Design without Joints

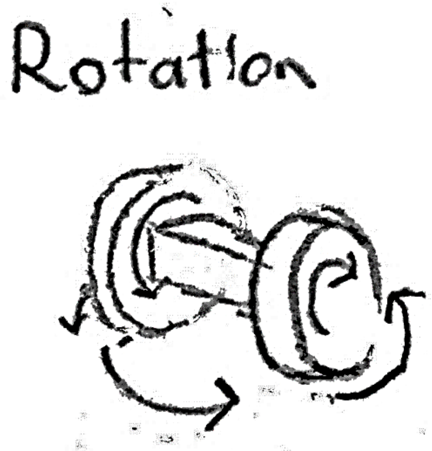
- Two legs attached without joints to a rigid body
- Electromagnets at the “feet”
- Servos placed in the legs move robot through waddling action
- Pros
  - Can turn any angle in one movement
  - Mechanically simplified
- Cons
  - Requires more movement controls
  - Cannot traverse inclines or corners
  - Feet will scrape floor during movement

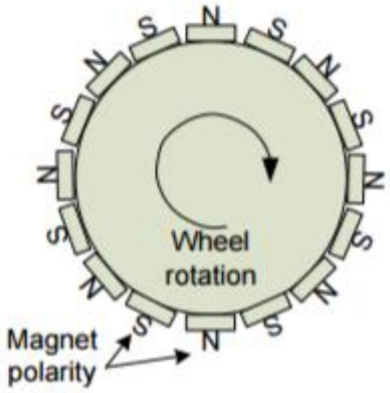


Mobility: Two-Wheeled Design

- Rigid body between two wheels
- Permanent magnets surround wheels
- Pros
  - Simple movement controls
  - Fast traversal of linear paths
  - More power efficient
  - Able to climb inclines
  - Rotate in place
- Cons
  - Body will not stay parallel to surface on inclines – requires additional system for accelerometer deployment
  - Magnets will keep wheels stationary when motors are driven

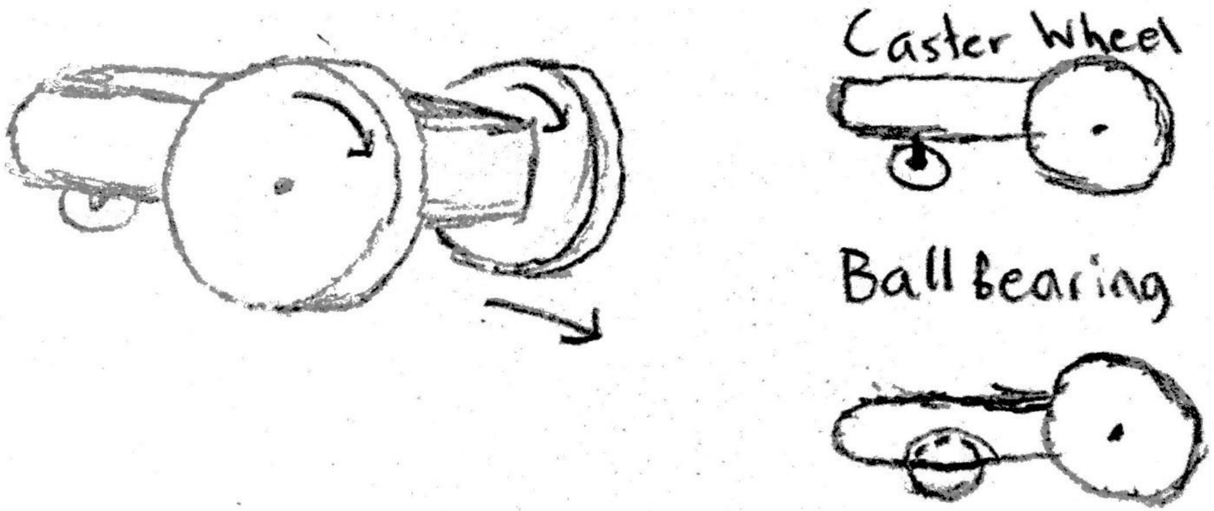






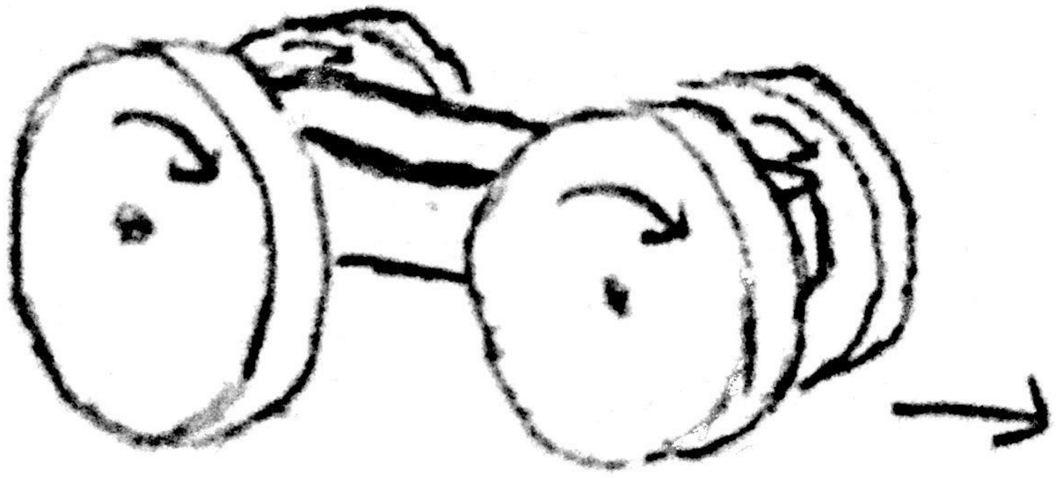
Mobility: Three-Wheeled Design

- Two motorized wheels in the front and a passive caster wheel/ball bearing at the back
- Permanent magnets surround motorized wheels
- Permanent magnet placed above ball bearing or around caster wheel
- Pros
  - Retains pros of previous design
  - Solves movement problem of two-wheeled design
- Cons
  - Third wheel or bearing is a more complex implementation



