Power Rack Occupancy System

ECE 445 Design Document

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1 Introduction

1.1 Objective

Power racks are often the most important piece of equipment at a gym for an individual’s work out routine. Due to the popularity of the equipment, it is rare to find an empty rack at either CRCE or the ARC at convenient workout times. Busy students who can only go to the gym on a tight schedule are often met with the frustration of just standing around waiting for a rack to open up with no knowledge of who just started their workout or who is almost finished. As it stands, there is no system in place to monitor the occupancy of the power racks, no system for being notified when there are empty power racks, and no way of determining how long someone’s been using a power rack.

We propose a network of sensors installed onto power racks in a gym to detect occupancy of the power rack, how long a power rack has been used, and to provide an online interface for viewing this information for all the equipped power racks at the gym. We believe that by designing a system that can be installed on any power rack with minimal hardware modification that is connected to a central processing unit with an arbitrary amount of connections, modern gyms would find this as a realistic service to implement. We aim to design a system that can provide the following quality of life improvements to the gym-going experience:

- Ability to remotely gauge how many racks are available for use and how they are being used
- Polite notification when a power rack has been used for an inordinate amount of time
- Ability to be be notified when there are available power racks

1.2 Background

When going to the gym at busy times, it can be extremely time consuming to have to walk all the way down to check if a rack is free, then go back to see if anyone is close to finishing up. It’s also frustrating to think you finally found a free rack, only to see someone’s phone on the bench and weights still on the bar. Additionally, at peak hours, the walkway across the gym floor is impeded severely by multiple groups waiting for racks. Somewhat inspired by the occupancy sensors in parking garages as shown below, and how they made parking much more convenient, we envision a more convenient gym experience as well, by freeing up gym floor space, and saving gym goers time.

We are not aware of any other similar implementations of this idea thus far. There are some services, such as Google Maps, that attempt to use location data to show how busy a business currently is, however this is less accurate and less informative compared to our proposed approach.

1.3 High-Level Requirements

Our base high-level requirements are the following:

- Sensor system must be able to detect occupancy within 1 minute of start of use of power rack
- System must accurately update online server with occupancy data for at least 2 power racks
- Users must be notified of power rack vacancy within 1 minute of registered vacancy

Our stretch high-level requirements are the following:

- Sensor system correctly differentiates between benching and squatting
- System determines the amount of weight being lifted

2 Design

2.1 Block Diagram

We have divided our power occupancy system into three primary subsystems: the system of sensors to be installed on each power rack, the central control system to aggregate the data and interface with the online server, and the server/web framework to provide a point of access to the data for the consumer. To contrast the wired connections shown in black, wireless connections between/within the subsystems are marked in blue. The central control system will be interfacing with several power rack sensor systems to wrap up the data to send to the online server.

