TECHNOLOGY DEVELOPMENT OF AN ACCESSIBILITY OBSTACLE MONITORING SYSTEM

by

Brandon Lancaster
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Committee:

__________________________________ Dr. Siddhartha Sikdar, Thesis Director

__________________________________ Dr. Shani Ross, Committee Member

__________________________________ Dr. Nathalia Peixoto, Committee Member

__________________________________ Dr. Kim Blackwell, Department Chair

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George Mason University
Fairfax, VA

Technology Development of an Accessibility Obstacle Monitoring System

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

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Brandon Lancaster
Bachelor of Science
James Madison University, 2013

Director: Siddhartha Sikdar, Professor
Professor, Bioengineering, College of Engineering and Computing

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George Mason University
Fairfax, VA

DEDICATION

I dedicate this work to my grandfather, “Pop Pop”. He lived in a wheelchair for over 10 years before passing away shortly before I started graduate school. Having a physical disability is often not easy, yet he continually demonstrated the importance of “always looking up”. It is in this theme of positivity that I humbly hope this work helps others like him who live daily with the challenges of a mobility impairment.

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ABSTRACT

TECHNOLOGY DEVELOPMENT OF AN ACCESSIBILITY OBSTACLE MONITORING SYSTEM

Brandon Lancaster, M.S.

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Thesis Director: Dr. Siddhartha Sikdar

It is often taken for granted by able-bodied people that they can input virtually any address into a wayfinding application (such as Google Maps or similar), get directions to the desired location in seconds and be on their way within minutes; often with complete foreknowledge of any barriers they may encounter. Sadly, individuals with physical disabilities do not have this luxury, which is becoming part of a modern definition of quality of life. There exist many accounts of people with mobility impairments who have decided to remain home due to the uncertainty about reaching their desired location in a timely manner, if at all. Thus, causing feelings of isolation and consuming unnecessary time on nearly every trip, a burden not experienced by the general population. This is inequitable and needs to change.

One major reason this group does not have access to quick and reliable directions that take into account their disability is because the real time geospatial data of the built

environment is not available. This project aims to address a small part of this problem. An often cited barrier by this population is elevator interoperability. This project will present the design and development of a low cost, low maintenance and long wireless range elevator sensor that makes real-time status information available to all. Specifically, it utilizes a newer radio technology (LoRa) designed specifically for long range, low power, low bandwidth applications. This information is then made available and hosted by Sozialhelden e.V., a registered nonprofit organization founded in 2004, aimed at breaking down barriers and creating accessibility. Thus, providing a uniform and future-proof method of storing and accessing this much needed information. This will enable developers of apps and websites around the world to incorporate this real-time accessibility data that is currently missing into future wayfinding applications and improve quality of life for people with mobility impairments.

1. BACKGROUND

1.1 TRAVELING WITH A MOBILITY IMPAIRMENT

For people with mobility issues, the ability to travel independently is one of the most important factors that affects the quality of life [1]. However, this basic human need is often very difficult. This is attested by many studies, interviews, newspaper articles, presentations by mobility aid users and surveys. In a work investigating how wheelchair users prefer to navigate, researchers stated that “traveling is a laborious task for wheelchair users, especially in unfamiliar environments because they have to overcome an array of interpersonal and environmental barriers” [2]. Furthermore, consider a recent review focused on empirical research relating to what factors people with disabilities face while traveling. 3394 studies were screened and 37 met inclusion criteria and a similar unfortunate claim was made. Specifically, people with disabilities often have difficulty navigating as a pedestrian due to physical accessibility factors [3]. Abundant first hand accounts of the difficulties experienced by this population can also be found in many newspapers and professional talks. One such example is a letter to the editor from a wheelchair user in the Washington Post chronicling the difficulties with the subway system in Washington DC [4]. Another instance is a New York Times article listing the difficulty of using public transit in New York City, NY [5]. Both are frustrating tales of cryptic or inaccurate directions, backtracking and unanticipated elevator closures. Raúl

Krauthausen, a disability rights activist and wheelchair user in Germany has described navigating the world as “brutal” for people who use mobility aids [6].

At the community level, issues with travel are prevalent as well. During a discussion between the author and a mobility aid user on GMU’s campus, it was found that it takes this individual an extra 30-60 minutes per trip over an able-bodied individual. Unfortunately, this is not an isolated case. A survey designed by the aforementioned NRT team to elucidate accessibility issues open to GMU students from the years 2021-2022 indicated other issues. Direct responses from students show that disruptions are faced traveling on campus at least once a week, that accessibility issues have unfortunately come to be accepted as normal and that events are missed due to the difficulty of traveling even in a familiar environment such as a college campus [7]. Looking at this from many different perspectives, one can now see that traveling is often a considerable barrier to people with mobility impairments.

Mobility impairment affects many across different societies as well. In the United States, individuals with a mobility limitation fall under the most common functional disability category. In fact, 13% of adults expressed difficulty walking or climbing stairs; which equates to about 8 million individuals [8]. In Germany the Federal Statistical Office indicates 1.5 million use a wheelchair every day and globally, it has been estimated that more than 65 million people require the use of a wheelchair [9]. To put these numbers into perspective, 65 million people was about the entire population of either France or Great Britain in the year 2021 [10].

1.2 ELEVATOR OPERATION IS IMPACTFUL TO THIS POPULATION

One barrier often faced by mobility aid users is inoperable elevators/lifts. As stairs are not traversable for many in this population, this causes significant delays or renders reaching a destination impossible. One article from the year 2020 investigated the needs of people with impairments in general but specifically what features are important to these users in the indoor context. It stated that the mobility impaired population mainly require structural information indoors, such as non-functioning elevators [11]. If one considers wheelchair users specifically but broadens the scope to the entire environment, elevators are still important. A month-long study, consisting of 614 daily interviews with people who are chronic wheelchair users reveals that broken/missing elevators were reported as insurmountable barriers by 28% of participants at the end of the study. Out of the 30 obstacles mentioned, there were only 5 others with a higher reported percentage [12]. To illustrate this, figure 1 was created to show the 5 obstacles reported by more participants than elevators, the percentage of participants having difficulty with elevators in the middle and then the next 5 most reported obstacles. All of the obstacles with a higher percentage would require modifications to the built environment.

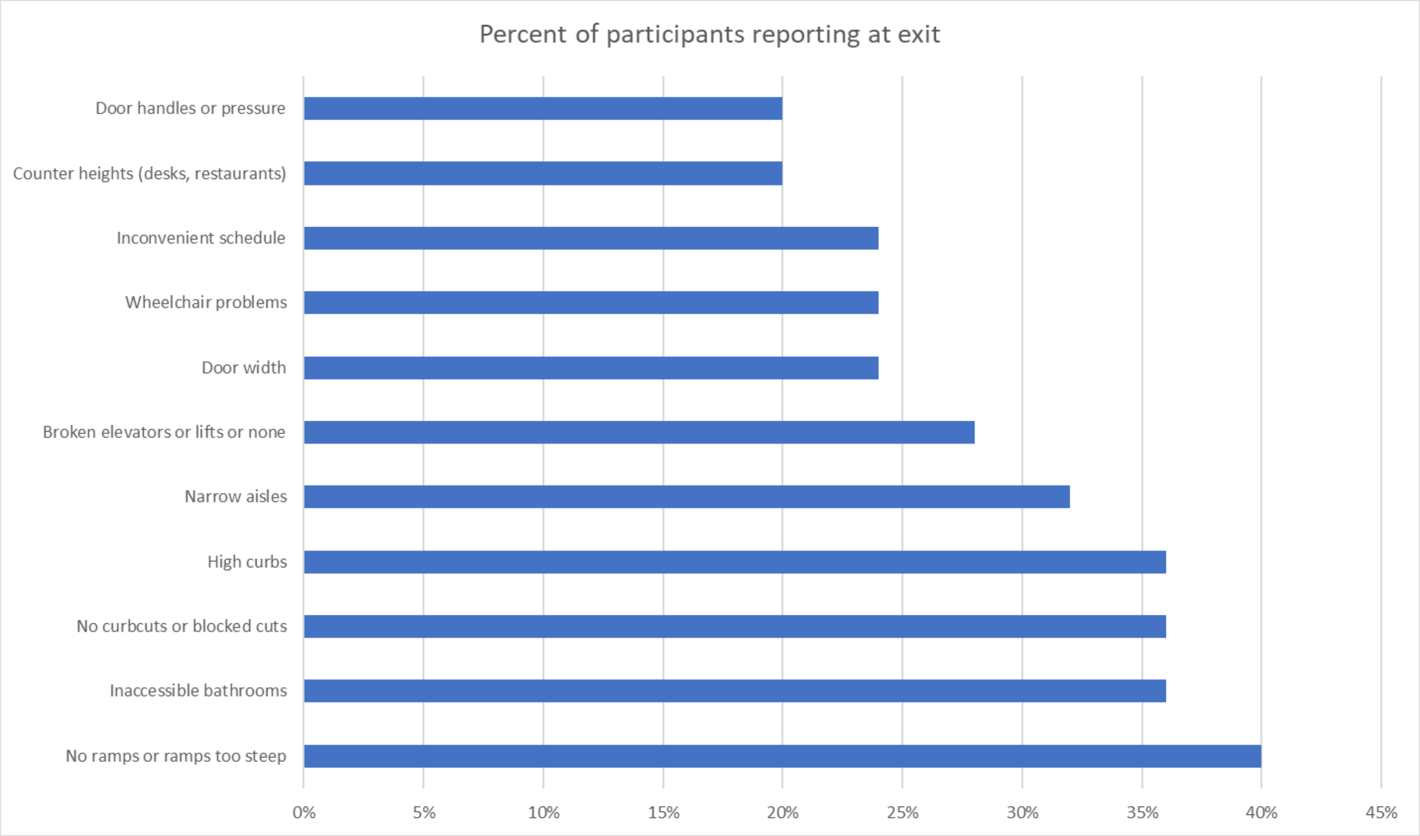


Figure 1. Top obstacles not overcome by wheelchair users

Modifying the built environment has its own set of challenges. The Americans with Disabilities Act of 1990 has mandated that buildings receiving federal money must be accessible. It outlines the criteria for what is considered accessible, what must be retrofitted and what is exempt [13]. Therefore, as old buildings are replaced due to age, newer buildings should become more and more accessible. If one looks at the literature before or shortly after the ADA was put into law, we see situations that would be considered unacceptable in the present. Two examples include dangerous freight elevators in use [14] and claims that we must accept "irresolvable conflicts" of certain accessibility barriers in favor of profitability [15]. However, even with full adoption, this does not guarantee smooth transportation from point A to B due to temporary obstacles, maintenance down times or broken equipment. In addition, some are critical of the ADA stating that it requires expensive upgrades [16]. Due to limited budgets in some locations, the ADA has had the unintended consequence of degrading the quality of systems such as public transit.[16] claims this is legal because everyone is subjected to the same poor experience. Hence, built environment modifications will be considered out of scope for this project.

Returning the focus to elevators, researchers that designed an accessibility map for students at the University of Pittsburgh, determined elevators were one indispensable POI which needed to be included. This conclusion was reached by a review of accessibility requirements in the literature, checking websites that collect and distribute geo-crowdsourced accessibility information and examining the accessibility maps produced by other universities. They found that elevators were the third most frequent accessibility layer found in the other campus maps; of the nineteen layers listed, elevators were only less frequent than accessible entrances and accessible parking. After researching these sources the authors concluded that an elevator database was important enough to be included in the general component of the map rather than restricting it to a component intended just for mobility aid users [17]. However, these layers contained static POIs, and were not dynamically updated if an elevator malfunction occurred.

The importance of elevator operation is not only recognized by mobility aid users and researchers; it has also been acknowledged by facilities managers and others in charge of their operation. In a 2018 interview, the Senior Advisor for Accessibility of New York City's Transit system, Alex Elegudin was quoted as saying "'The truth is, some of the elevators that were installed early on [in the subway system] aren't as reliable and don't provide the diagnostics we need,' Mr. Elegudin said. 'There is nothing worse than getting to a station and finding the elevator is not working.'"[17] . Thus, the significance is noted by a broad range of stakeholders.