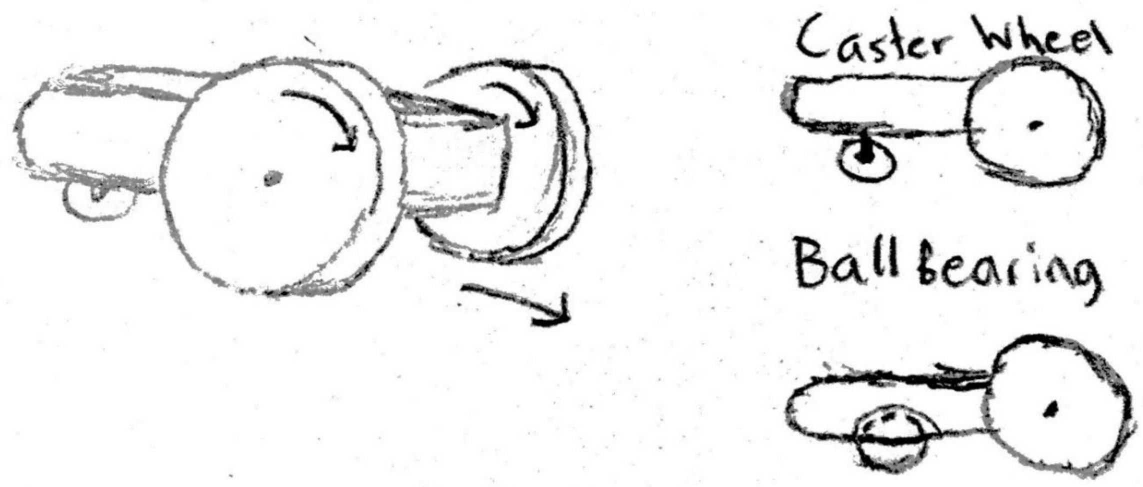
Mobility: Four-Wheeled Design

- Single rigid body with two motorized wheels in front and two motorized wheels in the back
- Permanent magnets surround wheels
- Pros
  - Smaller form factor
  - Stable
- Cons
  - Higher weight and power consumption from extra motors
  - Wheel width must be thin enough to allow slippage during turning but thick enough for magnetic forces



Mobility Choice: Three-Wheeled Design

- Overcomes forward movement problem of two-wheeled design
- Retains all the pros of the two-wheeled design
- Less weight and power consumption compared to four-wheeled design



Motion Requirements

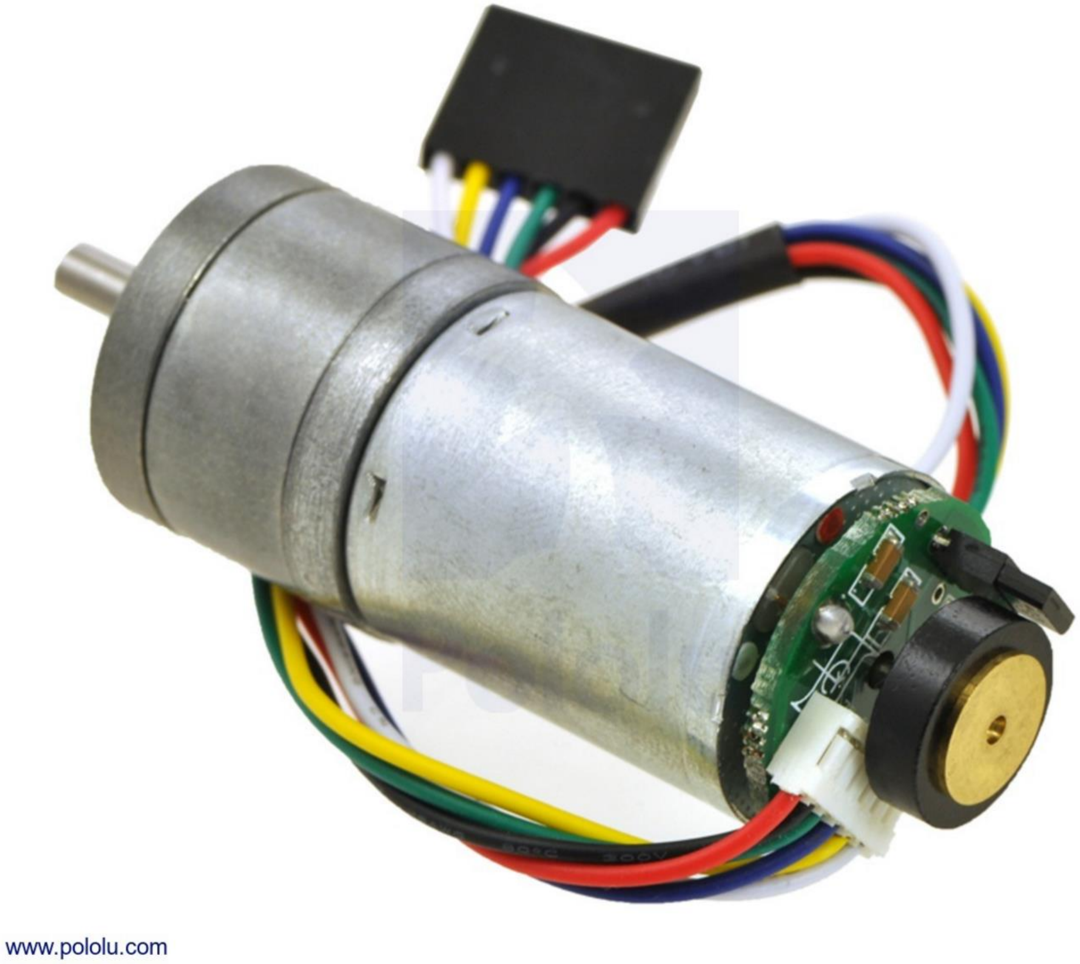
- For this design, weight and power consumption need to be minimalized
- RPM can be relatively low since the robot does not need to traverse the bridge extremely fast
  - A four inch wheel turning at 60RPM would travel ~20m per minute
- Moderate to high torque will be needed for angles up to 90°
- There are not major space constraints on the motor
- One motor would be required for each driven wheel
- Encoder would be required, either built-in or as a separate module

Motor Options

Motor Name	Motor Type	Operating Voltage	Current Draw	Torque	Speed	Interface	Weight
Dynamixel Ax-12	Servo	9V-12V	50mA/900mA	15.3kg-cm	59 RPM	Async Serial	55g
Futaba S3003	Servo	4.8V-6V	8mA/400mA	4.2kg-cm	52 RPM	Analog	44.2g
Tower Pro MG995R	Servo	4.8V-6V	30mA/400mA	10kg-cm	62 RPM	Pulse	55g
Micro Gear Box Motor	BDC	12V	110mA/800mA	4kg-cm	100RPM	PWM	193g
Pololu 37D metal gearmotor	BDC	6V 12V	250mA/2.5A 300mA/5A	9kg-cm 18kg-cm	80RPM 40RPM	PWM	205g
Pololu 25D metal gearmotor w/ encoder	BDC	12V	100mA/1.1A	6kg-cm 8kg-cm …	71RPM 55RPM …	PWM	104g

Motor Choice

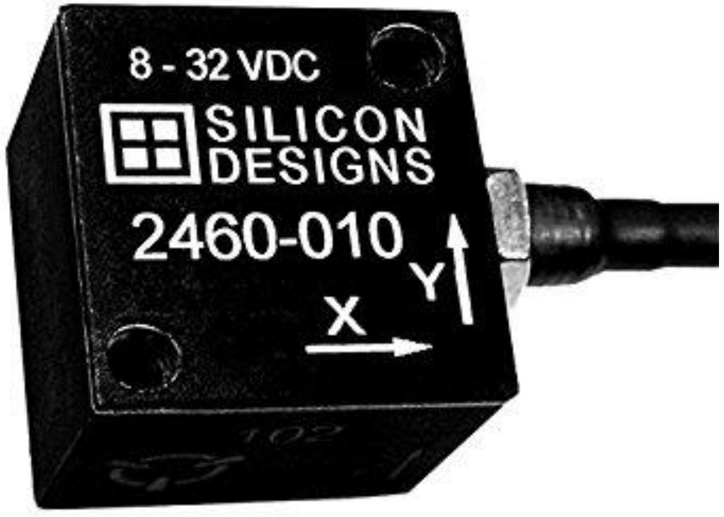
- The Pololu 25D metal gearmotor with encoder is our ideal motor
- The motor comes with a large variety of gear reduction options providing outputs ranging from 0.144 kg-cm at 5600 RPM to 23kg-cm at 100 RPM
- The motor also offers 3 power options, High, Medium and Low power at 12V



25D mm metal gearmotor with 48 CPR encoder.