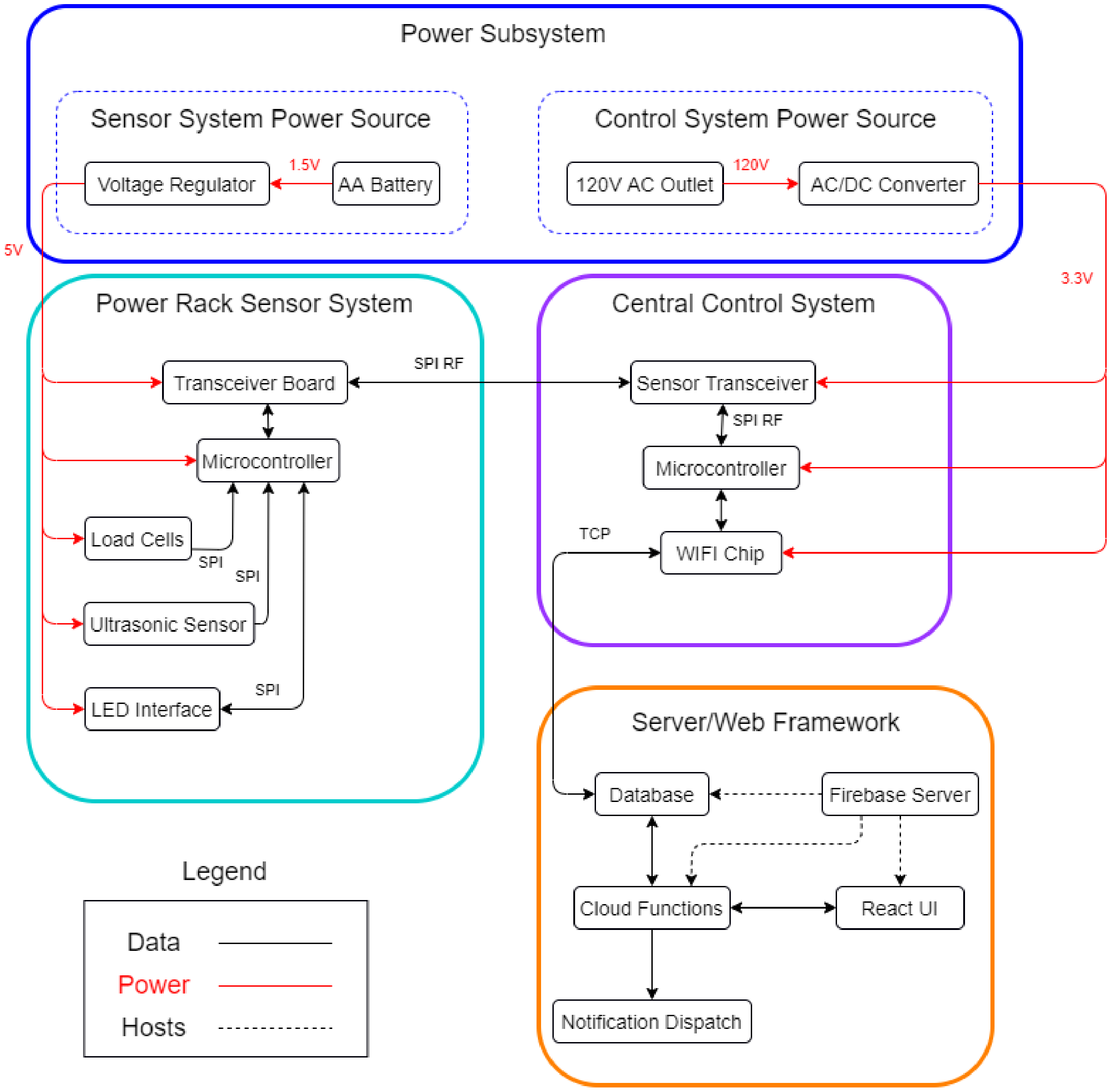


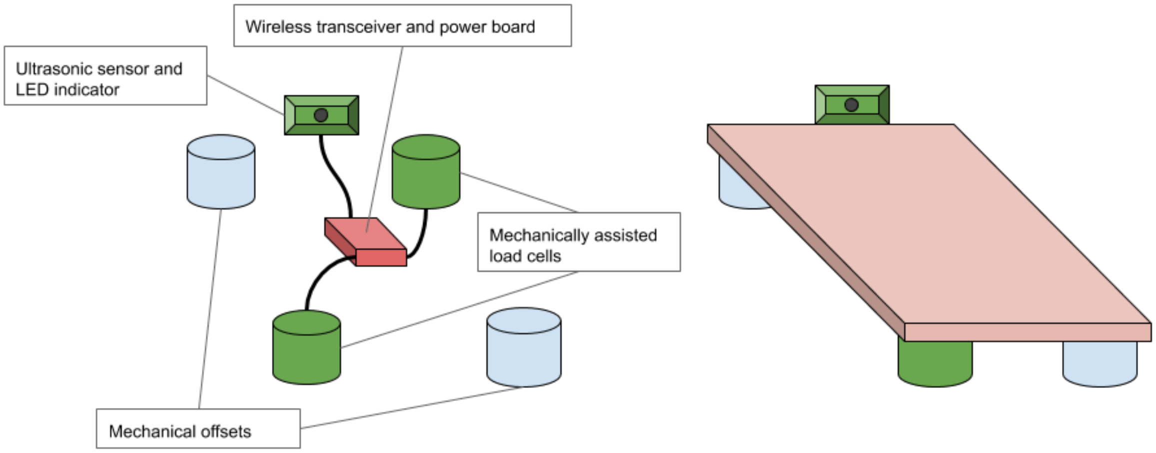
Figure 2.1 Block Diagram

2.2 Physical Design

Power racks come in a variety of shapes and sizes but their hole size (the dimensions of the space inside the rack where users perform lifts) remains relatively standardized across the board at about 40-50” deep and 46-52” wide [1]. In order to achieve maximum universality between different types of racks, we are implementing our sensor system as a platform to be inserted on the floor inside the hole of the power rack that is 48” wide and 80” long. By having the platform designed at an appropriate size, the platform will be able to support standing lifts as well as lifts utilizing a bench. This will avoid problems of incompatible installation/mounting protocols for the various types of power racks since it is not guaranteed that power racks will have a consistent bar-holding mechanism or floor footprint but they will almost always have a space in the middle to perform lifts in.

We believe a combination of two load cells staggered at the base of the platform combined with an infrared sensor to provide additional insight into movement of the exercise will be sufficient to calculate occupancy and general usage statistics. Shown in Figure 2.2.1 is the proposed layout of the sensors in the platform.

Due to the potentially extremely heavy loads the load cells may have to support, there must exist mechanical overload protection to protect the sensor from being irreversibly damaged [2]. Figure 2.2.2 shows the overload protection mechanical assistance to be implemented to protect the load sensors. We are not designing a trampoline so we are limiting the spring range of motion to half an inch where the springs would have a rating on the order of 1000 lb/in in accordance to the load cell maximum capacity of 440lb. Figure 2.2.3 provides a big-picture visual for the totally implemented system.