An additional factor, which is often not considered, is that elevator operation has the potential for psychological impacts. A well-cited ethnographic study found that students with disabilities very often would like to be seen as normal. There is often a desire to distance themselves from their disabled identity. This causes conflicts when something about the environment requires a request for help from others. Therefore, an inoperable elevator can contribute to this conflict by making their disability more conspicuous [14]. Also, this impact is not limited to mobility aid users; individuals with hidden disabilities, like heart and respiratory conditions or temporary injuries are affected as well. Some would prefer to keep these private but would no longer be able to without an elevator [18]. Therefore, elevator interoperability can also cause inward feelings of alienation, force people to reveal private information or ask for help when they would rather not. This is in addition to more conspicuous impacts such as acting as an obstacle on the way to one’s destination.

1.3 WHAT IS THE STATE OF THE ART?

It has been shown that up-to-date elevator operational status is important not only to mobility aid users but also to facilities managers and individuals with hidden disabilities. Given this user requirement, it is logical to consider a remote monitoring system that publishes public status information as a substantial solution to this need. Given the importance of elevators to multiple stakeholders, it is perhaps not surprising that there are some extant systems aimed at remote monitoring. However, they have several shortcomings, as will be seen.

A protocol called BACnet is the most common method used in commercial buildings to monitor elevators and other systems [19]. The global market share of BACnet in 2017 was estimated to be 64% and projected to increase in the future [20]. This estimate was made by BSRIA Inc., a publisher of independent authoritative market reports. The protocol has been standardized in ANSI/ASHRAE 135 and ISO 16484-5; this was originally published in 1995. The standard uses concepts from object oriented programming. At its core, it defines different objects such as analog out object, an analog input object or binary input object. The standard then requires certain object types to have certain properties with certain data types (such as “present value” or “description” for the analog output object). It allows transmission of data via various methods (known as physical and data link layers) such as IEEE 802.2 & IEEE 802.3 (commonly known as Ethernet) or EIA-485 (a low cost serial communication, also known as RS-485) [21].

This standard, while prevalent, was not designed with accessibility in mind. The primary purpose was to provide some level of interoperability between different building systems. In fact, elevator monitoring was not even part of the original scope of the standard - it was originally designed to monitor and control HVAC systems after the advent of DDC systems. Furthermore, Viktor Boed, one of the engineers who was on the committee to develop the standard, lamented in his book on networking & automating facilities, that many of the devices on the market did not show a full-scale compliance to the standard[22] . This means that even if BACnet compliance is claimed, the level of implementation varies drastically and a system which relies on the protocol to provide required accessibility information will not work universally. In 2021, a book on smart cities acknowledges BACnet’s existence but claims there is still a need to develop a formal schema to describe operational characteristics of elevators and that they have not yet successfully been integrated [23]. This claim makes sense. The BACnet standard was not updated to provide information about elevator status until the year 2012 with Addendum 135-2012aq[24]. Thus, elevators installed before this date would have no compatibility with BACnet and likely many after this date as well because manufacturers need time to update their products to conform to new addendums. Given the varying levels of implementation, it is logical to conclude that BACnet can not yet be relied upon to provide information on elevator operation.

Relying upon other standards to obtain this information would not be prudent because of BACnet’s majority market share and its projected growth. Also to note, one reason no universal monitoring system exists is that the elevator safety standard (adopted in North America as ASME A17.1/CSA B44, and most of the globe as ISO 8100-20) does not require the use of remote monitoring systems [25].

One system which is explicitly aimed to help mobility aid users is WMATA’s ElStat. WMATA is the government agency tasked with, among other responsibilities, running the subway system (called metro) in Washington DC, Maryland and Virginia. According to their website, they operate almost 1,000 elevators and escalators, which is more than any other transit agency in North America [26]. The ElStat system consists of a website where users can sign up to receive text message or email alerts when elevators go in and out of service. While no peer-reviewed information could be found on this system, ElStat was rolled out in July 2011 as mentioned in a Washington Post article from the time[27]. Users can select which stations to receive alerts for, in addition to the days of the week and times of interest. While this is undoubtedly useful, it is obviously limited to the elevators within WMATA’s system with no plans to expand beyond that area. Also worthy of a brief note is a similar monitoring and alert system located at California State University San Marcos but this restricts alert sign up to university affiliates only [28].

Other systems have been proposed in the literature to monitor elevator function. For instance, [29] investigates the use of the same IMU as this project to monitor the health of an elevator by measuring the acceleration profile of the elevator journey in both vertical and lateral directions. It discusses elevator design, calibration of the IMU and filtering of the high frequency noise of the IMU. However, it proposes no method of automating the process of detecting abnormalities, no means of communicating this information (other than an infeasible method of directly connecting the sensor to a computer via its programming interface), no permanent method of installation and no mention of it being applicable to individuals with mobility impairment. Another paper proposes a model-based method with high accuracy and strong robustness for real-time speed monitoring in an elevator system using a low-cost inertial measurement unit (IMU) as the data acquisition device [30]. The authors claim that the proposed method can provide a cost-effective and non-intrusive way to inspect and monitor the health of an elevator. Thus, providing a basis that the device proposed here could also have these features in the future. However, the paper does not mention the maintenance or power usage of the device. Nor do they mention the availability of the data via an API, especially not for individuals with mobility impairment. It makes no mention if people with disabilities were considered when designing the system.

Two references do mention wireless communication back to a base station. First, [31] proposes a method to monitor the health of an elevator using a low-cost Zigbee technology, which is a wireless communication protocol that enables data transmission between devices. It utilizes a microcontroller unit to control the operation of an elevator model, and sends the operation information of the elevator model to a PC monitoring system with a Zigbee module. The article claims that the proposed method can provide a cost-effective and non-intrusive way to inspect and monitor the health of an elevator and improve the user experience and safety. However, it does not mention the power use, maintenance required or the availability of the data via an API. The paper also does not discuss if people with disabilities were considered when designing the system. A second wireless system, [32] documents a method to monitor the safety of an elevator using the Internet of Things (IoT), which is a network of devices that can communicate and exchange data with each other. The paper does not provide many details of their system but they do say that it consists of three parts: the front-end monitoring system, the command and control center, and the data storage center. However, it is also focused on facilities and not people with disabilities. They also claim that the system can only operate for a week. This is likely due to the device also streaming a video feed of the elevator, a feature not required for people with mobility impairments. Elevator functionality is the main concern.

1.4 DESCRIPTION OF THE EXISTING GAP

As can be seen, elevator operation is impactful for many groups of people, including individuals utilizing mobility aids. Despite this importance, most projects in the literature appear to have a different focus and do nothing to address this particular gap. A recent, well-cited review article was written to address the research question: “which devices and software applications for accessible wayfinding and navigation have been proposed in scientific literature?”. The systematic mapping study looked at articles from the years 2009-2021 and found that 111 of these articles met inclusion criteria [33]. After review, it was found that the overwhelming majority (98 articles or ~88%) of the papers focused on building a mobile or web application. This contrasts sharply to only 14 of the 111 papers (~13%) that were related to smart devices or public interfaces. It was concluded that “In the indoor case, there is the need of retrofitting existing facilities with proper sensors, or to design and construct new ones by adopting the most suitable instrumentation for intensive data collection”[33] . Thus, illustrating the need for more work in this area.

Looking at specific projects, some acknowledge that elevator operation is important, yet they list this in future work or even then to attempt to solve a different problem. For instance, a paper that described the design for a sophisticated smart environment lists out of service elevators as something to be detected by environmental sensors. Yet, despite developing a smart wheelchair, a ceiling mounted tracking system, other wirelessly networked sensors and even a software stack capable of supporting different applications, the authors only mention that a non-existent application running on their platform could possibly warn users of busy elevators in the future [34]. Another project that utilized an iterative universal design approach to develop a navigation and wayfinding app puts documenting elevators in its future work section [35]. One more innovative approach makes use of a web crawler to examine public websites and then build a database with accessibility information [36]. While the authors mention this attempts to capture the location of elevators, it is only stored as a static POI so users of the subsequent mobile application have no way of discovering if a particular elevator is operational or not.

2. A SOLUTION TO THE GAP

2.1 LONG TERM GOALS AND REQUIREMENTS

To help address this gap, this paper proposes a wireless elevator operational sensor to be installed into elevator cars. A receiver base station that has a connection to the internet is outside the car and listens for these transmissions from the sensor. The base station can be installed in any suitable location with power and an internet connection, such as an office. To encourage widespread use and scalability, the system should be economical, easy to install, require little or no maintenance, provide the elevator operational data in a standardized format specifically designed to exchange accessibility data and be compatible with a wide range of elevators. Table 1 outlines these requirements and assigns a suitable metric to each criteria.

Table 1. Long term requirements

Requirement	Metric	Notes
1. Economical	Sensor cost less than $40 United States Dollars (USD), base station cost less than $120 USD	Base station can cover sensors in multiple locations
2. Easy to install	Take less than 10 minutes	By novel user with instructions
3. Low maintenance	Powered by elevator motion. Sensor program memory rated to 25 years endurance.	
4. Universal format	In A11yJSON format	See later sections for more information
5. Wide compatibility	Cause no conflicts with elevator safety code. Universal mounting to flat surface.	

Note the base station has an additional cost that is higher than the sensor itself. However, this is mitigated if one base station is able to cover multiple sensors. Thus, long range transmitters are an additional secondary requirement of the project.

Furthermore, it is important to note that the project is not anticipated to cause conflicts with the safety code mentioned in a previous section. This is because the code explicitly allows for what is termed “overlay monitoring systems”. This refers to any monitoring system that is not built into the elevator itself. An overlay monitoring system does not have to conform to the code requirements if it does not connect to the elevator’s control systems or communication links [25]. Thus, this necessitates that the system have its own power and communication. As this code applies to elevators nationally in the United States, this contributes to a wide range of compatibility.

The requirements in table 1 are long term. This means that the components have been selected and the software is structured with these in mind. However, the primary & immediate goal of this project is to provide proof of concept for the proposed sensor system and create a minimum viable product to provide end users some functionality. Note that the system design as it stands only enables detection of when the elevator was last known to be *working*. In its current form, it is not able to definitively determine when the elevator is not functioning. The rationalization is that users or other programs will be able to see this time and make educated decisions for themselves about if they would like to take a certain route. Additional functionality could be addressed by developing and installing a new node type that is able to sense when the elevator’s call button has been pressed. This way, the system would be certain there is a problem because it would look for elevator motion sometime after a call button was pressed. If no motion is detected, it can reliably determine the elevator is not functioning. Especially if this occurs multiple times. Only floors that are the primary ingress and egress from the building would need a call button sensor, as these are the most frequently used [19].

2.2 SYSTEM OVERVIEW

An overview of the system is provided in this chapter, while details will be listed in the following chapters. A system diagram outlining main components can be seen in figure 2 below. Briefly, the sensor (also called a “node”) in the elevator consists of an Inertial Measurement Unit (IMU) that is responsible for reporting acceleration values to the microprocessor to sense normal elevator motion from floor to floor. The lithium battery has a high energy density and provides a stable voltage for operation, even at extreme temperatures. The microprocessor (ATMEGA328) is responsible for a wide range of tasks including running a calibration routine, storing calibrated values in non-volatile memory (so they are retained after power loss or reset), monitoring the battery voltage, sending node health messages over the radio, performing analysis of the acceleration values reported by the IMU to discern normal elevator motion from other possible motions, and of course sends a radio message when elevator motion is sensed. The LoRa module is a Transceiver module and modulation technique designed for long range and low power use. It is responsible for sending messages to the base station and receiving acknowledgment messages back.

The base station consists of a similar LoRa receiver module connected to a single board computer which processes the data sent from the node, maps the node ID number to a specific elevator, calculates the time the elevator was last known to be working and uploads this information to the internet in a standardized format.