Accelerometer: Silicon Designs 2460-002

- 3-Axis version of the original Model 2012-002
  - Significant lateral vibrations noted alongside vertical vibrations on the MARC bridge during previous testing
- Input Range: ± 2 g
- Frequency Response: 0 – 300 Hz
- Differential Sensitivity: 2000 mV/g
- Input Voltage: 8 – 32 VDC
- Operating Current: 19 – 27 mA DC
- Mass (without cabling): 21 g



Accelerometer Deployment Method

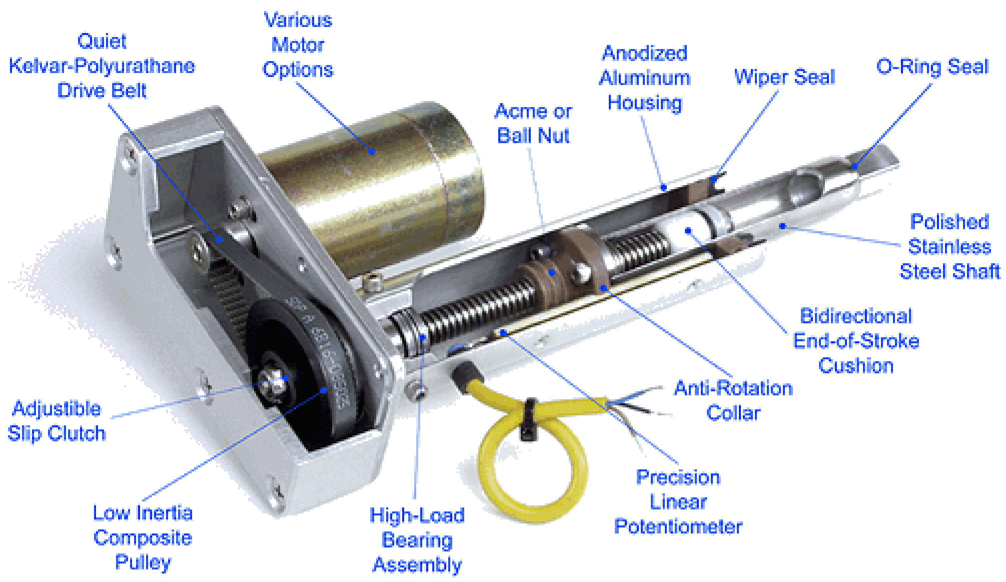
- Requirements
  - Accelerometer shall mount directly onto bridge
  - Accelerometer shall be flush with bridge to ensure accuracy of measurements
- Design must incorporate vertical motion w.r.t. the Bridge Inspection Robot frame

Method 1: Rack & Pinion

- Pros
  - Low torque and power requirements
  - Simple design concept
- Cons
  - No existing prepackaged solution
  - Rack adds excess weight

Servo	Torque	Speed	Input Voltage	Current Draw	Mass	Encoder?	Interface
Hitec HS-422	4.1 kg-cm	0.16 sec/60°	4.8 V to 6.0 V	8 mA / 150 mA	45.5 g	No	Pulse
Futaba S3003	4.2 kg-cm	0.19 sec/60°	4.8 V to 6.0 V	8 mA / 400 mA	44.2 g	No	Analog
Goteck GS-9025MG	2.5 kg-cm	0.10 sec/60°	4.8 V to 6.0 V	250 mA / 1000 mA	14.7 g	No	FET drive

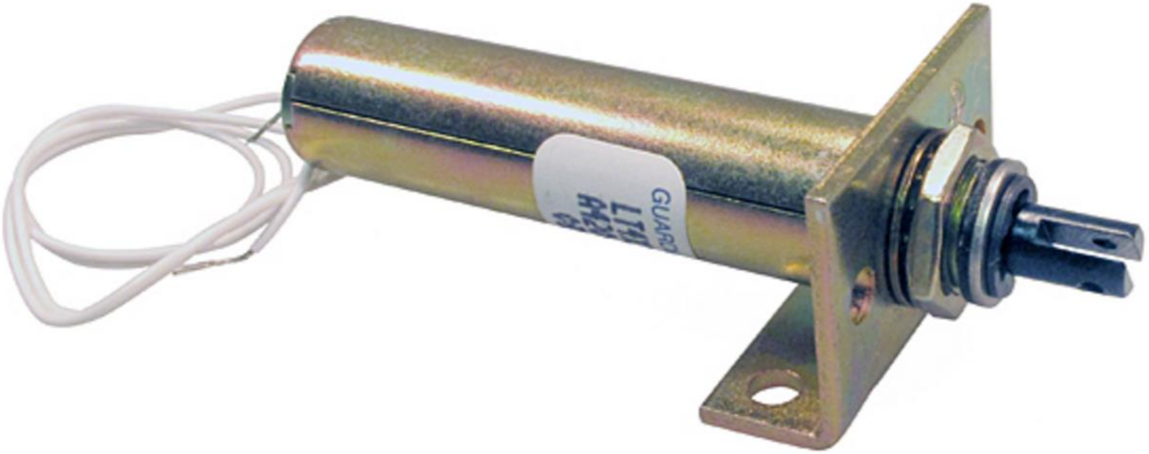
Method 2: Linear Actuator



- Pros
  - Store-bought plug-and-play piece
  - Less mass than rotary actuator for rack & pinion method
- Cons
  - Expensive to purchase
  - Vertically space consuming

Actuator	Stroke	Accuracy	Input Voltage	Current Draw	Mass	Potentiometer?	Interface
PQ12 20mm	20 mm	± 0.1 mm	6 V 12 V	550 mA (Stall) 210 mA (Stall)	15 g	Yes	Analog
L12 30mm	30 mm	± 0.2 mm	6 V 12 V	7.2 mA / 460 mA 3.3 mA / 185 mA	34 g	Yes	Analog
L12 100mm	100 mm	± 0.3 mm	6 V 12 V	7.2 mA / 460 mA 3.3 mA / 185 mA	56 g	Yes	Analog