Component layout without platform

Layout with platform

Figure 2.2.1 Power Rack Platform Unit Design

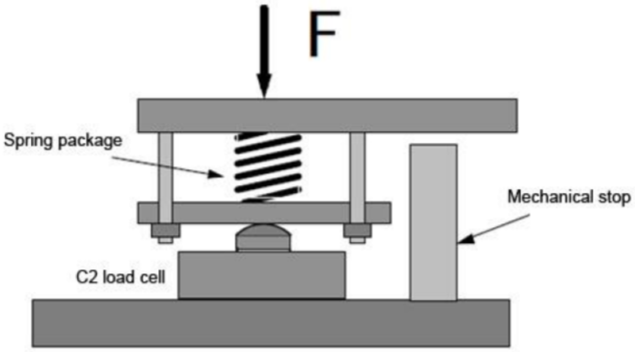


Figure 2.2.2 Load Cell Mechanical Protection Diagram [2]

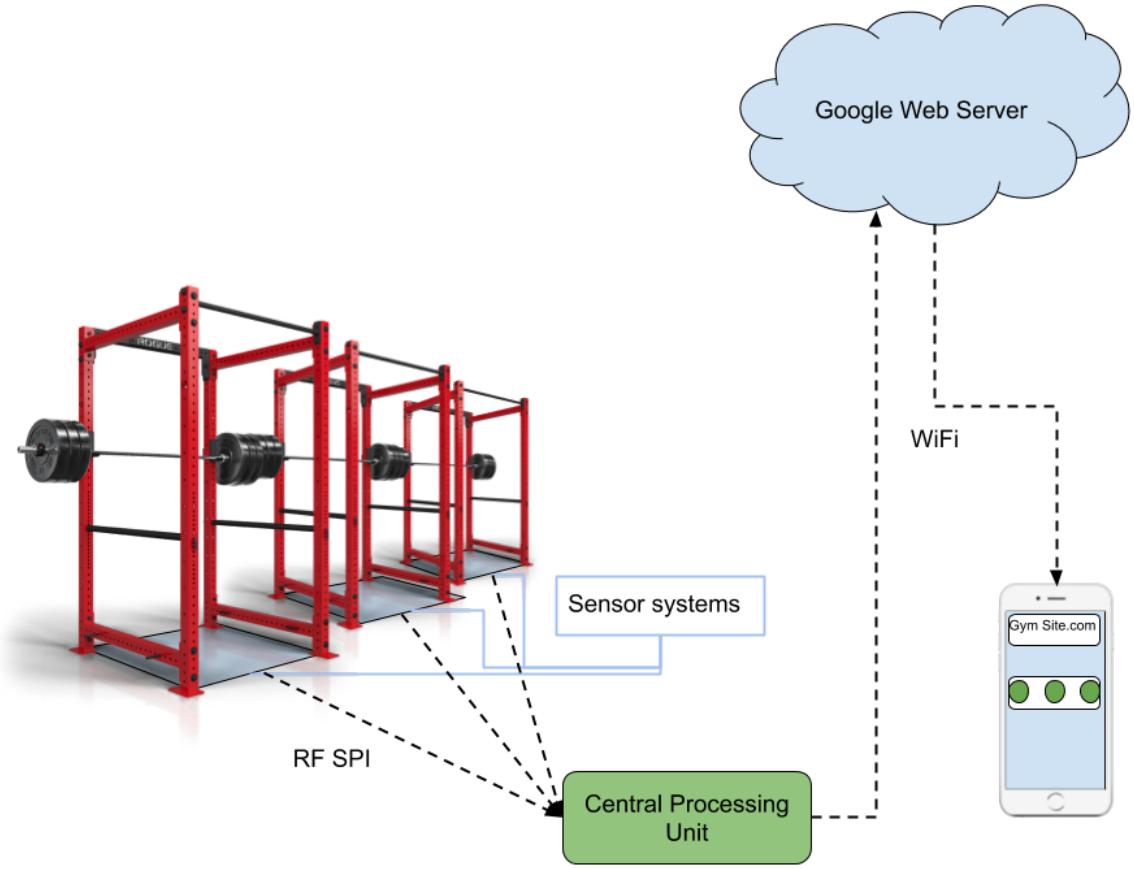


Figure 2.2.3 Physical Design Overview

2.3 Power Rack Sensor System

The power rack sensor system is the most crucial part to our design because the system must be able to gather information about the use of the power rack. As laid out in Figure 2.2.1 and Figure 2.2.2, the system will involve a significant amount of mechanical design for safe use. By having a dedicated sensor unit to each power rack, a potentially arbitrary number of power racks can be implemented in the overall power rack occupancy system. Power racks are already on the expensive side, but we believe that the benefits of implementing the sensor will justify the estimated cost of 15-20% of the total cost of an individual power rack. Each sensor in the power rack sensor network will be piped to a single board per power rack that will provide power and interface with the central control system. This board will house the wireless transmission chip, the battery power supply, and implement the SPI communication protocol from the RF transceiver to each of the sensors. By designing each power rack to be able to individually be able to interface with the central control system wirelessly, we believe it gives consumers of the system great flexibility in terms of modularity and not having to route additional wirings.

2.3.1 Power Rack Sensor System Power

The power rack sensor system will be powered by rechargeable AA battery packs. We decided on batteries instead of wall power since there may not be outlets in convenient locations near each power rack. We chose AA batteries due to their ubiquity and greater safety compared to lithium batteries. We will use a step up converter to boost the voltage from 1.5V to 5V, which will be used to power all the rack electronics. By our calculations, four AA batteries in parallel will give us 39 hours of continuous battery life. In real use, this number will likely be higher due to low power modes available for our electronics.

2.3.2 Power Rack Microcontroller/Transceiver

All of the sensors in our power rack sensor unit are analog with no predefined SPI interface to take advantage of. Therefore, we will be using the ATmega328P microcontroller to digitize the analog outputs from the sensors and execute the SPI commands from the central processing unit. This means that the microcontroller in the power rack will be functioning as an SPI slave to the master microcontroller in the central processing unit.