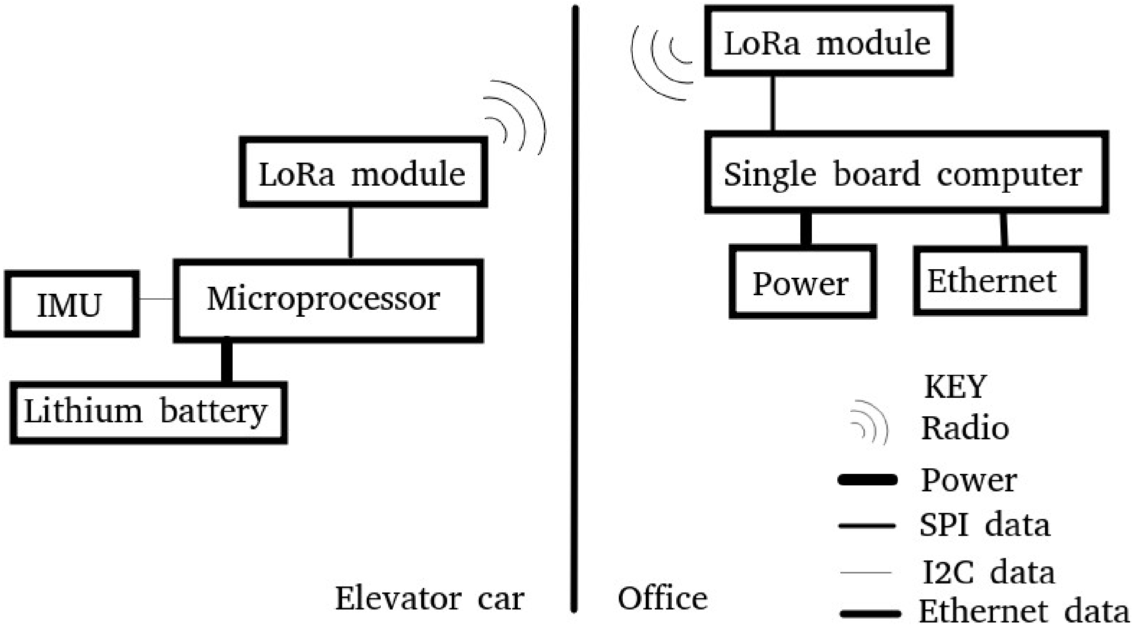


Figure 2. Major system components

2.3 WIRELESS PROTOCOL DESCRIPTION

An outline of the data format to be transmitted wirelessly over the LoRa modulation scheme is presented here. According to the data sheet, transmitting data consumes the most power of any other component on the node (90 mA at 3.3 V), so it is important to develop a power efficient yet flexible data transmission format [37]. Power efficiency in this case translates to minimizing time on air. After a normal elevator motion is detected, it generates what is termed a “motion event”. When not transmitting, it will record detected motion events in the microcontroller's Static Random Access Memory (SRAM). Currently, the node attempts to transmit after each valid motion event but this behavior is adjustable. Due to the fact that the most recent motion event is the most relevant, the node only stores the timestamp of the most recent motion event. However, it also reports the number of motion events it saw since it last received an acknowledgement from the base station. This enables the possibility to discern if the node has been out of range of the base station during some transmissions. The time stamps are all reported in seconds since the node first powered up. This reduces the cost of the node and allows for easy installation by not requiring the node to have a real time clock or require the installer to set a clock. This can be converted to a real time and date on the base station (which is aware of the time via an internet time server) in a method described later.

Once a valid motion event occurs, the sensor node will then transmit a *node information message.* This consists of a comma separated ASCII string consisting of: *message type, sensor type, firmware version, the node ID, battery/supply voltage, number of motion events, timestamp of last motion event*.

The node then waits for an acknowledgement message back from the base station. If received, it clears: *number of motion events* and *time stamp of last motion event* from its SRAM. If no acknowledgement is received, it tries again twice more after waiting a random delay between 1 and 10 seconds. The justification for this delay is that if something such as the elevator door is blocking the signal during the first transmission, the subsequent messages have a better chance of being received. Due to the repeatable nature of elevators, a fixed delay is likely to result in repeated successes or failures each time. By randomizing the interval, this is a simple way to ameliorate the situation where the node is never able to send a successful transmission. Of course, this comes at the expense of potentially missing out on an optimal delay of a retransmission attempt. Due to the protocol’s use of ACK messages, some failed transmissions are not a problem from a data integrity standpoint.

Transmitting the *message type, sensor type* and *firmware version* at the beginning of the message allows the base station to infer the format of the rest of the data. This will flexibly handle future updates to the protocol (and thus the firmware version). It also allows for the possibility of different kinds of accessibility sensors to be added to the network in the future and further allows each one to send its own set of messages with little coordination of a unified message format across sensors. Currently there are only two message types: a normal *node information message* (described earlier) and a debugging message that contains extra information about different phases of the acceleration motion processing algorithm. As these are inconsequential to the protocol, they are not discussed further here. The repository in the appendix may be seen for further information.

In addition, the node also sends *node information message*s at two other times. The first is when the node first powers up and is ready to monitor. When this occurs, a reserved value of 65535 (which is 2^{16}-1) is reported for the *number of motion events* field. This serves two important purposes. First, it makes the base station aware of the node’s existence on the network. Second, it allows the base station to know when the node first powered up. Thus, allowing conversion of the node’s timestamp which are all reported in seconds since boot to a real time. The base station only needs to record the UNIX time (number of seconds elapsed since January 1, 1970) and the node ID when it last received a power up message from that node. When the base station receives later messages from that node, it can simply add the UNIX time it saved earlier to that value. Hence, the sensor does not need to be aware of the real time or date.

The node is also programmed to send a *node information message* four times per day, regardless of if any motion events have occurred. This allows for the base station to monitor the health of the node, namely battery voltage.

In terms of data size, there are 7 data fields which consist of 7 primitive data types for one *node information message*. The largest primitive data type on the ATMEGA328 is 4 bytes (float and long data types both consume 4 bytes). There are 7 delimiter characters, each consuming 1 byte so the message is expected to be 35 bytes (280 bits) or less (7x4+7=35). For perspective, data rates of 300 to 50,000 bps are possible with LoRa [38]. Of course, the LoRa modulation format includes some overhead in the form of preambles and error checking (as do physical data transmission protocols) so this discussion is just to gain perspective of time required to transmit just the message itself.

3. TECHNOLOGY DEVELOPMENT PROCESS

3.1 SELECTION OF COMPONENTS

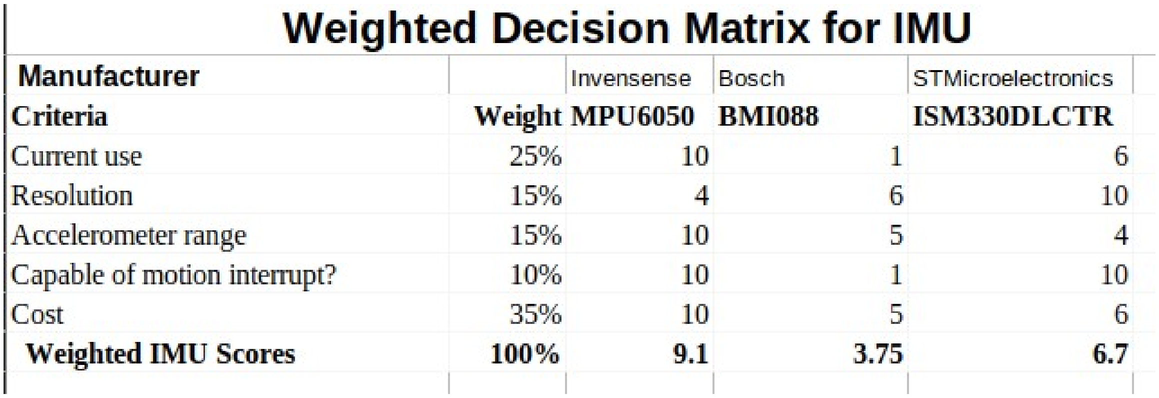
3.1.1 IMU selection

As stated previously, the IMU enables the node to sense elevator motion. The MPU6050 by InvenSense was deemed a good choice for this component because it is widely available, very economical, has the ability to send interrupts and allows sampling rate adjustment while sleeping to allow for lower power consumption, has the ability to turn off unneeded axes entirely to save further power. In fact, the MPU6050 was the first MEMS device that allows motion tracking on 6 axes [39]. In addition, it has a programmable low pass filter, which will likely be useful in future versions of this type of sensor and other accessibility sensors, such as ones which sense automatic door operational status. Importantly, it is capable of being programmed to generate an interrupt when motion is detected, allowing for the accompanying hardware (such as the microprocessor and Transceiver module) to be put into a very low power sleep state until they are awoken by the interrupt. These items combined to help to towards fulfilling requirements 1 and 3 of table 1. It has also been tested to have sufficient sensitivity to detect the acceleration of an elevator. See further section for details. Also, the IMU's default measurement range of ±2g is within the range of deceleration allowed by the safety standard under *typical use* [40].

Even under the worst conditions, the IMU's absolute maximum rating of 10,000 g is well within anything ever expected to be seen within an elevator [40, p. 6]. Sometimes in an elevator, buffers are required to be installed under the elevator car to prevent the car from crashing into the bottom of the elevator shaft in an emergency. Different buffer types are allowed different maximum decelerations but the global maximum is when elastomeric buffers are in use. In this case, a maximum deceleration of 58.86 m/s2 (6 g) is allowed by section 2.22.5 [25]. Hence, while an emergency would cause the IMU to go out of its measurement range, no damage would occur. It is important to note that the full scale range of the IMU can also be reprogrammed to up to ±16g, with an obvious loss to resolution (from 1/16384 g to 1/2048 g) [40, p. 60]. Thus, this selection has a good chance of meeting the overall goals of the project.

Different inertial measurement units from three popular companies were compared using data from the website mouser.com. Information was also gathered from data sheets if it was not available directly from the website. The relevant metrics were rated on a 1 to 10 scale, with 10 being the best rating. A search in the academic literature was also performed. However, the articles located were either studies that used IMUs as part of a study looking at some other phenomena (such as accuracy of fitness tracker predictions) or were reviews about the basic MEMS technology to build such a sensor. See table 2 for the results of this decision matrix. As can be seen, the decision matrix indicates that the MPU6050 is a good selection for this application because the weighted score is higher than the other options evaluated.

Table 2. Decision matrix for IMU with weights and rating (1-10 with 10 the best rating)



Weighted Decision Matrix for IMU

Manufacturer		Invensense	Bosch	STMicroelectronics
Criteria	**Weight**	**MPU6050**	**BMI088**	**ISM330DLCTR**
Current use	25%	10	1	6
Resolution	15%	4	6	10
Accelerometer range	15%	10	5	4
Capable of motion interrupt?	10%	10	1	10
Cost	35%	10	5	6
Weighted IMU Scores	**100%**	**9.1**	**3.75**	**6.7**

3.1.2 Transceiver selection

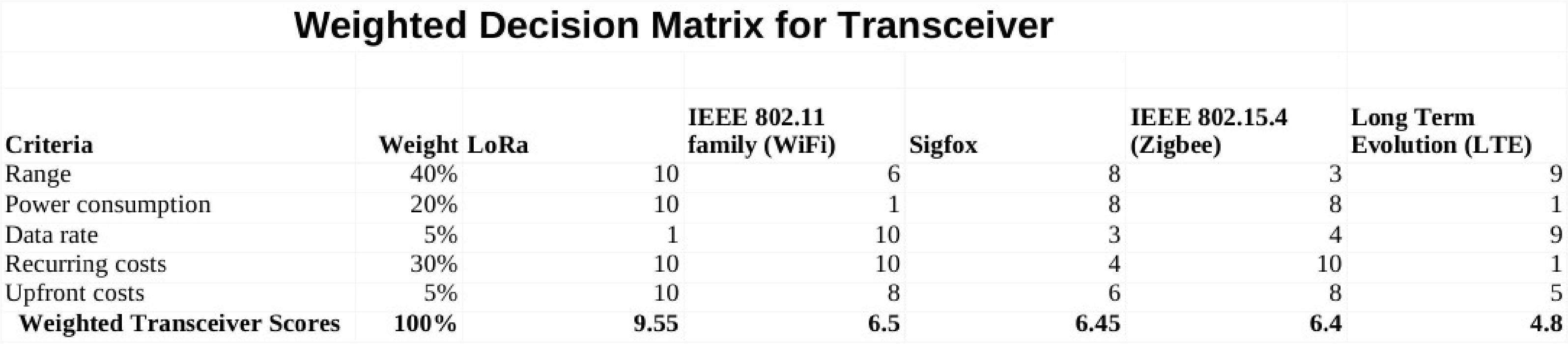
There are many different methods of wireless data transmission. For this application, the most important parameter is power usage, as the sensor will run on battery power. The coverage range is also important for the future because this will reduce the number of base stations needed and hence cost. Longer range will also allow for easier scalability. Thus, helping to meet requirements 1, 3 and possibly 2 of table 1. It may help with requirement 2 because if a Transceiver has a shorter range, it may necessitate installing a base station closer to an elevator in an otherwise inconvenient or inaccessible location. For this radio, data rate is not a priority, since messages are expected to be on the order of bytes, not kilobytes or megabytes (as mentioned).Some of the most common wireless communication methods are LTE, Sigfox, BLE, (maintained by Bluetooth Special Interest Group), WiFi (family of IEEE 802.11x standards) and LoRa [38], [41].