Method 3: Solenoid



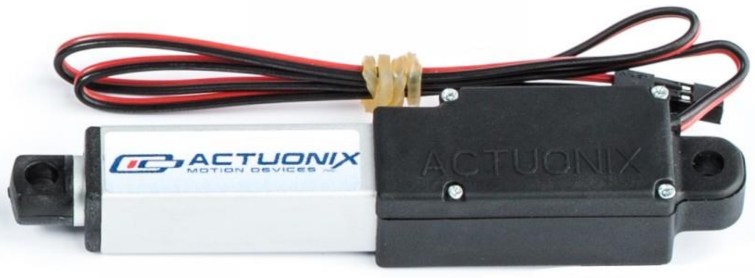
- Pros
  - Fast actuation from robot to bridge and back
  - Easy start and stop indications for data collection
- Cons
  - No holding force, may be difficult to ensure proper contact
  - High power consumption

Actuator	Stroke	Input Voltage	Watts	Mass	Interface
Series S-20-90-H	50.8 mm	12.1V	9W	155g	DC

Design Decision: Linear Actuator

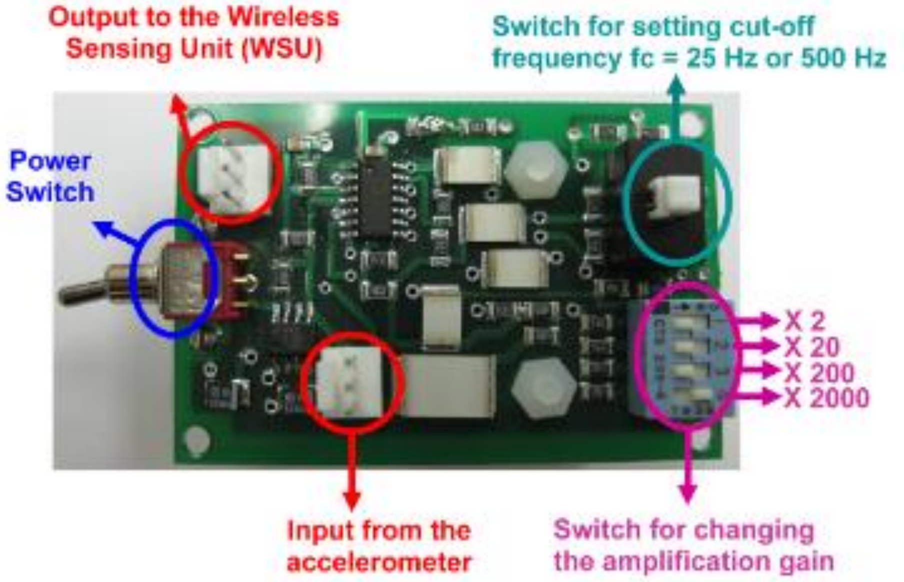
- Actuonix L12 30mm Linear Actuator
  - Prepackaged solution
  - Very low mass
  - Potentiometer already available for control

- May explore Rack & Pinion further if Mechanical Engineer joins team or if complications occur



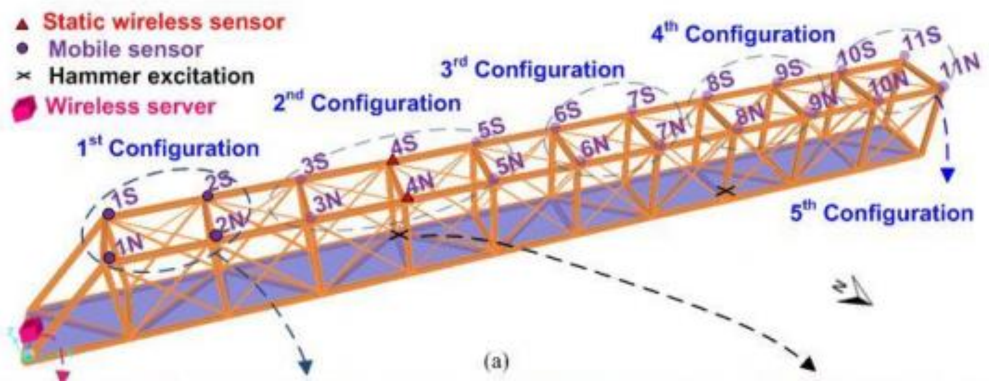
Accelerometer Signal Conditioning Module

- Prior testing showed structural vibrations yielded peak amplitude of only 0.125 mV at a vibration amplitude of 0.001 m/s^2
  - Susceptible to circuitry noise
  - Difficult to digitize with standard A/D Conversion



- Custom Signal Conditioning Module used in previous design
  - Amplifies and conditions signal before A/D Conversion
  - Receiving support from Dr. Wang for updating the current module to work with new accelerometer

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

Requirement 1: Straight Path

- Need to go in a roughly straight path so robot won't need to continuously correct path (only yaw is considered)
- Possible Solutions:
  - Gyroscope
    - Pros: Cheap, simple data
    - Cons: No constant reference, just measures change of angle so error can accumulate
  - Magnetometer (basically compass):
    - Pros: Cheap, simple data, constant reference of earth magnetic field
    - Cons: Magnetometer reference will be skewed by permanent magnets on wheels
  - Encoders
    - Pros: Cheap, simple data, probably not much drift due to permanent magnets holding the wheels well to the bridge, can be used for path correction by spinning one wheel more than other
    - Cons: Still potential for drift and no constant reference

Requirement 1: Straight Path Cont.

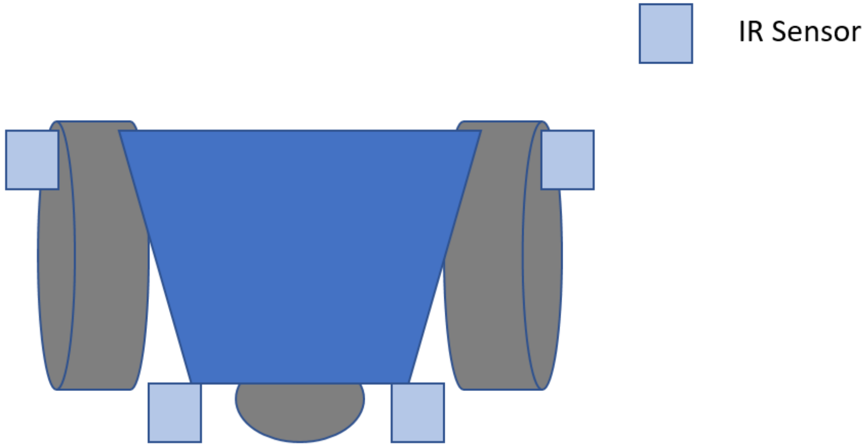
- Proposed solution:
  - Use Encoders on motor
- Stretch Goal:
  - Implement gyroscope as well
  - Will buy gyroscope and make sure gyro data is at least accessible