SPI communication between the power rack sensor system and the central processing system will be done using dual nRF24L01+ RF transceivers over the 2.4 GHz band. The transceiver is specifically designed for SPI communication at long range and low power, and can take the same voltage as the rest of the rack system, thus fitting our design perfectly.

2.3.3 Power Rack Load Cell System

The load cells in the power rack sensor systems are heavy lifters in more ways than one. The primary advantage of the power rack is its flexibility in where the barbell can be stably supported-- it can be placed along an adjustable height axis on one or both sides of the rack or the bar can be placed along the safety crossbars that extend from front to back. This uncertainty in measurement from not knowing where the bar may be placed is amplified when the power rack had holder bars for additional plates to be stored along the side of the power rack. By having two load cells staggered at the base of the power rack platform, we can gain insight as to how weight is being used in the rack. Because the change in resistance for our load cells will be extremely small, each load cell will be hooked up to an amplifier in order to accurately read the data.

2.3.4 Power Rack Infrared Sensor

As a supplement to the detection of how weight is being transferred around the power rack, we have also decided to utilize an infrared sensor to provide a sense of what is inside the power rack. The benefits are three-fold: the presence of a large static object likely denotes the presence of a bench for something like the bench press, detection of a clear platform will help determine when load cells can be zeroed/recalibrated, and it also gives an added security to detecting if the power rack is being used for something that does not involve unloading and reloading weight onto the rack.

2.3.5 Power Rack User Interface System

An array of three distinctly colored LEDs will comprise the sensor unit's user interface system. Through an SPI command from the central processing unit, the LED array unit will be addressed and decoded to light the appropriate LED. The colors and meanings will be the following:

- Green LED: Vacant power rack ready for use

- Blue LED: Occupied power rack within certain usage session time length
- Orange LED: Occupied power rack with a usage session beyond certain time

2.3.6 Power Rack Sensor System Requirements and Verifications

Table 1. Power Rack Sensor System Requirements and Verifications

Requirements	**Verifications**
Load Cell System 1. Load cell-equipped legs of the platform must be able to support at least 400lb without damaging the electronics.	**Load Cell System** 1. Verification process for Item 1: a. Connect load cell system to Raspberry Pi b. Incrementally load 45lb to the system every 10s and record weight readings up to 400lb c. Decrementally deload 45lb to the system every 10s and record weight readings down to 0lb d. Confirm readings from the corresponding weight loads from the increment and decrement phases are within 10% of each other
2. Load cell-equipped legs of the platform must have a weight sensitivity of at least 5lb between loads of 20-200lb	2. Verification process for Item 2: a. Connect load cell system to Raspberry Pi b. Place load cell system under 20lb load c. Incrementally load 5 lb to the system up to 200 lb d. Confirm each reading is within 5 lb of the true weight load
Microcontroller/Transceiver System 1. Wireless transceiver board must be able to poll each sensor and send it to the central processing unit at a frequency of at least 1Hz. 2. Wireless transceiver system must be able to maintain connection up to 100 feet LOS	**Microcontroller/Transceiver System** 1. Verification process for Item 1: a. Manually activate sensors over a one minute time span and check central processing unit has received at least 60 samples 2. Verification process for Item 2: a. Test to see if wireless transceivers can send and receive data b. Move back 10 feet each time and repeat until connection is lost
Power Supply System 1. Must step up AA battery voltage from a range of 1.6V to 1.2V up to a stable 5V +/- 5% 2. Must have reverse polarity protection	**Power Supply System** 1. Verification process for Item 1: a. Connect step-up regulator to bench power b. Step bench power throughout entire AA battery voltage range c. Verify that output is within 5% of 5V 2. Verification process for Item 2: a. Connect regulator in reverse polarity b. Verify that output is 0

2.4 Central Processing System

The central processing system is the brains of our design. It will take in data wirelessly from the power rack sensor systems, process that data, then send it to our online server where it can be shown to the user.

2.4.1 Central Control System Processing Unit

For the sake of modularity and cost efficiency, we are piping all raw sensor data to a single processing unit to be processed, wrapped up, and sent to the online server. In the absence of real data, the exact processing needed is unclear. Our system will initially be prototyped using a fully featured single board computer like a Raspberry Pi but the final implementation of the processing unit will surely require some

2.4.2 Central Control System WiFi Transceiver

In this design, we are using two nRF24L01+ wireless transceivers for communication between the racks and the central control system. This chip is designed for SPI communication and supports the queuing of data in a buffer for both reception and transmission of signals. This will be leveraged to collect time series data from individual sensors for analysis.

The control system will then use an ESP8266 WiFi module in order to communicate with the web/server framework.

2.4.3 Central Processing System Power System

To power our central processing system, we chose to draw power from a wall outlet to impose less maintenance responsibilities for gym employees. Since data communication with the rack sensor systems would be wireless, there is a great deal of flexibility in placing the unit, meaning the chances are high that a gym would have an usable spare outlet. The power reliability of using a wall connection will also ensure that the power rack occupancy system will always be able to provide data to the web framework given a reliable internet connection. The system will consist of a 120V AC/DC converter, a 3.3V voltage regulator, and the appropriate power circuit safety components.