LTE is commonly used in cell phones but can also be used to transmit data from sensors. Compared to other technologies, LTE has the highest power consumption (>1W) [41]. It is not suitable to install in many nodes due to the cost of a subscription for each node and these costs have been claimed to be dramatically higher than technologies like LoRa [41]. Based on these two characteristics, it is not very well suited for this application. Sigfox is a similar concept to LTE in that it is controlled by a single network operator. This requires the operator to install base stations and provide coverage. However, unlike LTE, it was designed with IoT/M2M communication in mind. It would be an option to consider but the coverage in the United States in the year 2022 was almost non-existent and hence would not be of use [42]. Even if coverage improves in the future, messages are limited to only 12 bytes and 140 messages per day [43]. This daily message limit is a restriction not present in any other technology mentioned. Combined with a relatively small message size, this could restrict flexibility in the future. BLE is an economical option with low power usage (~10 mW) but it has a shorter range (<10 m) than LTE [41], [44]. Due to longer range technologies available, BLE is not an attractive option. WiFi has gone through 5 iterations and each one has mostly been focused on increasing data rate and entrancing security. Of all the mentioned technologies, it has the fastest data rate but consumes over 1 watt of power and has a shorter range (<100 m) [41], [44].

Given the information above, LoRa is ideal for this type of application. It has the longest range and power consumption is relatively low -- on the order of 10-100 mW, slightly higher than BLE [41]. There have been similar use cases and conclusions that LoRa is optimal for building monitoring. For instance, a study that looked at building monitoring in multi-story school environment concluded that LoRa provides the longest distance communication for the lowest cost [45]. LoRa also has high immunity to multipath signal propagation, caused by reflections off building structures, an obvious benefit to this project [43]. Further [38] concludes that LoRa is best for smart buildings. In regard to range, LoRa was tested to reach up to 30 km between a transceiver on a boat and a transceiver on an antenna tower [46]. However, this should be considered best case. In an urban setting, a range of 5 km is estimated in [38] and 3-15 km is estimated in [41]. For comparison, GMU’s Fairfax campus is about 2.7 km at the two furthest points (38°50'05.7"N 77°17'50.5"W to 38°49'51.6"N 77°19'40.5"W). Hence, only a single base station should be able to cover the entire campus under ideal conditions.

Due to the requirement that the project can be easily scaled to larger areas, minimization or elimination of recurring costs such as radio band licensing fees and subscription fees has a high weight in the decision matrix for transceiver selection. Of particular desirability were transceivers capable of transmitting on a license free ISM frequency as defined by International Telecommunications Union region 2 [47]. Another advantage of ISM bands is that regulatory agencies around the globe have typically not required operators of these types of transceivers to follow strict frequency standards and spectrum use requirements of other licensed radio frequencies [48]. Typical transmission range and power consumption were two other criteria given much weight. To determine the ratings, a search was performed in the literature for comparisons between transceivers for IoT or M2M applications. table 3 shows that LoRa stands out as having the highest weighted score, while the other options all had relatively the same weighted score.

Table 3. Decision matrix for Transceiver with weights and rating (1-10 with 10 the best rating)



Weighted Decision Matrix for Transceiver

Criteria	Weight	LoRa	IEEE 802.11 family (WiFi)	Sigfox	IEEE 802.15.4 (Zigbee)	Long Term Evolution (LTE)
Range	40%	10	6	8	3	9
Power consumption	20%	10	1	8	8	1
Data rate	5%	1	10	3	4	9
Recurring costs	30%	10	10	4	10	1
Upfront costs	5%	10	8	6	8	5
Weighted Transceiver Scores	**100%**	**9.55**	**6.5**	**6.45**	**6.4**	**4.8**

3.1.3 Other components

A development circuit board called Moteino from LowPowerLab [49] has been selected for prototyping. This was for several reasons. First, it can be ordered with the LoRa radio module already soldered to the board. A 1/4 wavelength monopole antenna ships with the product and there are solder pads to allow other antenna connections. Third, it was specifically designed with a minimal component count and battery powered use in mind. There is also an option to wirelessly reprogram nodes if this feature is needed in the future. A photograph of this board may be seen with a helical antenna in figure 3 with calipers in inches for scale. One can observe the ATMEGA328 microprocessor soldered to the front with all required supporting circuitry (red circuit board), along with the MPU6050 IMU attached via soldered wires to one side (blue circuit board).

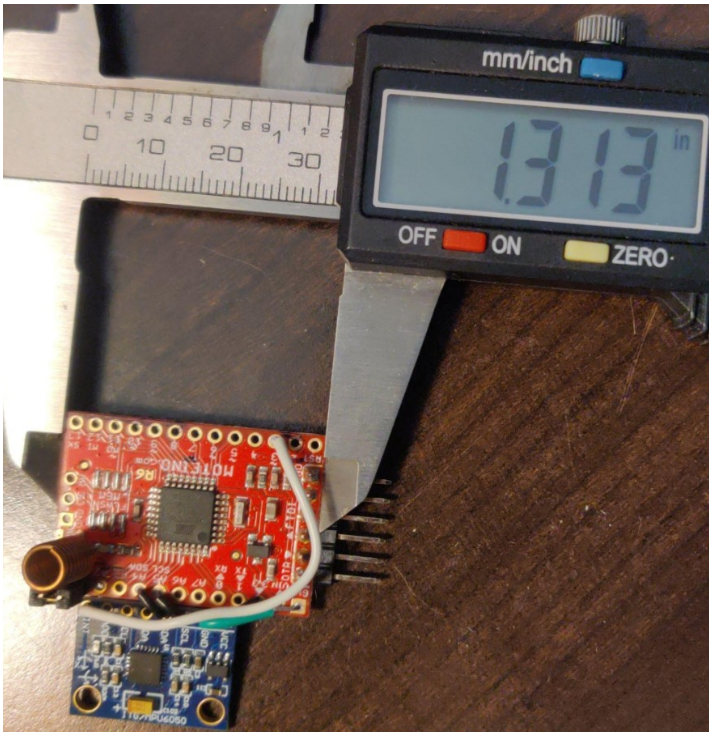


Figure 3. Moteino development board from LowPowerLab

The system is powered by a lithium primary cell in a 2S1P configuration. This provides an operating voltage range of 3.6-2.7V. Lithium cells are ideal for this application because of their voltage stability in many operating environments, high energy density and low self-discharge rate [50].

For the base station, the same model of development circuit board Moteino transceiver as is on the wireless sensor. There are not many requirements for this system. The base station will require power and a connection to the internet via an RJ45 connector running Ethernet. The LoRa module will be connected via an SPI interface. These features are available on many single board computers. For the initial prototype, it is planned to use a Raspberry Pi 4 Model B for this purpose. It has the required connectivity and library support for LoRa has been documented in the literature [51], [52]. Furthermore, the same library can also be used on the wireless sensor platform.

3.2 DEVELOPMENT OF STATIONARY CALIBRATION ALGORITHM

In order for the IMU to reliably sense elevator motion, it first needed to be calibrated while stationary to define a upper and lower threshold for one the the IMUs acceleration axes.

Due to the geometry of the case and the directionality of one of the antennas tested, the x axis of the IMU was chosen to be installed vertically. Using one axis requires that the sensor be installed in the proper orientation but this trade off was deemed acceptable because it eliminates the chance that motion in a non-vertical axis will confuse the elevator motion sensing algorithm and also eliminates noise from the other two axes. Additionally, while the firmware for the initial MVP described in this project does not yet have the IMU waking the microcontroller from sleep, this threshold from the calibration procedure would also be needed by the IMU when programming it to send an interrupt.

As a side note, the firmware code is already structured assuming this power saving functionality will be added in the future. Thus saving a major rewrite when the time comes to implement this feature. This is because interrupts typically drastically change the execution flow of a program on a microcontroller. To illustrate the importance of using sleep modes, under typical conditions, a power reduction of 98% has been documented in a text book by using the ATMEGA328's deepest sleep state [53, Ch. 21].

To determine how long the IMU should be left stationary, an experiment was conducted. It was deemed important to make this time as short as practical to help fulfill requirement 2 of table 1. The procedure was to program two microcontrollers (ATMEGA328) to continually read values from two IMUs (MPU6050) at the maximum sample rate they were capable of (1000 Hz). The IMUs were set to a dynamic range of +-2g. To see if there was any variation between axes or IMUs one was set to read values from the z axis and the other, the x axis. Each axis being measured from was placed parallel with the gravitational force of the earth, as they would be if installed in an elevator.

Both IMUs were started within 5 minutes of each other and left for approximately 11 hours. The microcontroller was connected to a computer via a Universal Serial Bus (USB) to Universal Asynchronous Receiver-Transmitter (UART) adapter (running at 9600 baud, 8 data bits, no parity, one stop bit) to send back data. The program stored the maximum and minimum values it had seen previously since power up. Then, whenever a new reading went out of this range, it was programmed to send this new value to the serial port. A graph of these maxim and minimum values may be seen in figure 4. Note that the values are reported in raw units from the IMU because the units are not important for this application. To convert, the values may be divided by 16384 to get acceleration in units of g.

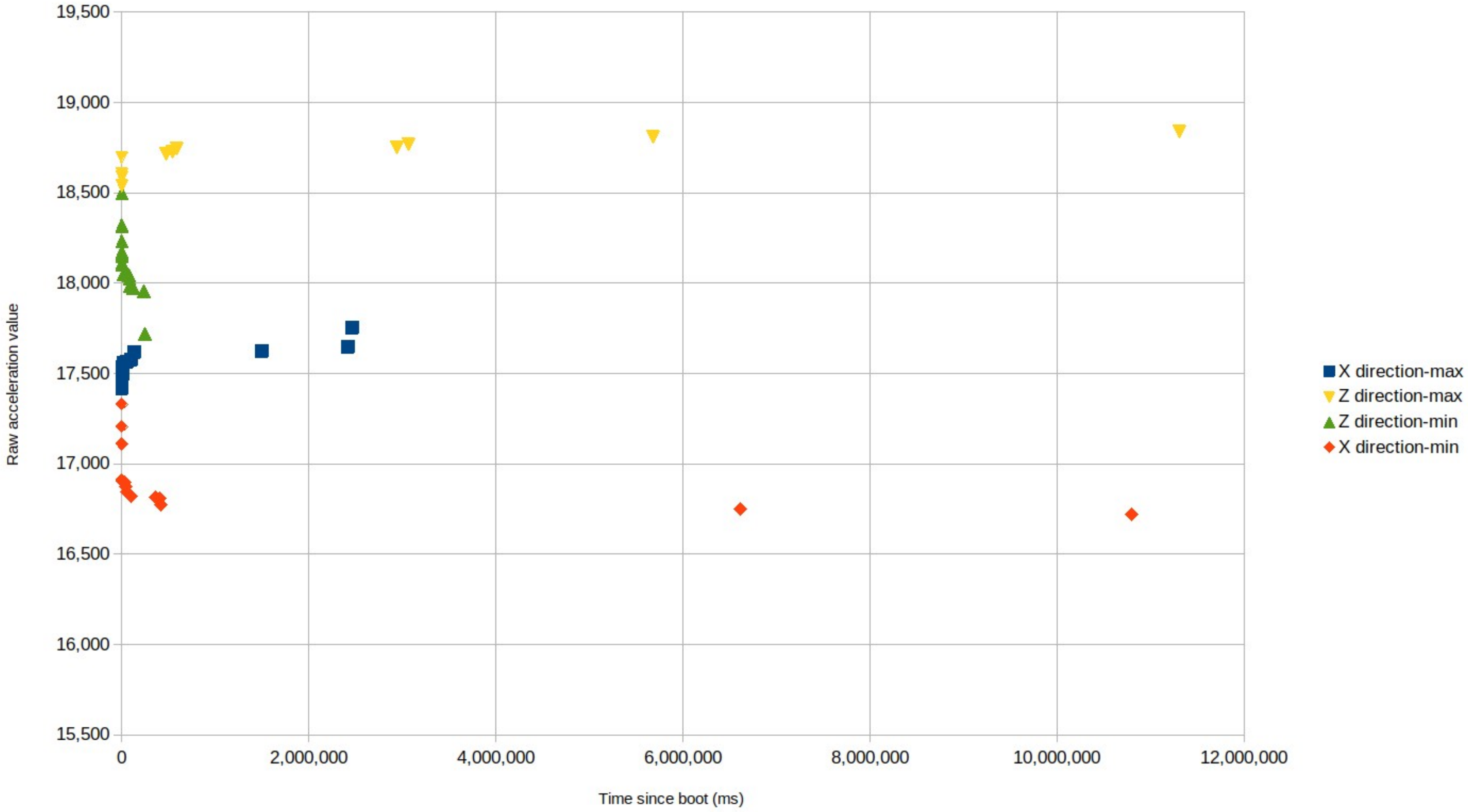


Figure 4. Maximum and minimum values of two MPU6050s sitting stationary

As can be seen from figure 4 , both IMUs stopped reporting new values after about 3.3 hours. This shows the experiment is likely sufficient to capture any maximum or minimum values that might be experienced while the IMU was stationary. It can be observed that most of the maximum and minimum values occur at the beginning of the test. This can be seen more dramatically only the first 11.7 minutes (700,000 ms) of the test are shown, as can be seen in figure 5.