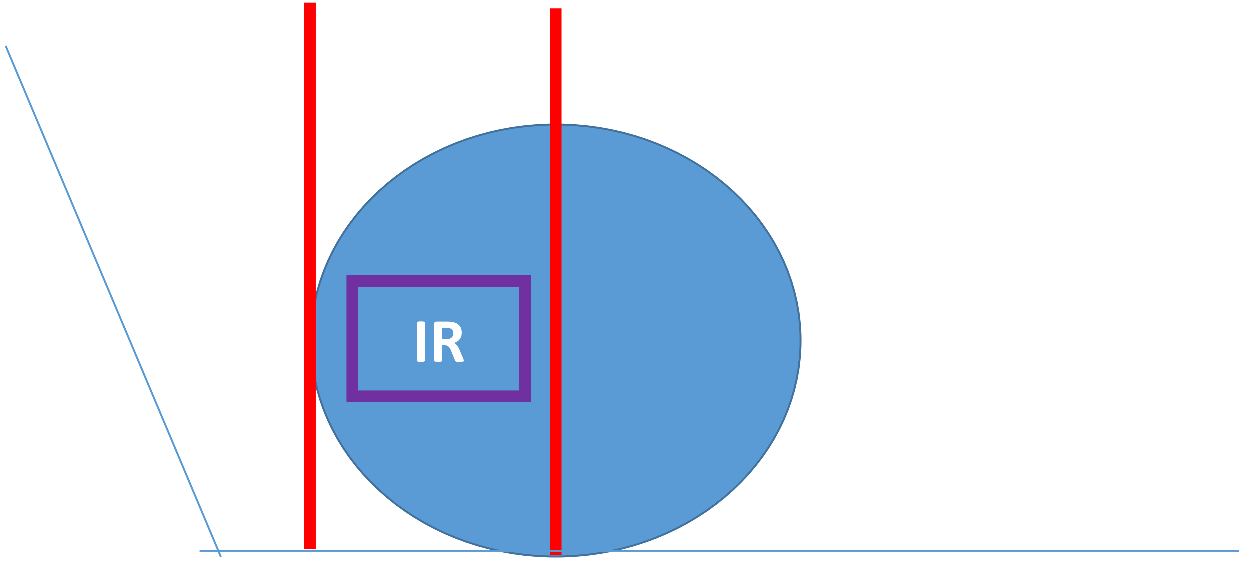
Requirement 2: Edge Detection

- Need to be able to detect edges so robot won’t fall off
- Possible Solutions
  - IR Sensors
    - Pros: Implemented before, simple output, cheap
    - Cons: Color of bridge could affect edge detection capabilities (may need to adjust thresholds for an edge "hit" from bridge to bridge)
  - Ultrasonic sensors
    - Pros: Color no longer an issue
    - Cons: Generally more expensive than IR Sensors, sound-absorbent material blinds the sensor

Requirement 2: Edge Detection cont.

- Proposed Solutions
  - IR Sensors
    - Four IR sensors mounted close to wheels and near edge
    - Will verify that wheels will hit inclines so that sensors will not scrape against surfaces





Requirement 3: Motion Tracking

- Need to be able to identify locations of structural health measurements to around about 2m resolution fairly accurately as in experiment in thesis paper
- Possible Solutions
  - Solely Encoders
    - Pros: Already on robot for previous requirements so dual purpose
    - Cons: Encoder measurements not absolute so drift over long range
  - GPS
    - Pros: Absolute reference of position, pretty accurate (2m resolution)
    - Cons: Won't work in regions with poor receptions and under the bridge
  - Separately bought IMU
    - Pros: Very accurate for small movements, can potentially localize, and all filtering and sensor data-fusion already done
    - Cons: Not accurate over large distances, can be expensive
  - Use existing accelerometer in conjunction with encoders and gyroscope
    - Pros: Very accurate for small movements, save money and weight by using sensors already needed for robot
    - Cons: Need to implement filtering, sensor data fusion, and movement interpolation ourselves

Requirement 3: Motion Tracking Cont.

- Proposed Solutions
  - Implement Now: Use encoder movement, combined with GPS for absolute position recalibration every 2m
    - Pros: Removes drift of encoder, when under bridge can rely purely on encoders
    - Cons: Extra part
  - Future: Incorporate accelerometer and Gyroscope for extra position verification, and discard GPS
    - Pros: Less cost
    - Cons: Harder to implement accurately

Gyroscope

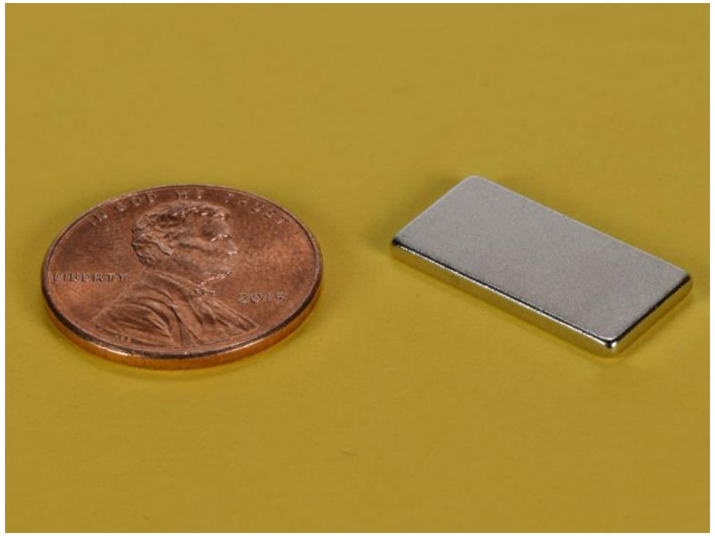
Name	# of axes	Price	Resolution	Accuracy	Power Draw	Interface	Other
SparkFun Triple-Axis Digital-Output Gyro Breakout - ITG-3200	3	$24.95	± (2000°/sec) /(2^16) = ± .0305°/sec	Zero Bias: ± 40°/s	23.4 mW	I2C	user-selectable internal low-pass filter bandwidth. Fast-Mode I2C (400kHz). Temp sensor. Optional external clock inputs of 32.768kHz or 19.2MHz to synchronize with system clock
ST L3GD20H	3	$3.42	±245/±500 /±2000°/s with 16 bits	Zero Bias: ±25°/s	15 mW	I2C/SPI	User enabled integrated low-pass and high-pass filters. Temp sensor.
SparkFun Tri-Axis Gyro Breakout - L3G4200D	3	$49.95	±250/±500 /±2000°/s with 16 bits	Zero Bias: ±245/±500/±2000°/s	21.96 mW	I2C/SPI	Integrated low- and high-pass filters with user-selectable bandwidth

GPS

Name	Price	Accuracy	Update Frequency	Sensitivity	Power	Interface	Other
Adafruit Ultimate GPS Breakout - 66 Channel MTK3339	$39.95	1.8 m	10 Hz	165 dBm	100 mW	Serial Comuniation	Comes with breakout board. Has in-built data-logging. SMA connector to connect external antenna.
GPS Bee with Mini Embedded Antenna	$16.00	2.5 m	4 Hz	160dBm	200 mW	UART, USB, DDC and SPI interfaces	SMA connector to connect external antenna.
Venus GPS with SMA Connector	$49.95	2.5 m	20 Hz	165dBm	297 mW	UART, SPI	Internal flash for optional 75K point data logging. SMA connector to connect external antenna.