2.4.4 Central Processing System Requirements and Verifications

Table 2. Central Processing System Requirements and Verifications

Requirements	**Verifications**
Central Processing System 1. System must properly error report to the server when a power rack sensor system is out of power or malfunctioning.	**Central Processing System** 1. Verification process for Item 1: a. Connect central processing unit to sensor unit and listen to output using Raspberry Pi b. Disconnect sensors from sensor unit c. Confirm error code is sent for sensor unit from central processing unit d. Disconnect power from sensor unit e. Confirm error code is sent for sensor unit from central processing unit

2. System must be able to interface with at least two sensor system transceivers 3. System must be able to detect occupancy and report to the server within one minute of sensor detection.	2. Verification process for Item 2: a. Check if system is receiving data wirelessly from rack sensors 3. Verification process for Item 3: a. Manually trigger sensors and load cells and check if server has been updated
Power Supply System 1. Power supply must be within 3.3 +/- 10%	**Power Supply System** 1. Verification process for Item 1: a. Verify output of DC converter and regulator is 3.3V +/- 10% when powered by 120V AC

2.5 Server/Web Framework Software Subsystem

The software subsystem is the main point of interaction between end users and our system besides the gym sensors. The sensor data is sent and stored into our database, in which the software will use to determine whether a rack is occupied or vacant and display it onto the user interface. The user interface will also allow users to subscribe and unsubscribe to our notification system, in which we will notify subscribed users of unoccupied power racks with SMS text.