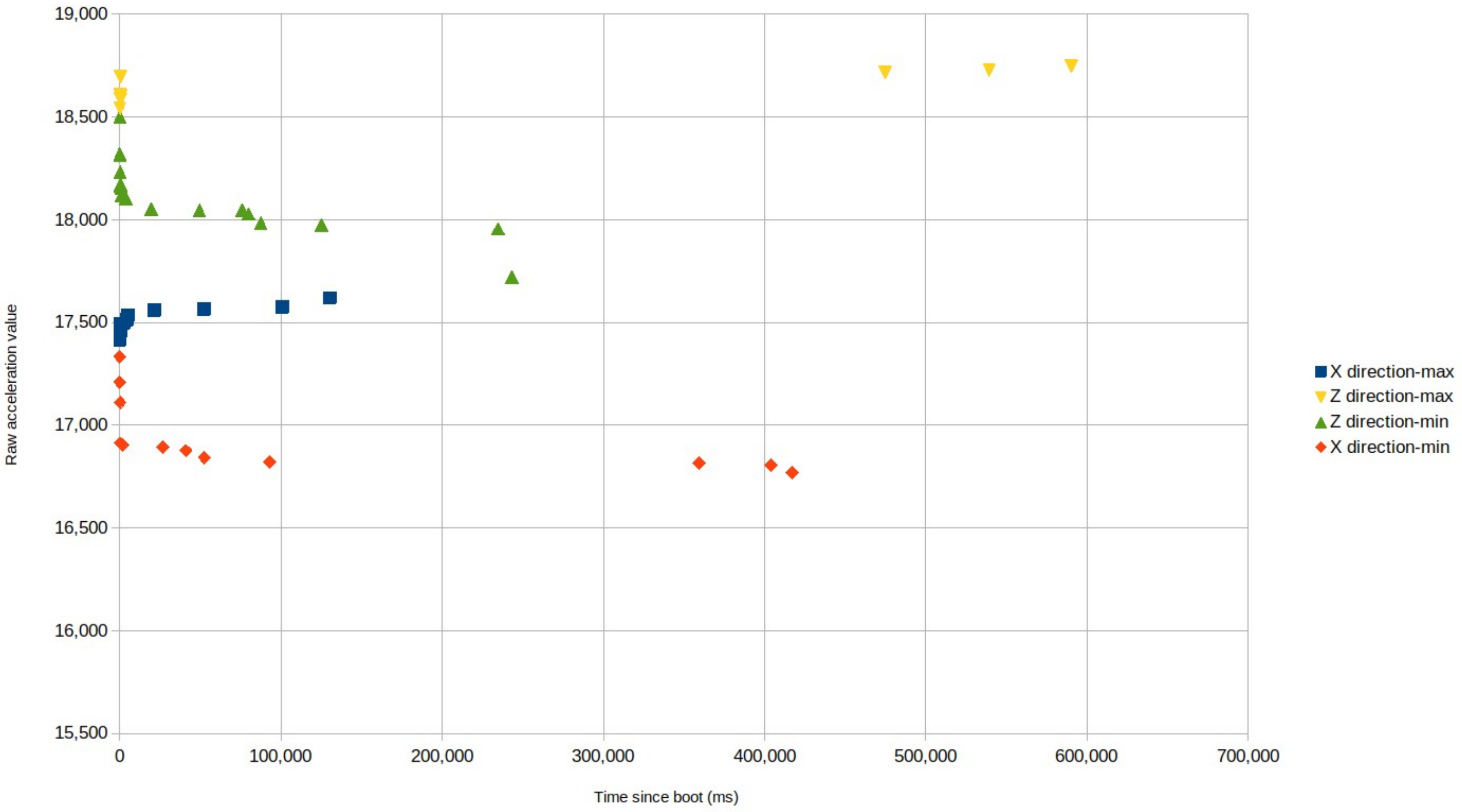


Figure 5. First 700,000 ms of IMU static experiment

It was determined that if just the first 1.7 minutes (100,000 ms) of the data was used, simply subtracting 264 in the worst case (z axis, minimum value) would result in reaching the final lowest value. Other axes required adding or subtracting lower numbers. This is about 1.5% of the value itself, a small amount. To add an additional margin, this number was doubled to reach 528 and then rounded to 550. Thus, running this program for 1.7 minutes and simply adding or subtracting 550 value from the resulting maximum and minimums has a high chance of producing a threshold that would never be exceeded at rest. See table 4 for the maximum and minimums at 1.7 minutes, the actual maximum and minimum seen during the experiment and the difference between the two for both IMUs. Thus this algorithm was used in the programming for the node sensors to calculate thresholds. Above or below these thresholds, the node is programmed to start looking for elevator motion.

Table 4. The results of truncating an stationary MPU6050 calibration

	value at cut off	true max/min value after 11 hours	difference (absolute value)
X direction-max	17564	17752	188
X direction-min	16820	16720	100
Z direction-max	18,696	18,840	144
Z direction-min	**17,984**	**17,720**	**264**

When extending this test to include additional 11 hour tests of x, y and z axes of different accelerometers, the same result is obtained, indicating the robustness of such a method. See figure 6 for the graph of all the data, including the above two trials of x and z (denoted as x axis trial 1 and z axis trial 1). Note that the second trial of the x axis does produce a new maxim at a time point beyond any other trial, but its difference between the value at the cutoff point is less than that of trial 1 of the z axis (see table table 5).

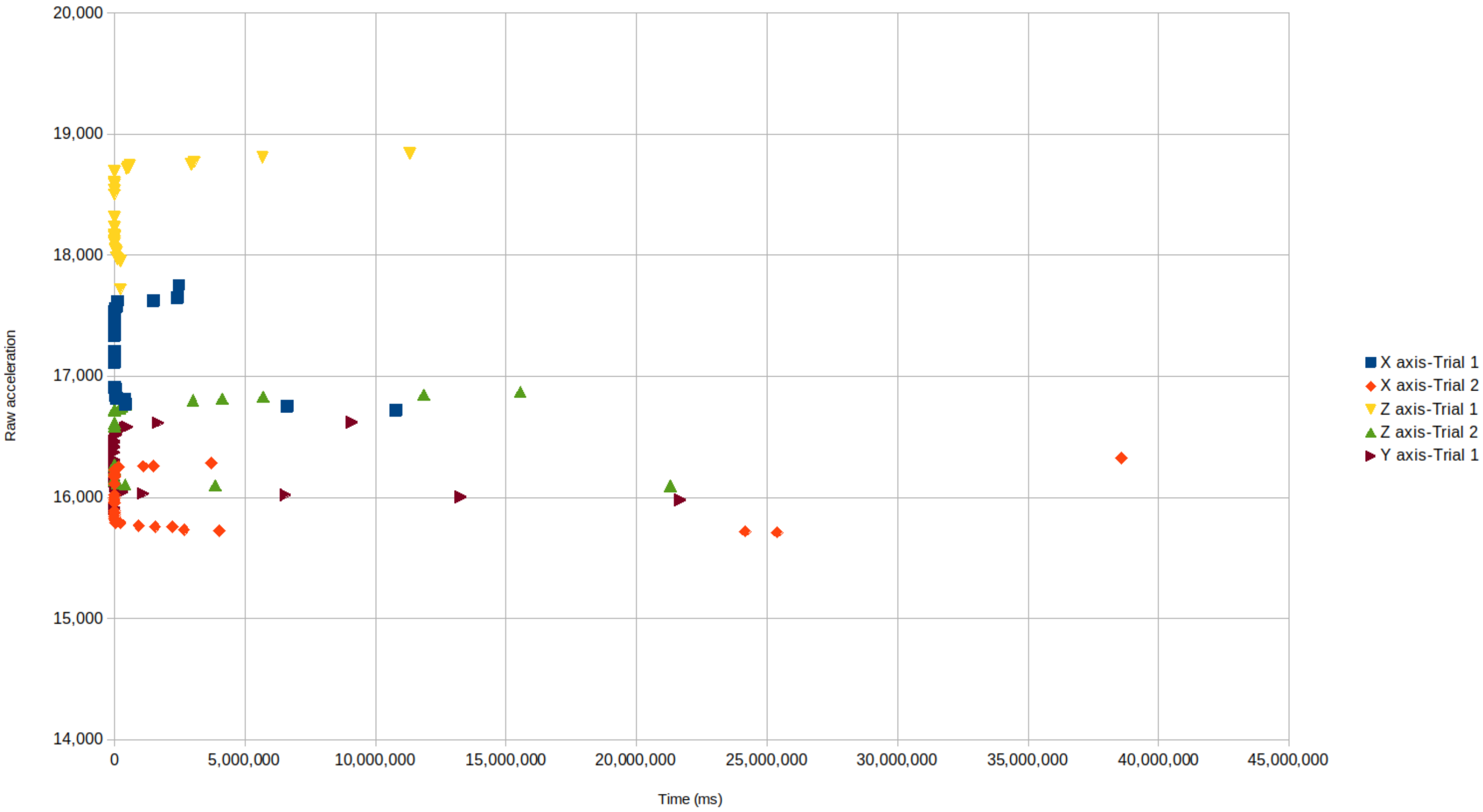


Figure 6. Three additional maximum and minimum tests, along with original data

In table 5, one can observe that the first trial of the z axis still produces the largest value to add and subtract. Thus, one can have reasonable assurance this procedure will be effective for IMUs of the same model in the future.

Table 5. Truncating a stationary MPU6050 calibration with more axes

	value at cut off	true max/min value after 11 hours	difference (absolute value)
X axis-Trial 1 Max	17,564	17,752	188
X axis-Trial 1 Min	16,820	16,720	100
X axis-Trial 2 Max	16,224	16,324	100
X axis-Trial 2 Min	15,792	15,712	80
Y axis-Trial 1 Max	16,556	16,640	84
Y axis-Trial 1 Min	16,048	15,912	136
Z axis-Trial 1 Max	18,696	18,840	144
Z axis-Trial 1 Min	**17,984**	**17,720**	**264**
Z axis-Trial 2 Max	16,724	16,872	148
Z axis-Trial 2 Min	16,144	16,096	48

3.3 DEVELOPMENT OF ELEVATOR MOTION DETECTION ALGORITHM

Another task was to develop a motion detection algorithm that could reliably sense elevator motion but filter out other motions. It was observed that while the threshold calculated in section 3.2 was sufficient to wake the device from sleep, using the maximum and minimum values from the short 1.7 minute test was actually beneficial for some parts of the algorithm. In this section we will call these the "lower threshold" and the other determined in section 3.2 the "higher threshold". The algorithm decided upon was this:

1. When higher threshold is exceeded, begin to monitor for "motion 1"
2. Read acceleration values from IMU. Start a timer every time it exceeds the lower threshold. If it remains outside of this lower threshold for 550 ms, then exit and record if the acceleration was exceeding the max or min threshold. If it does not remain outside the lower threshold within a 3 second window, time out and do not report a motion event.
3. Delay 700 ms while the elevator is in constant velocity before it decelerates
4. Begin monitoring for motion 2, requiring the acceleration exceed the lower threshold for the same length of time as step 2. If exceeded for this length of time, also record if it was the minimum or maximum threshold it was exceeded. If this does not occur within 16 seconds, time out and do not report a motion event.
5. Check to see that motion 1 and motion 2 were exceeding opposite thresholds. If and only if this condition is met, report a motion event.

To better illustrate this, see figure 7. The higher threshold has been drawn in red and the lower threshold has been drawn in blue. The acceleration values as the elevator moves from floor to floor is plotted in blue. Note how the only times all 5 conditions above are met is when the elevator is moving from one floor to another. Here we see it move from floor 1 to 2 and then from floor 2 to 3.