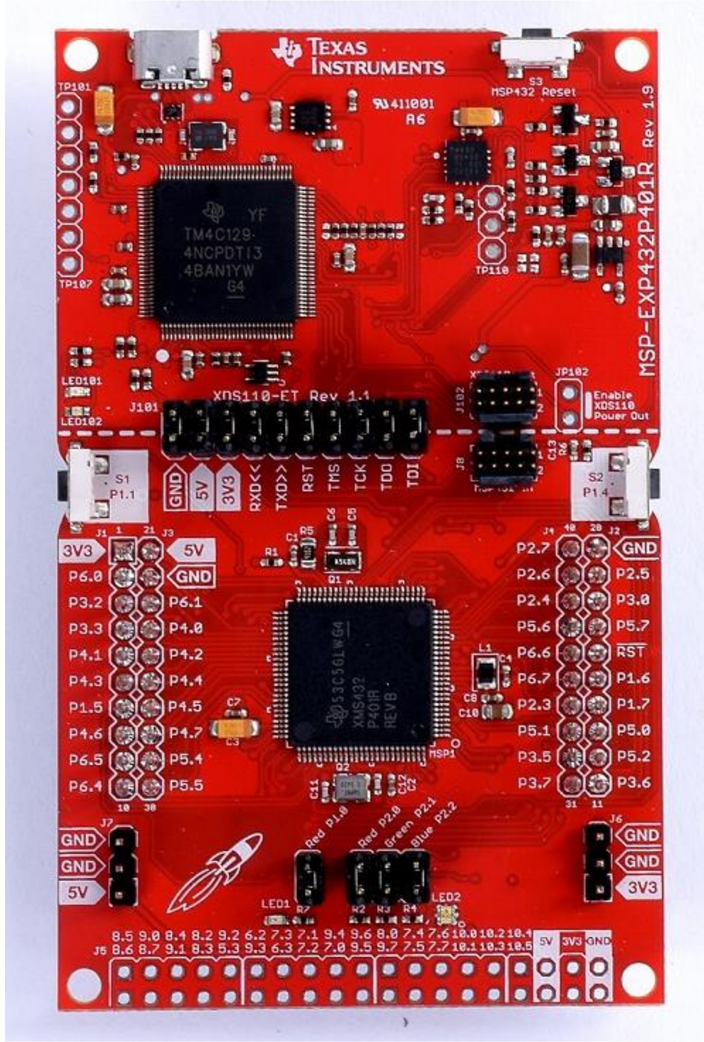
Magnets

- Electromagnet
  - Example specifications
    - 20x15mm
    - 12VDC @ 0.25A
    - Strength: 5.5 lb.
- Permanent magnet (neodymium)
  - Example specifications
    - No power cost
    - 3/4" x 3/8" x 1/16"
    - Strength: 3.86 lb.



Microcontroller – TI MSP432P401R

- Specifications
  - 48 MHz ARM 32-bit CPU
  - 256 kB of flash memory
  - 64 kB SRAM
  - 14-bit ADC
  - Current draw (active mode, typical): 7.8 mA
- Programmed via Code Composer Studio IDE
- MSP432 Launchpad will be used for rapid prototyping
- Surface-mounted MSP432 will be incorporated into final design



Wireless Module - XBee S2C DigiMesh 2.4

- Specifications
  - Max outdoor range: 1200 m
  - Throughput: up to 250 Kbps
  - Data payload per frame: up to 256 Kbps
  - Interface: SPI
  - Current draw (typical): 28-33 mA
  - Wireless Protocol: Digimesh
- Raw conditioned data will be sent to PC for post-processing

Power Requirements

- Power requirements will be mainly dependent on the following:
  - Motors
  - Wireless
  - Accelerometer
  - Acc Deployment
- The robot is expected to run for at least one hour actively and an additional hour stationary
- The robot will require a maximum voltage of 12V to accommodate the accelerometer and motors. Power conversion circuitry will be used to create lower voltages for other components

Battery Options

Battery Type	Voltage Rating	Capacity	Recharge?	Weight	Vendor
Alkaline AA	1.5V	1000mAh	No	23g	Duracell
Alkaline 9V	9V	500mAh	No	45g	Duracell
Ni-Mh AA	1.2V	2600mAh	Yes	26.5g	Tenergy
Ni-Mh AAA	1.2V	1000mAh	Yes	13g	Tenergy
Ni-Mh 9V	9V	250mAh	Yes	86g	Tenergy
NiCd AA	1.2V	1000mAh	Yes	27g	Tenergy
Li-Ion	3.7V	3000mAh	Yes	45g	EBL
Li-Ion	9V	600mAh	Yes	30g	EBL
Lipo 3S	11.1V	2200mAh	Yes	170g	Turnigy
Lipo 3S	11.1V	5000mAh	Yes	489g	Turnigy

Battery Choice

- Ni-Mh AAA (10 in series) or Lipo 3S
- The Lipo can provide a higher continuous current and doesn't need several in series, but would need a special charger

Structure

- A holding structure will be needed for the battery and circuitry
- It can be rapidly prototyped using Inventor 2017 and 3D printing with the Senior Design Lab
- A chassis is needed to support the motors and previously mentioned holding structure. Aluminum or acrylic sheets will be cut for a high strength support. This can also be designed in Inventor 2017 and machined at the invention studio
- Both of these tasks will likely require assistance from and mechanical engineer