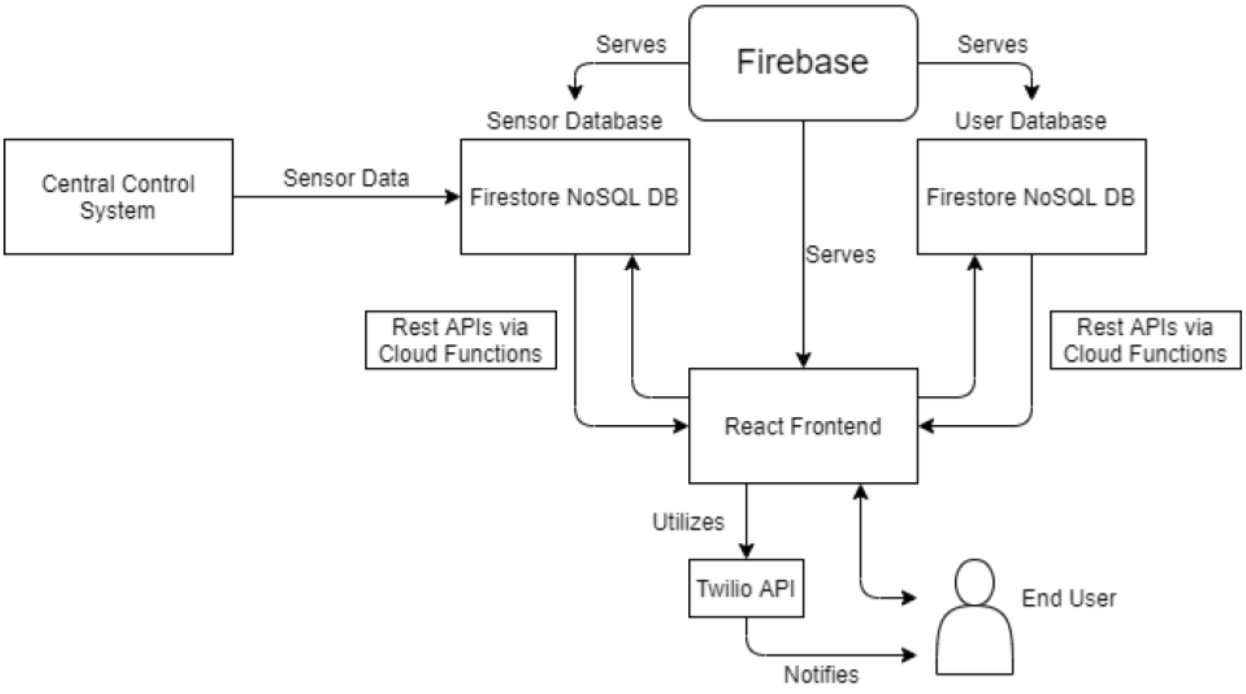


Figure 3. Software Block Diagram

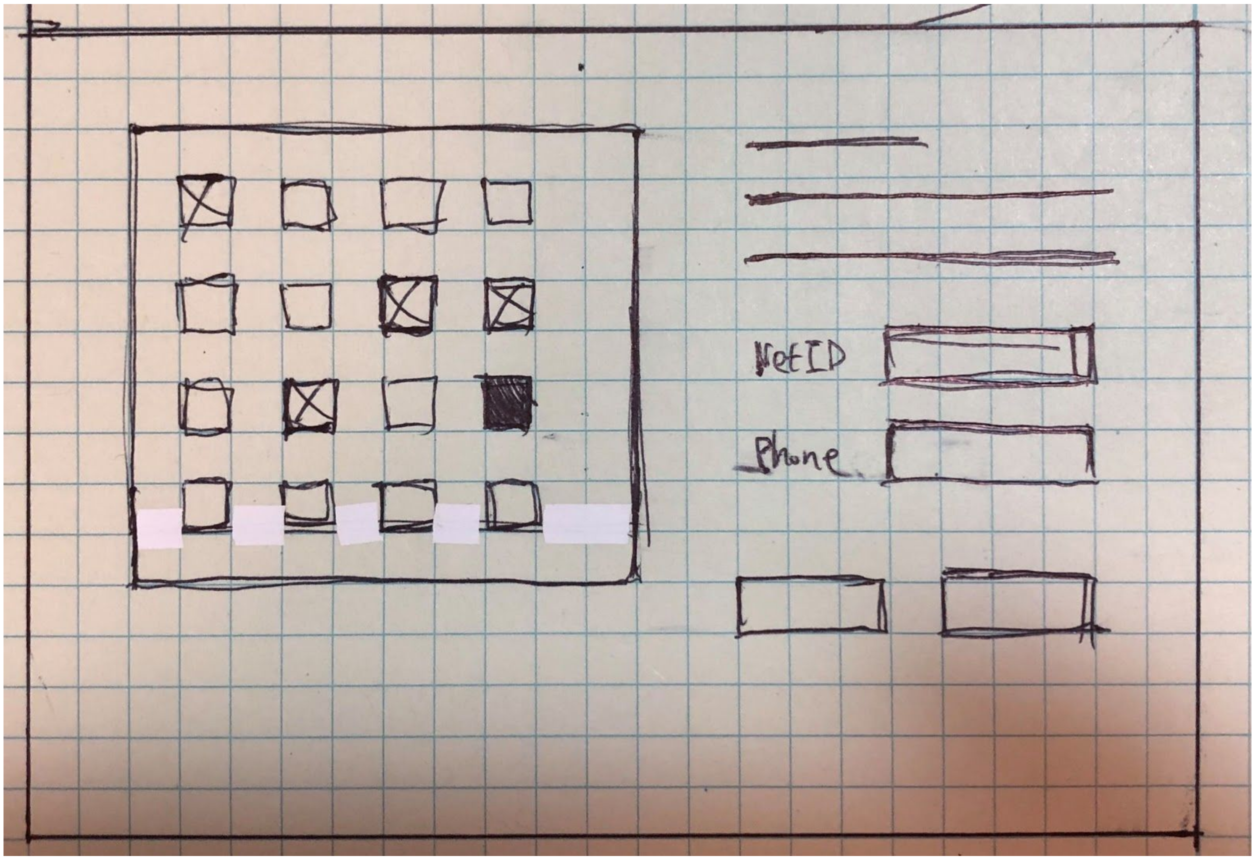
2.5.1 Google Firebase Server

Our Firebase server will be hosting our React frontend, which will allow gym-goers to access the site as long as they have internet. Our Firebase server will also utilize Google's NoSQL database, Firestore, to store data sent from our sensor networks and keep track of the users currently subscribed to our power rack vacancy notification service. Firebase will also be allowing us to call our REST APIs, which will be written using Google Cloud Functions, to read and write to our Firestore databases.

2.5.2 React Web Framework

Our React code, which is being hosted by Google Firebase, is our main software component that connects everything together. Users can view the real-time vacancy of the power racks at the gym and can subscribe or unsubscribe to our notification service. The React code will be reading and writing to our database via REST APIs when viewing occupancy and subscribing/unsubscribing to our notification service.

Low-Fidelity Prototype of User Interface:



2.5.3 Notification Dispatch

Once our system has detected that a power rack is vacant by using our sensor database, we will send a SMS text to all users currently subscribed to our service, notifying them of the vacancy. We will go through our database and gather all the numbers of our users and send them a SMS text utilizing Twilio's API.

2.5.4 Server/Web Framework Requirements and Verifications

Table 3. Server/Web Framework Requirements and Verifications

Requirements	**Verifications**
Firebase Server	**Firebase Server**
1. Website must be accessible from remote internet connections.	1. Access the website using different platforms such as mobile and desktop using cellular data, WIFI, and ethernet.
2. Website must be able to support traffic up to at least 50 people.	2. Verification process for Item 2: a. Simulate multiple users using devices and tabs accessing the website. b. Make sure the website doesn't crash when high amounts of users access the website at the same time. c. Monitor our website's usage data using Firebase's built-in usage and analytics data for our website.
Database + Cloud Functions	**Database + Cloud Functions**
1. Database must be able to support up to at least 10 people in the notification system.	1. Verification process for Item 1: a. Manually input 10 or more users into our user database. b. Simulate the detection of a vacant rack and call the notification dispatch. c. Count the number users that receive the SMS text.
2. Subscribing/unsubscribing to our notification service must add/delete the user to/from the database within 3 seconds.	2. Verification process for Item 2: a. Input/delete dummy users into/from our database using our web interface. b. Measure the time it takes the database changes to take place with a stopwatch.
Notification Dispatch + Cloud Functions	**Notification Dispatch + Cloud Functions**
1. Users subscribed to our notification system must receive the notification within a minute of the detection of a vacant rack.	1. Verification process for Item 1: a. Simulate the detection of a vacant rack by changing a rack's status from occupied to vacant. b. Measure the time it takes starting from the status change to receiving the SMS text.
React UI + Cloud Functions	**React UI + Cloud Functions**
1. Our live view of power rack occupancy must be updated within a minute of power rack status change.	1. Verification process for Item 1: a. Simulate the status change by changing a rack's status from vacant to occupied and its converse. b. Measure the time it takes for the

	status change to take effect on our live view interface from both vacant to occupied and occupied to vacant.