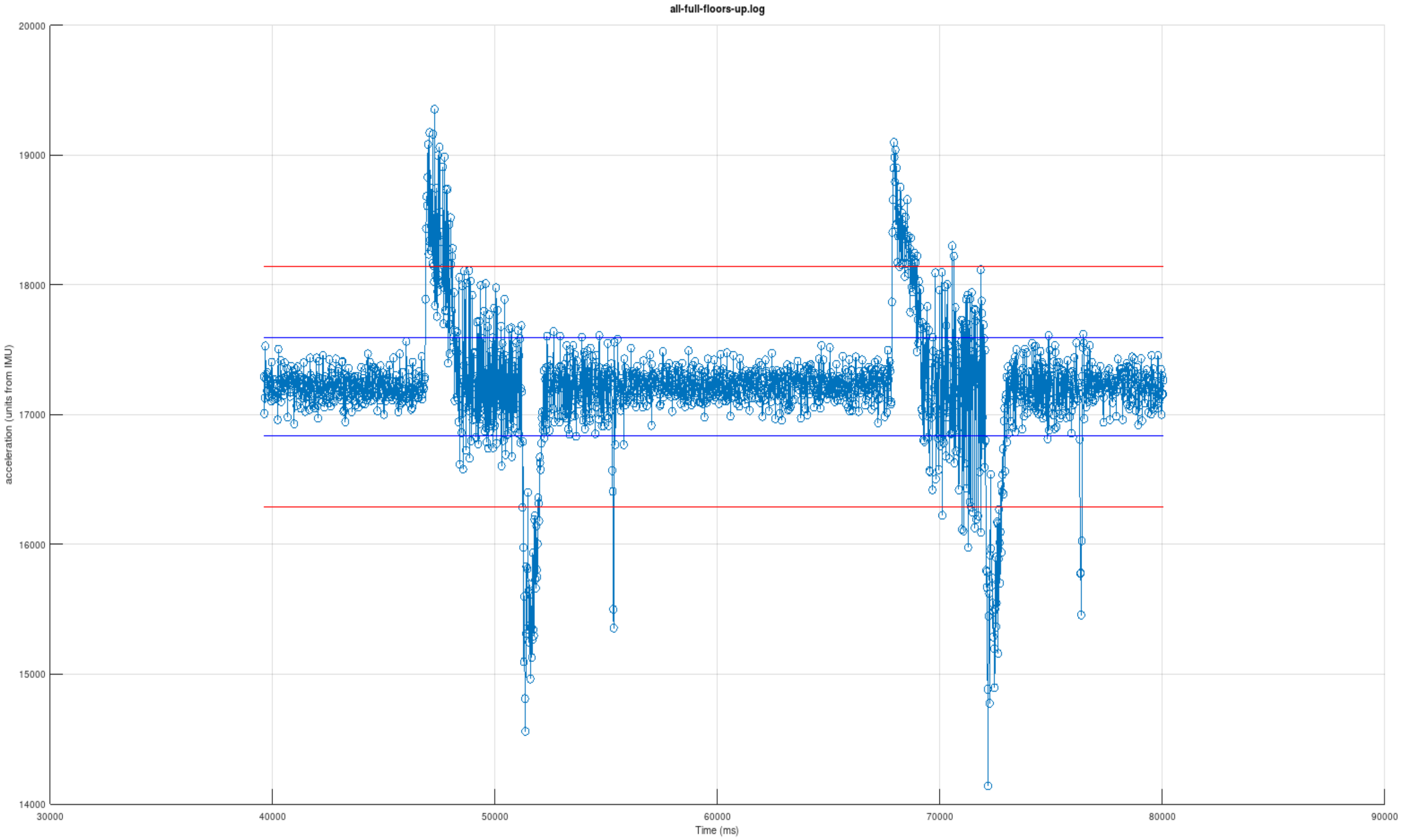


Figure 7. Typical elevator motion with the thresholds used also drawn

4. TECHNOLOGY VALIDATION

4.1 INITIAL IMU FEASIBILITY TEST

To ensure the feasibility of the selected IMU MPU6050, tests were conducted in an elevator in the student union building 1 on GMU's campus. This building was chosen because it houses the office of disability services for the university. Tests were conducted going up and down one floor and then up and down four floors. Due to the fact that a reliable mounting point or case was not developed this early in the timeline, the values seen here are the sum of the raw acceleration values from all three axes. This was done so that the orientation of the IMU would not matter. The units are not very relevant for this initial test because the goal was simply to test if this IMU was sensitive enough to detect elevator motion reliably. The sensitivity of the unit was set to +- 2g. The results from one of the tests can be seen in figure 8.

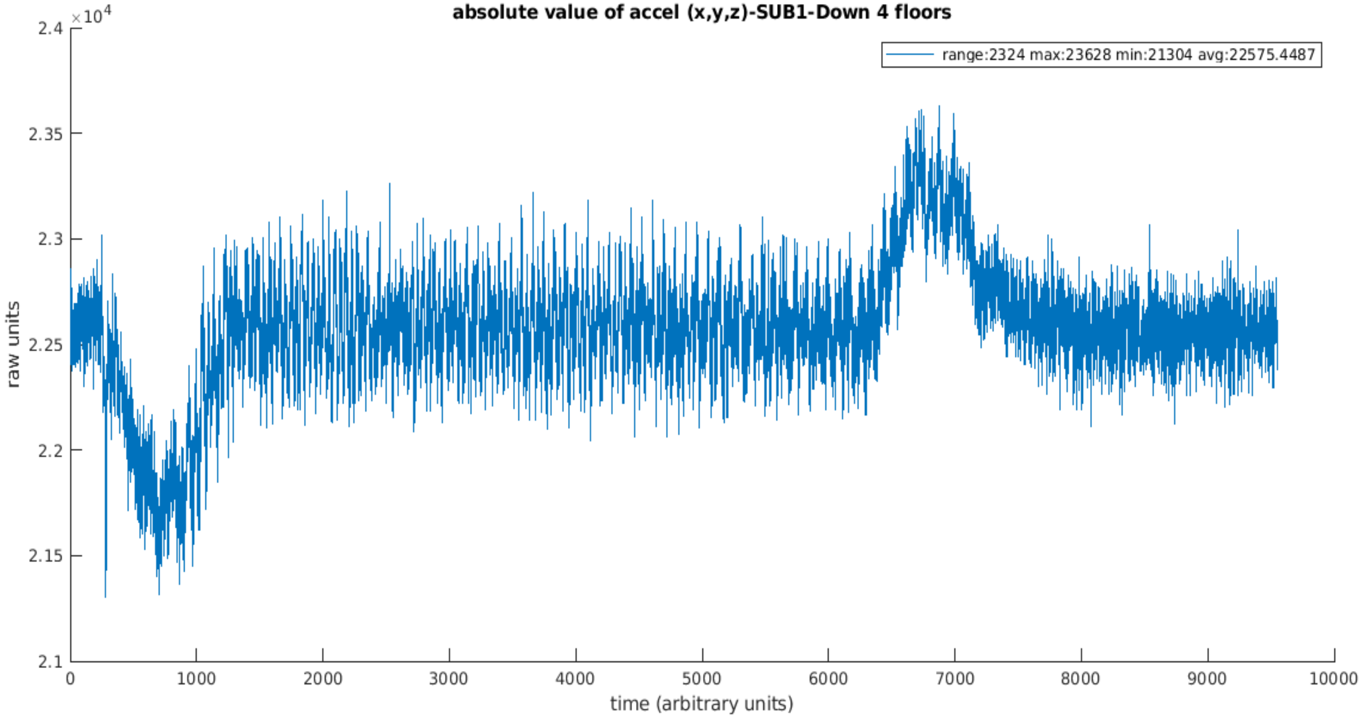


Figure 8. Accelerometer data-traveling down 4 floors

As expected, one can observe the decrease in the measured force of gravity as the car accelerates down. Then there is a constant force of gravity (with some noise) as the car travels at a constant velocity. Finally, an increase in the force detected is observed as the car decelerates as it reaches the desired floor. From these results, it can be seen that the IMU is able to detect both when the car starts to move and when it slows to a stop.

4.2 TRANSCEIVER VALIDATION & ANTENNA TESTING

To validate the transceiver selection and the viability of transmitting in the defined format, a Moteino with its LoRa radio module attached was programmed to send messages almost identical to the *node information packet*, outlined in the wireless protocol description section. The test program replaces the *number of motion events* data field with an integer starting at 0 and counting up. The test program delays 4 seconds before the next transmission to allow more than ample time to send the data, even at the lowest possible rate of 300 bps. By monitoring for missing integers in the received messages, a metric called Packet Reception Rate (PRR) can be calculated. PRR is a common metric in radio networks [54]. PRR is the ratio of correctly received packets divided by total packets sent. The receiver was also programmed to log the Signal to Noise Ratio (SNR) in dB and the Received Signal Strength Indicator (RSSI) in dBm of each message it received [55], [56]. SNR compares the strength of the desired signal to the level of background noise. A higher value indicates a stronger signal relative to the noise and is usually better for message transmission. On the other hand, RSSI measures the power level of the received signal. It indicates how strong the signal is at the receiver's end. Again, the higher the number, the better it generally is for data transmission [57].

In LoRa radio, there are different transmission parameters that may be adjusted to tune things like range, battery use, air time, resistance to multipath propagation, etc. Some include transmission power, the number of forward error correction bits (called the “Coding Rate”), and bandwidth [37]. As each parameter is only allowed to be set to a range of discrete values, there are 6,720 possible transmission settings. Thus, it is not feasible to test all of them for an initial prototype or in the field. As such, the test was conducted with the most robust settings. The purpose of this test was to measure the quality of data transmission using the PRR, SNR and RSSI metrics and to make sure it is suitable for this application. The optimal transmission settings obviously change as the transceiver and elevator move relative to the base station and with other interference sources. Thus, for this prototype, the radio will be set at the most robust setting at the expense of battery life. In the future, there are adaptive algorithms that can be implemented [54]. A 90% PRR is considered more than adequate for these kinds of networks [54]. A RSSI value of above -75 dBm has been shown to have a low value of dropped packets for LoRa in the past with a value of -60 dBm being excellent [58].

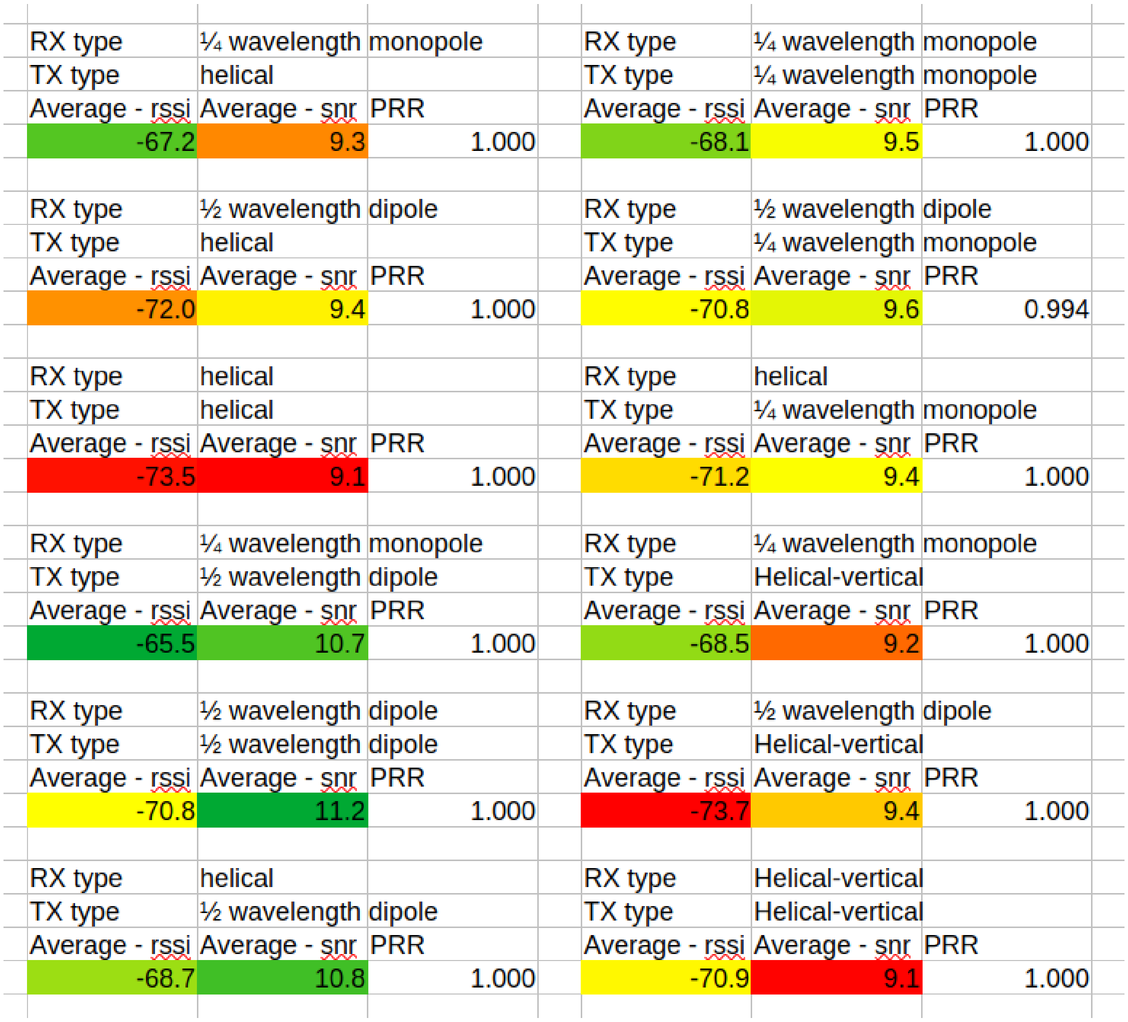
Using the parameters outlined above, the following test procedure was used to test the LoRa transceiver’s PRR and RSSI when used in this specific application. First, the Moteino was placed in an elevator. Next, three different base stations were placed in a room adjacent to the elevator shaft. Each base station had a different antenna provided by the manufacturer of the Moteino units [59]. One was a ½ wavelength dipole antenna, another was a ¼ wavelength monopole antenna and the last was a helical antenna. The helical antenna's dimensions were D=5.5mm, S=~0.5, n=9, A=~12.4mm and d=0.8mm, as defined in [60]. If a particular antenna was directional, it was oriented such that the receiver and transmitter electric field pattern intensities were aimed in the same general direction (i.e. within 45 degrees of ideal) according to [60]–[62]. Perfect alignment would not have been a realistic test of the conditions under which the system is expected to operate nor was it feasible to achieve while the elevator was in motion.