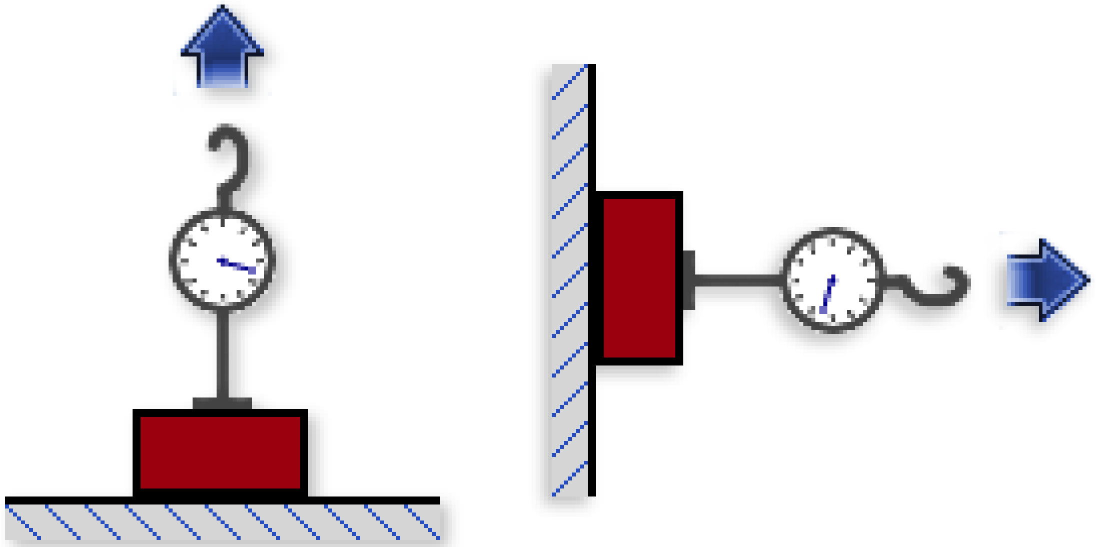
Circuit Design

- The design will use a single circuit board for power, data transmission, and motor control
- It will be designed in using the educational license of Autodesk Eagle
- Printing will be completed professionally by one of the following:
    - Advanced Circuits - $33, 2 layer board up to 4”x6”, 2 week turnaround
    - OSH Park - $5/sq-in for three boards, 12 day turnaround
    - Senior Design Lab– Potentially free, 10 day turnaround

Verification – Holding Force

- Holding force of magnets will be verified by measuring the amount of time a magnet can maintain its position in different configurations

- Requirement is verified if magnets can maintain their position with a 1kg mass attached at various locations for at least 2 minutes



Verification – Accelerometer Data Accuracy

- Verification of the accelerometer data accuracy will require 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

Verification – Battery Life

- Battery life analysis will be divided into traversal lifetime and holding lifetime
- Traversal lifetime will be measured by having the motors drive continuously on metal surface as if it were traversing a bridge until the battery runs out
- Holding lifetime will be measured by having the robot collect ambient vibration data until the battery runs out
- Requirements will be met if each lifetime surpasses one hour

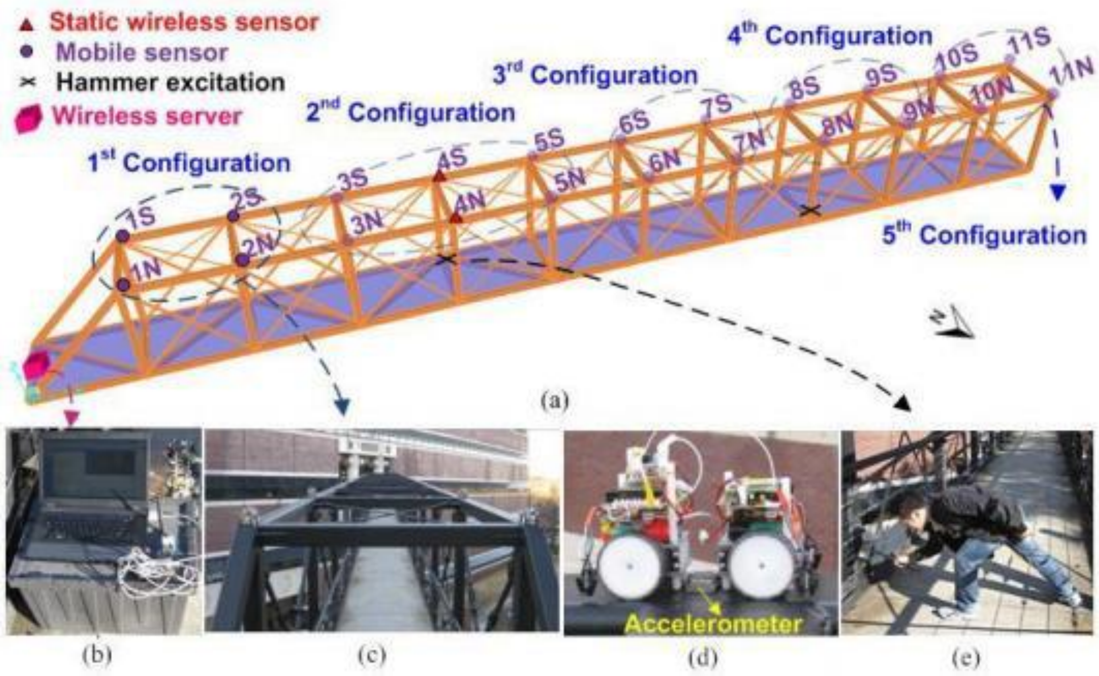
Verification – Wireless Communication Distance

- 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

Final Demonstration

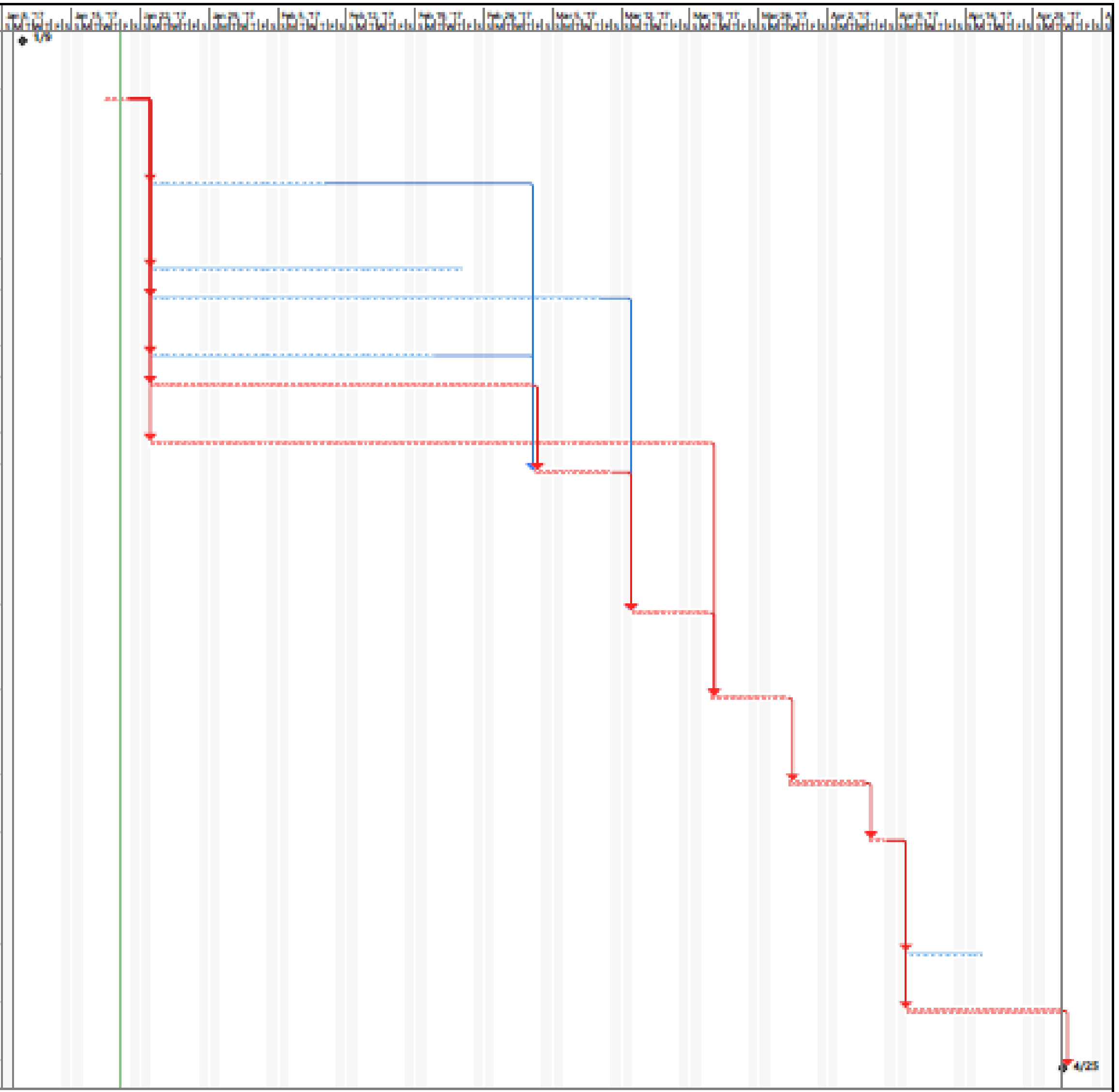
- The robot will be placed on the bridge located at the MRDC and be expected to traverse to one of the measurement locations in each configuration
- At each configuration, the robot will take measurements at one location simultaneously with stationary sensors at the remaining locations and send the data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