2.6 Tolerance Analysis

The most critical aspect to our project's performance is that occupancy is able to be reliably calculated. The sensor that we will be relying on most to calculate this will be the two load cells located at the front-right and back-left of the platform. We will be primarily looking to leverage the load cell readings in time to measure usage statistics such as time the power rack has been used by a single person and how much weight is being lifted. These measurements, however, are extremely limited by the resolution of the sensors and the memory/processing power of the microcontrollers to look at the distribution of weight in time.

2.6.1 Measurement of Weight

The load cells we are using in this project design are analog button load cells using four strain gauges in a wheatstone bridge formation. The load cells have no means of self-calibration and are therefore reliant on being able to be recalibrated when it is calculated that nothing is on top of the platform. Assuming no flexion of the platform, distribution of the platform weight is a function of the linear combination of moments of the center of mass of the platform weight to each of the legs.

$$Eqn.\ 1:\ F_{Load\ Cell} = \frac{M_{Load\ Cell}}{\Sigma M_i}$$

For loads centered exactly in the middle of the platform, this means that the weight will be distributed equally across all four legs and is our ideal usage scenario as it would minimize the error of the individual load cells. The strain gauges are subject to drift and error due to vibration and the microcontroller ADC module is documented to have a 10-bit resolution with +/- 2 LSB accuracy.

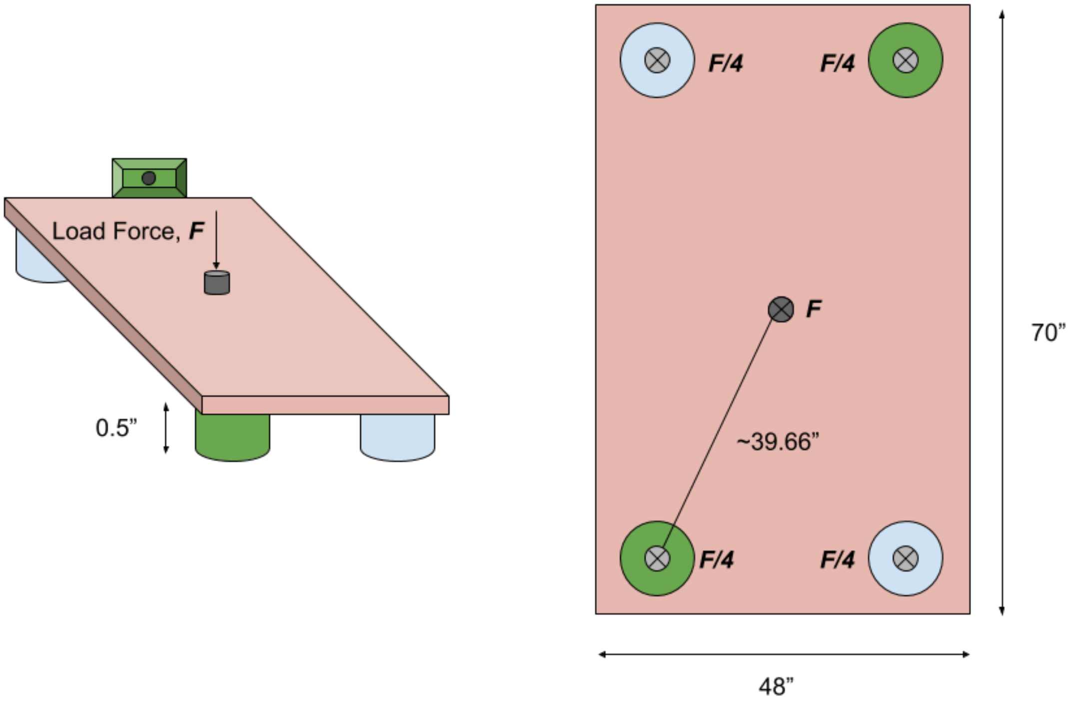


Figure 2.6.2 Power Rack Platform Force Diagram

2.6.2 Measurement of Time

The bottleneck for the sampling speed of the load cells is the ADC inside the microcontroller. This should not pose an issue, however, as events we are interested in detecting (e.g. stepping onto platform and performing the exercise) can be detected at a sampling rate of less than 1Hz. There exists a very real design consideration, however, when considering the memory and computation costs to process data at too high of a resolution since any overhead in computation time or significant memory use will be multiplied for every additional power rack sensor unit in the system.

Our project has designated 1 minute as the goal processing overhead to detect occupancy. This means there is a great deal of room for power consumption considerations in the computation of our data. This will have to be experimentally determined, however, as it directly depends on the efficiency of the transfer of weight from the mechanical components of the design.