The base stations were given the command to start logging messages to a file. Next, the Moteino in the elevator was powered up and began transmitting with the doors open. It was verified that at least 5 packets were being received before shutting the elevator doors. The elevator was then sent to each publicly accessible floor, starting with the top floor and then going to the bottom. The elevator was then sent back to the top (with the transmitter on) and the procedure down was repeated once. The same entire procedure outlined in this paragraph was also repeated two additional times, each with a different antenna on the transmitter unit. The same procedure was also repeated with the helical antenna pointing vertical instead of in its ideal direction in accordance with [60]. The antennas tested individually on the transmitters were identical models to the three on the base stations. Success was defined as a packet reception rate of 90% or better for all floors. A photograph of the three base stations and three transmitter units may be seen in figure 9.

Figure 9. Base stations and transmitter units used for transceiver validation

This resulted in 1556 total transmissions. Every single packet was received except for one which occurred with a half wave dipole serving as both the antenna for the receiver and transmitter. An overall PRR of 99.9% indicates that the radio selected is a very good choice for this application. However, it also means that it is instructive to calculate the averages of SNR and RSSI for each transmit and receive pair to attempt to determine which antenna is best suited for this application. The results can be seen in table 6. The color scale in the table is red for the lowest values and green for the highest values. It is two separate independent scales for the SNR and RSSI.

Table 6. Averages of RSSI, SNR and total PRR for each antenna transmit (TX) and receive (RX) pair



RX type	¼ wavelength	monopole	RX type	¼ wavelength	monopole
TX type	helical		TX type	¼ wavelength	monopole
Average - rssi	Average - snr	PRR	Average - rssi	Average - snr	PRR
-67.2	9.3	1.000	-68.1	9.5	1.000
RX type	½ wavelength	dipole	RX type	½ wavelength	dipole
TX type	helical		TX type	¼ wavelength	monopole
Average - rssi	Average - snr	PRR	Average - rssi	Average - snr	PRR
-72.0	9.4	1.000	-70.8	9.6	0.994
RX type	helical		RX type	helical	
TX type	helical		TX type	¼ wavelength	monopole
Average - rssi	Average - snr	PRR	Average - rssi	Average - snr	PRR
-73.5	9.1	1.000	-71.2	9.4	1.000
RX type	¼ wavelength	monopole	RX type	¼ wavelength	monopole
TX type	½ wavelength	dipole	TX type	Helical-vertical	
Average - rssi	Average - snr	PRR	Average - rssi	Average - snr	PRR
-65.5	10.7	1.000	-68.5	9.2	1.000
RX type	½ wavelength	dipole	RX type	½ wavelength	dipole
TX type	½ wavelength	dipole	TX type	Helical-vertical	
Average - rssi	Average - snr	PRR	Average - rssi	Average - snr	PRR
-70.8	11.2	1.000	-73.7	9.4	1.000
RX type	helical		RX type	Helical-vertical	
TX type	½ wavelength	dipole	TX type	Helical-vertical	
Average - rssi	Average - snr	PRR	Average - rssi	Average - snr	PRR
-68.7	10.8	1.000	-70.9	9.1	1.000

Observe that the antenna pairs which have relatively high values for both RSSI and SNR are the ¼ wavelength monopole antenna for both, the ½ wavelength dipole transmitting with the ¼ wavelength monopole receiving and the helical antenna transmitting with the ½ wavelength dipole receiving. Thus at least for this specific environment, the best antenna for the base station seems to be a ¼ wavelength monopole where the transmitter could have the same or a ½ wavelength dipole. The clear combination to avoid is the helical antenna on both the transmitter and receiver. In general, it appears that the helical antenna performs relatively poorly. This could be due to the directional nature of its electric field pattern [60].

4.3 RANGE TESTS OF TRANSCEIVER

In order to determine the limits of the selected transceiver, several different tests of the range of transmission were conducted in real world environments. The transmission parameters remained the same as in the transceiver validation & antenna testing section.

The first and most instructive test is a log of RSSI at the base station of the signal from a node as it was traveling away slowly. The base station was installed in a 3rd floor lab at Peterson Hall at GMU. The node was set up to send test messages which count up in integers, exactly as in the transceiver validation & antenna testing section. Both the base station and the node had ½ dipole antennas. A GPS logging application was set to record the seconds elapsed and the latitude and longitude of the node. At the same time, the node was turned on and the base station was set to log the RSSI (and other metrics) and the packets it received. The GPS logging app recorded at one sample per second, slightly higher than the node sent packets. As such, each packet received by the node was able to be matched to a specific and unique GPS coordinate using the time elapsed since the test began (to the nearest second) as the key value pair. Over the test, the average horizontal accuracy was 7.2 meters and the worst case was 16 meters for only 1 point. This was close to the base station when the node had not yet started moving. To ensure all signals were received, the node was left on for 20 minutes, while the base station stopped receiving packets at 5.4 minutes (324 seconds).

The results of this test can be seen in figure 10. The base station’s location is shown with an accessibility symbol and the RSSI seen by the base station at each location the node transmitted can be seen as a red circle with a shade from black (the strongest signal) to white (the weakest). A legend at the top indicates what RSSI value corresponds to which shade. Also note the scale bar and the north compass for orientation. As can be seen, messages can be received up to about 500 meters away from the base station. This could likely be improved by better aiming of the directional antenna used, placing the base station further away from existing metal shelves or using an omni directional antenna if aiming cannot be reliably achieved.

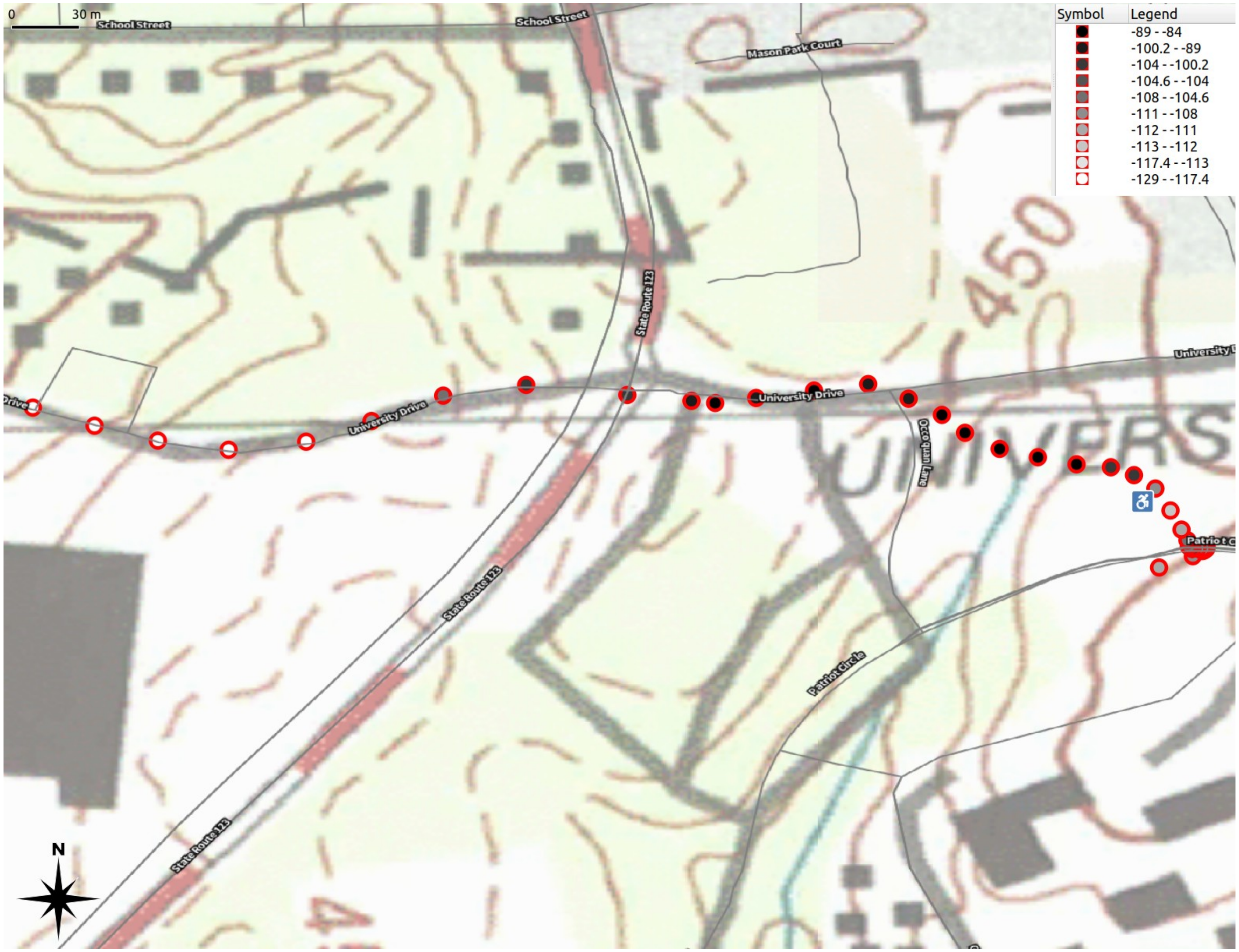

0
30 m
School Street
School Street
Mason Park Court
Symbol
Legend
-89 - -84
-100.2 - -89
-104 - -100.2
-104.6 - -104
-108 - -104.6
-111 - -108
-112 - -111
-113 - -112
-117.4 - -113
-129 - -117.4
450
University Drive
University Drive
University Drive
State Route 123
State Route 123
State Route 123
Occoquan Lane
UNIVERS
Patriot C
Patriot Circle
N

Figure 10. Map the RSSI at a base station of a node along a path leading away

To allow for a sense of scale, figure 11 shows the same data but at a zoom level where observing the entirety of GMU’s Fairfax campus is possible.