Cost Analysis

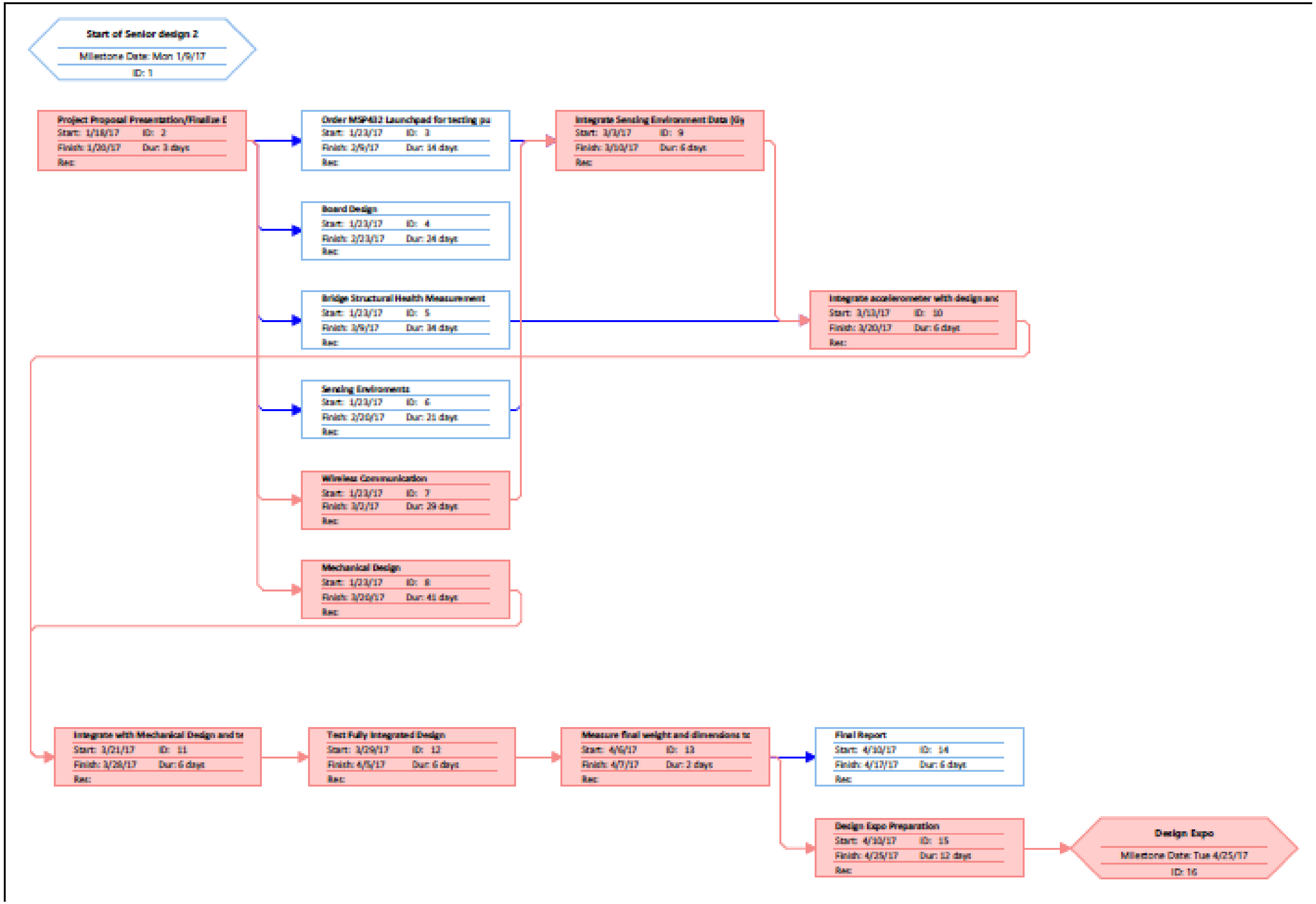
Item	Unit Price	Units per Bo	Cost Per Bo
IR Sensor	$10.00	4	$40.00
Pololu Metal Gear Motor	$35.00	2	$70.00
Permanent Magnets	$0.80	100	$80.00
Acrylic Body	$5.00	1	$5.00
Wheels (3D Print)	$2.50	2	$5.00
Ball Bearing (3rd Wheel)	$10.00	1	$10.00
Battery	$30.00	1	$30.00
Accelerometer	$18.00	1	$18.00
Gyroscope	$15.00	1	$15.00
GPS	$40.00	1	$40.00
Linear Actuator	$70.00	1	$70.00
Microcontroller	$15.00	1	$15.00
Wireless Module Dev Kit	$90.00	1	$90.00
PCB Printing	$25.00	1	$25.00
Caps/Res/Power Conv	$30.00	1	$30.00
Screws/Wires/Misc	$15.00	1	$15.00
Added Taxes/Shipping	$40.00	1	$40.00
		Total Cost	$598.00

ID		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
Start: 1/18/17 ID: 2
Finish: 1/20/17 Dur: 3 days
Res:
Order MSP432 Launchpad for testing
Start: 1/23/17 ID: 3
Finish: 2/9/17 Dur: 14 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:
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 Sensing Environment Data
Start: 3/3/17 ID: 9
Finish: 3/10/17 Dur: 6 days
Res:
Integrate accelerometer with design
Start: 3/13/17 ID: 10
Finish: 3/20/17 Dur: 6 days
Res:
Integrate with Mechanical Design and
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
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

QUESTIONS?