3 Cost and Schedule

3.1 Cost

Table 6. Parts Cost Summary

Description	**Quantity**	**Vendor**	**Total Cost**
nRF24L01+ Wireless Transceiver	2	Sparkfun	$43.90
SEN-13332 Load Cell	1	Sparkfun	$59.95
HX711 Load Cell Amplifier	1	Sparkfun	$9.95

GP2Y0A02YK0F Infrared Sensor	1	Sparkfun	$14.95
ATMEGA328P-PU Microcontroller	1	Digikey	$2.08
ESP8266 WiFi Module	1	Sparkfun	$6.95
PCB Printing (General)	2	x	~$70
Mechanical build budget	1	Machine Shop	$200.00
Capacitor and Resistor Budget	x	x	$20.00
Pinout/PCB Interface Budget	x	x	$30.00
			Total: $457.78

Table 7. Labor Cost Summary

Engineer	**Hours Expected**	**Hourly Rate**	**Cost + Overhead**
Ben	156	$50	$19,500.00
Brandon	156	$50	$19,500.00
Cooper	156	$50	$19,500.00
(Machinist)	20	$40	$2,000.00
			Total: $60,500.00

Table 8. Grand Total Cost

Section	**Total**
Materials	$457.78
Labor	$60,500.00
Grand Total	$60,957.78

3.2 Schedule

Table 9. Project Schedule

Week	Tasks	Responsibility
02/10/20	**1. Project Proposal** 2. Complete general idea of prototype design	1. All 2. All
02/17/20	**1. eCAD Assignment** 2. Research and select hardware components 3. Initial design of mechanical layout and tolerance analysis 4. Rough design of electrical schematic 5. Initial design of software schematic	1. All 2. All 3. Brandon 4. Cooper 5. Ben
02/24/20	**1. Complete Design Document** 2. Order parts for prototyping 3. Ensure compatibility of proposed hardware components	1. All 2. Brandon 3. Cooper
03/02/20	1. Prototype and characterize sensor systems 2. Prototype RF communication 3. Prototype WiFi communication	1. Cooper 2. Brandon 3. Ben
03/09/20	**1. Teamwork Evaluation I** **2. Soldering Assignment** 3. Design sensor unit electrical schematic 4. Design central processing unit electrical schematic 5. Communicate with Google Firebase using WiFi prototype	1. All 2. All 3. Cooper 4. Brandon 5. Ben
03/16/20	1. Spring Break	1. All
03/23/20	**1. Submit final mechanical design to machine shop** **2. Submit first sensor unit PCB design** **3. Submit first central processing unit PCB design** 4. Collect sensor data from real use-case scenarios 5. Design NoSQL Database	1. Brandon 2. Cooper 3. Brandon 4. Cooper 5. Ben
03/30/20	**1. Individual progress reports** 2. Prototype model for occupancy calculation 3. Prototype model for usage type calculation 4. Design NodeJS website	1. All 2. Cooper 3. Brandon 4. Ben
04/06/20	**1. Final central processing unit PCB design** **2. Final sensor unit PCB design** 3. Implement notification system in web framework	1. Brandon 2. Cooper 3. Ben
04/13/20	1. Validate and debug central processing unit for demo 2. Validate and debug sensor unit for demo 3. Validate and debug server/web framework for demo	1. Brandon 2. Cooper 3. Ben
04/20/20	**1. Mock project demonstration** 2. Implement suggestions from mock demonstration	1. All 2. All
04/27/20	**1. Project demonstration**	1. All
05/04/20	**1. Complete final paper** **2. Lab checkout** **3. Teamwork Evaluation II**	1. All 2. All 3. All

4 Safety and Ethics

There are several potential safety hazards with our project, in addition to the base dangers of lifting heavy weights. Our first safety concern would be the dangers of utilizing a wall socket to supply electricity for our central control system. Poor wiring could increase the chance of fires, power surges, or other serious consequences [4]. Proper wiring should be able to prevent this hazard.

Many people in the gym bring liquids such as water and shakes, which could cause electric shock [4] if the liquids come into contact with the wall outlets. Accidental spillage of liquids could also cause damage to our system, which is being powered by electricity. The load cells that we plan on using are IP66 certified, which should be more than adequate to protect against any accidental spillage of water or other liquids. For any parts near the power rack that are not IP certified, we plan on using conformal spray to protect against liquid.

Another safety concern would be the increased risk of injury following improper installation. If not properly secured, the rack could become unbalanced and tip over, causing serious bodily harm or death, due to the heavy weights it holds. To prevent this, we would need a proper installation tutorial to prevent accidents.

In regard to ethics, we believe our project has no conflicts with either the ACM Code of Ethics nor the IEEE Code of Ethics, given that fair access to the data is given to the involved parties.

5 References

[1] *The Trusty Spotter,* “How big is a power rack?”, 2018. [Online] Available: https://trustyspotter.com/blog/power-rack-size/. [Accessed: 23-Feb-2020].

[2] *HBM,* “Overload Protection - Good Protection for Load Cells”, 2020. [Online] Available: https://www.hbm.com/en/3541/overload-protection-good-protection-for-load-cells/. [Accessed: 23-Feb-2020].

[3] *IEEE,* “IEEE Code of Ethics”*,* 2020. [Online] Available: http://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 23-Feb-2020].

[4] *The Spruce,* “The Dangers of Broken Electrical Outlets”, 2019. [Online] Available: https://www.thespruce.com/hidden-dangers-of-cracked-outlets-1152458. [Accessed: 27-Feb-2020].

[5] *ACM,* “ACM Code of Ethics”*,* 2020. [Online] Available: https://www.acm.org/code-of-ethics