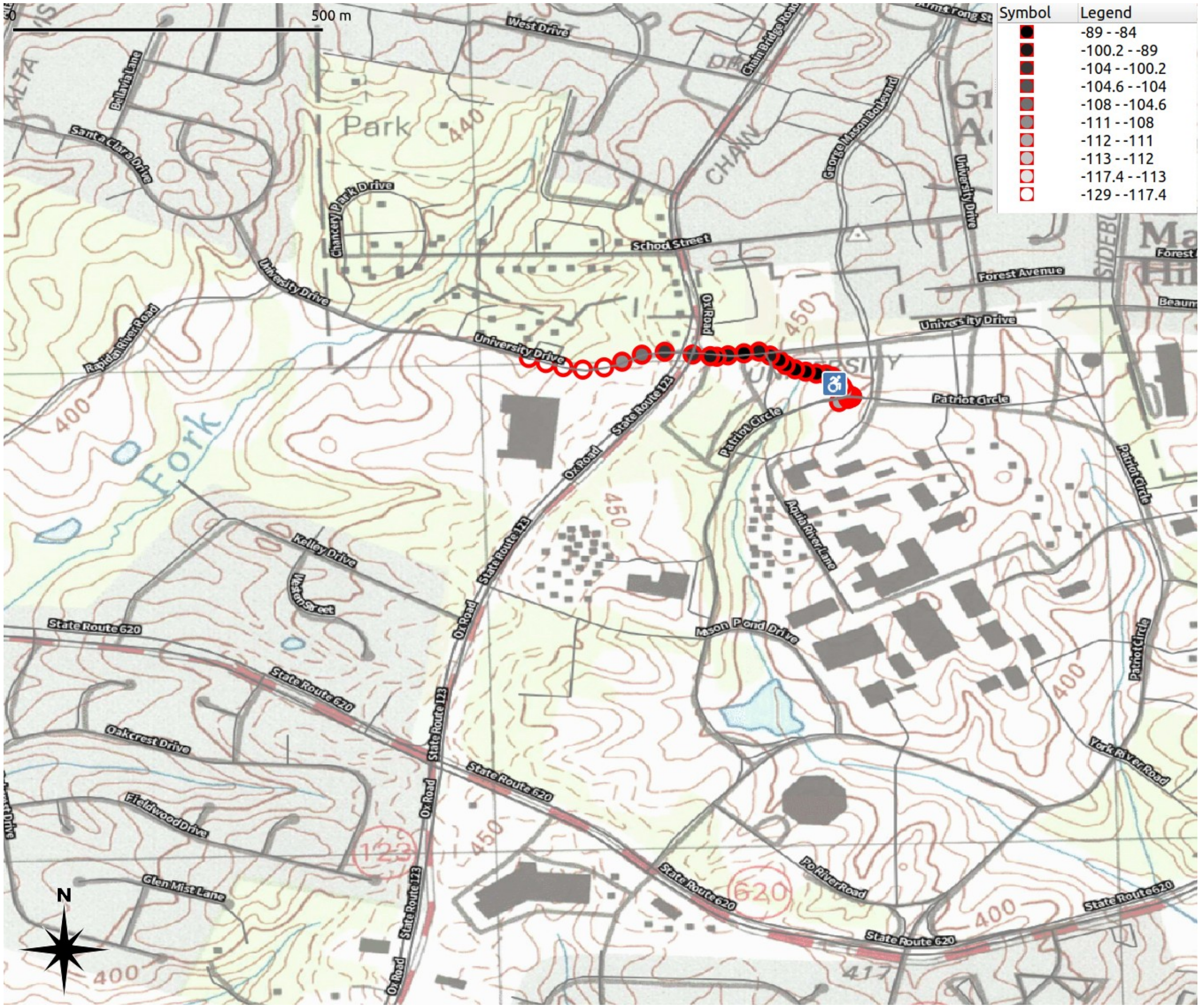

0
500 m
Symbol
Legend
● -89 - -84
● -100.2 - -89
● -104 - -100.2
● -104.6 - -104
● -108 - -104.6
● -111 - -108
● -112 - -111
● -113 - -112
○ -117.4 - -113
○ -129 - -117.4
N
West Drive
Bellavia Lane
Santa Clara Drive
Chancery Park Drive
Park
440
Chain Bridge Road
George Mason Boulevard
University Drive
School Street
Forest Avenue
Ox Road
450
University Drive
Rapidan River Road
Fork
400
State Route 123
Patriot Circle
Kelley Drive
Aquia River Lane
Mason Pond Drive
State Route 620
Oakcrest Drive
Fieldwood Drive
Glen Mist Lane
123
620
Po River Road
York River Road
417

Figure 11. GMU Fairfax campus with RSSI of a roving node.

Another test conducted was at a different site. It does not have as many data points because the location was recorded manually along with the time value of the node. It is mainly included here to corroborate results. Again, the transmission parameters remained the same as in the transceiver validation & antenna testing section. The base station was installed in a 2rd floor office at a public building in Arlington, VA. The node was set up to send test messages which count up in integers, exactly as in the transceiver validation & antenna testing section. The base station had a ¼ monopole antenna and the node had a helical antenna. The results of this test can be seen in figure 12. As one can see, the range is about the same, 350 m. This is likely due to the less optimal helical antenna.

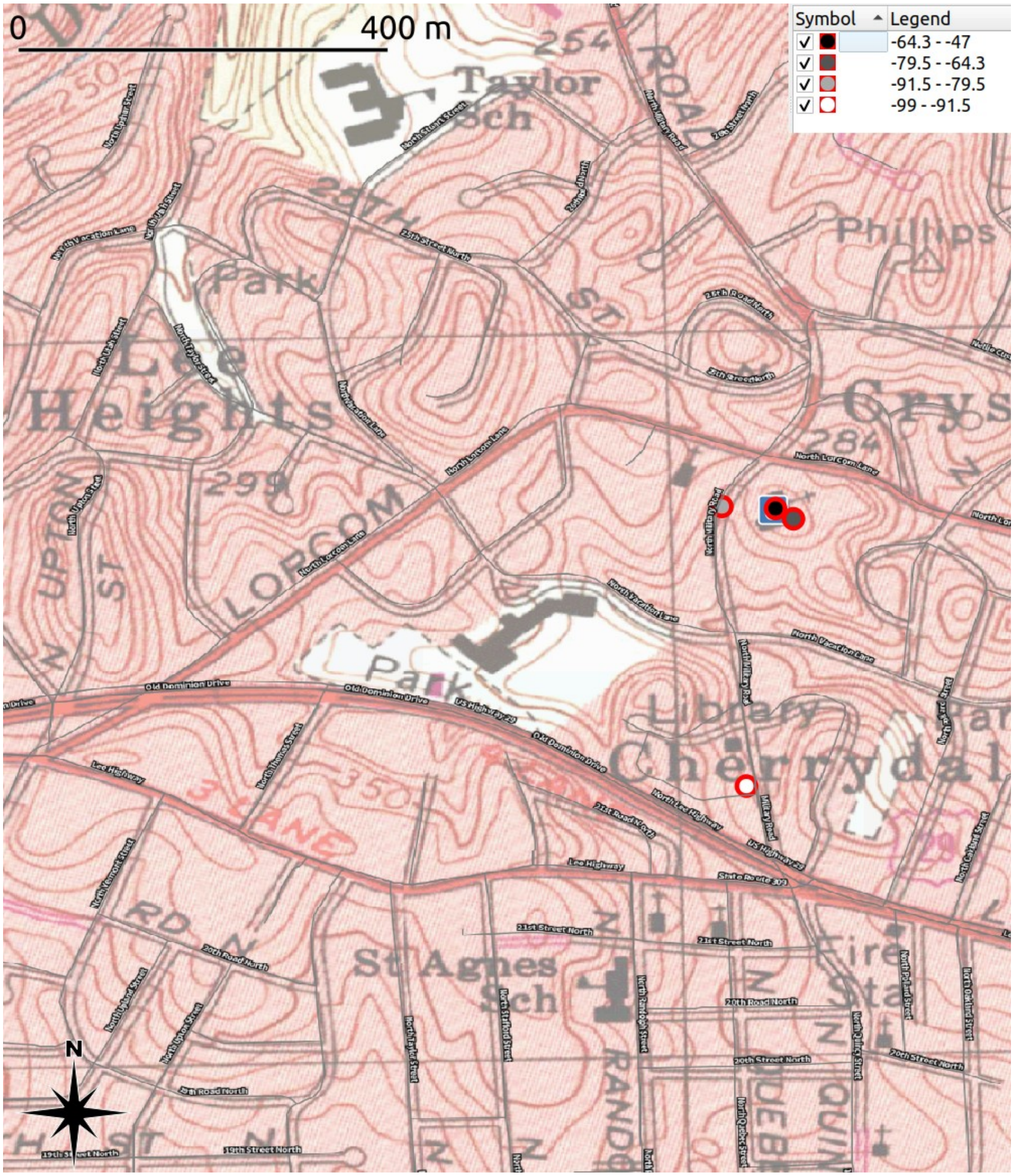


Figure 12. Another range test with less location data

4.4 FULL SYSTEM TEST

Once each component was tested and the firmware had been debugged, a full system test was performed. The base station and node were set up as they would be installed, with the exception that the node was connected to a USB to UART adapter (running at 9600 baud, 8 data bits, no parity, one stop bit) in order to send back status information to a laptop computer. The elevator the system was tested on had three floors. The experimenter instructed the elevator to move eight times between floor 3 and floor 2 and then back for a total of sixteen trips. This then was repeated for floors 2 and 1 and then again for floors 1 and 3. This resulted in a total of 48 trips. The experimenter was watching the computer to ensure the sensor was in the proper phase of its motion detection algorithm at each phase of elevator motion (accelerate, constant velocity and decelerate). The time stamps of each trip were also recorded and compared to the log on the base station. The elevator sensor was then installed overnight. The test site is locked at night so there is reasonable assurance the elevator does not move during this time.

The results were that the sensor performed as intended for each of the 48 trips. it was in the proper phase of its detection algorithm during each phase of elevator motion. The logs on the base station also matched the time stamps of the log created by the experimenter. This provides additional validation beyond section 4.2 that the system is also capable of correctly sending these events to the base station. Additionally, the system did not report any motion while the test site was locked, as intended. The only messages received from the base station were status messages informing the base station of battery voltage. The test site remained locked from 22:30 to 6:30 the following day. Resulting in 480 minutes of testing time with the elevator stationary. Assuming each of the motion trials earlier in the day in the elevator took 1 minute, this 480 minute period can be broken into 480 individual tests, each lasting a minute, the same as the motion tests. Below, table 7 shows the actual and expected behavior of the system. This indicates the system is performing as intended with the false positive rate being 0 and the false negative rate also being 0.

Table 7. Summary of final system validation test

	Actual motion	Actual stationary
Reported motion	48	0
Reported stationary	0	480

5. FINALLY

5.1 LIMITATIONS AND FUTURE WORK

As mentioned previously, as it exists, the system can only provide the “last known working time” of the elevator. Detecting an out of service elevator is unreliable because simply relying on motion timeouts is also unreliable. Adding a sensor that is capable of monitoring when the call button is pressed would be a wise next priority. It is also suggested for future work to include more information about each motion event such as maximum value of acceleration, time between peak acceleration and deceleration and maximum value of deceleration. This would provide much more information to the base station & could possibly enable early detection of elevator issues using data analysis techniques. This approach is better than simply transmitting all the IMU data samples, as this would take up much more transmit time and thus consume more power. It is generally better to do simple computations on the sensor node and have it send a summary of that data.

5.2 CONCLUSION

As can be seen, this project has the potential to fill a gap in the area of accessibility data reporting and monitoring that can be easily installed. It has exciting areas of extension for use by individuals with physical disabilities. An often cited barrier by this population is elevator interoperability. This elevator motion detection system has the potential to provide some live status data relevant to individuals living with a mobility impairment. With future work, the system can also serve to give notice to facility workers when an elevator needs service. Filling this need for reliable information about the built environment can increase equity and improve the quality of life for all people.

APPENDIX

A permanent link to the code repository, documentation, bill of materials and assembly instructions may be found at the following URL:

https://gottalovebrando.has.coffee/mobility

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BIOGRAPHY

Brandon Lancaster received his Bachelor of Science in Engineering from James Madison University in 2013. During this time he also passed the NCEES professional exam, earning him the title of Engineer in Training (E.I.T.). He has traveled across the United States and to Africa, Europe, and South America, enjoys experiencing other cultures and perspectives of others. He was a Technical Specialist at North Anna Nuclear Power Station in Virginia where he performed varied engineering tasks including producing drawings for a modular climbing aid design for construction workers to access confined space piping. He has several publications related to a Deployable Stereo-Hearing Test Package. While studying at George Mason University he has been a Graduate Teaching Assistant and a Graduate Research Assistant. Brandon is committed to using his Engineering skills and training to improve the quality of life for others in all walks of life.