Upgraded Auto Belay Systems

March 24, 2016

A Major Qualifying Project Report Submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements
for the Degree of Bachelor of Science

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Abstract

The following report describes the process undertaken to retrofit auto belay devices used in climbing gyms. The retrofit design enables the climber to have options to rest while climbing, continue to climb, or descend to the ground. Based on the system's engineering approach I used, a working prototype of the user input component was created to fill this research gap.

Acknowledgements

I would like to acknowledge anyone who helped guide this project especially Professor Fred Looft, for his advice and expertise during this capstone design experience. I would like to extend gratitude to Professor Alexander Wyglinski for providing his expertise on wireless networks. This capstone would not have been as successful as it was without the help of William Appleyard for providing the necessary parts for this project and Joe St. Germain for his knowledge on Arduino boards.

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1 Introduction

The sport of indoor climbing encompasses two major activities: bouldering and indoor rock climbing. Both activities are performed on artificial constructions to simulate the experience of outdoor climbing in an indoor environment. In bouldering, the typical challenge is to climb a short, but tricky route up a structure similar to a large boulder[1]. Bouldering climbs are often short enough that minimal safety equipment such as proper footwear is required. By comparison, indoor rock climbing occurs on high climbing walls with steep terrain where during competitive events, the challenge is to climb as fast as possible to the summit of the structure.

Safety equipment is imperative for participants while indoor or outdoor rock climbing. Climbers are often at risk for serious impact injuries from slips and falls therefore, protection methods are critical. Key components of safety equipment include climbing shoes, rope, harnesses, and helmets.[2] Climbing shoes typically have a close fit with a rubbery sole enabling the climber's feet to grip a wall or rock face more firmly.[3] Helmets protect the head from trauma caused by falls or falling objects. Ropes and harnesses are essential for virtually all climbing situations and are integral when belaying climbers.

Belaying is a procedure to ensure a climber's safety while on a climbing course. The belay rope is attached to the harness worn by the climber through a carabineer (a metal loop with a spring-loaded gate). The rope is then wound through an anchor point and then through a manual belay device such as a gri-gri. Gri-gris thread the rope through a series of pulleys that enable the belayer to manage the positioning of the ropes. This setup, which is depicted in more detail in Figures 1.1 and 1.3, is referred to as top rope climbing and is a common practice in most climbing gyms.

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[1] "WHAT IS BOULDERING? ." What Is Bouldering? Accessed November 15, 2015. http://www.boulderbrighton.com/what-is-bouldering.

[2] "10 Indoor Rock Climbing Safety Tips." Made Man. March 25, 2010. Accessed November 15, 2015. http://www.mademan.com/mm/10-indoor-rock-climbing-safety-tips.html.

[3] "How to Make Climbing Shoes Stick Better." LIVESTRONG.COM. July 27, 2015. Accessed November 15, 2015. http://www.livestrong.com/article/548024-how-to-make-climbing-shoes-stick-better/#ixzz1VDPr4L6ZIn.

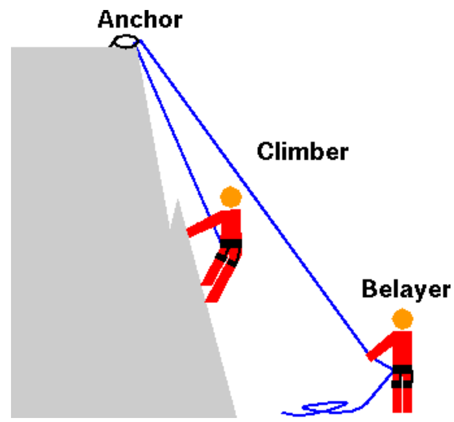

Figure 1.1: Top Rope Climbing[4]

An alternative for beginner climbers, while building skills, is to deploy an automatic belay system (auto belay). An auto belay is a mechanical system that automatically lowers the climber to the ground similar to a human belayer. Auto belays are attached to the summit of the climbing wall instead of the anchor point shown in Figure 1.1. Rope extends out of the auto belay and the climber clips the rope into the harness. If the climber falls, the auto belay simply lowers the climber to the ground at a safe descent rate. Auto belays are a feasible option for new climbers because they eliminate the need for additional personal to serve as a manual belayer. Auto belays are illustrated in more detail in Figure 1.2. Typically, gyms have climbers pay one set rate for a day pass for full access to the gym, including the auto belay stations.

Unfortunately, auto belays have some less desirable features. Most significantly, auto belay systems that exist today do not offer the option to engage a brake while the climber is climbing or falling. This limitation means that if a climber were to let go of the wall, either intentionally or unintentionally, the system will lower them all the way to the ground. For beginner climbers, this hampers their learning since they are unable to work on new techniques while climbing without the risk of falling and having to start the climb over.

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[4]Edwards, Stephen. "Rock Climbing and Equipment Techniques." Rock Climbing and Equipment Techniques. Accessed November 15, 2015. http://alumnus.caltech.edu/~sedwards/climbing/techniques.html.

Figure 1.2: Auto Belay[5]

Figure 1.3: Manual Belay Gri-Gri[6]

[5] "Stay in Climbing Shape for Winter With the 8-week Reach Your Peak Program." TRUBLUE Auto Belay. December 4, 2014. Accessed November 15, 2015. http://www.autobelay.com/news/stay-in-climbing-shape-for-winter-with-the-8-week-reach-your-peak-program/.
[6] "GRIGRI 2: Versatile Control | TopKit." TopKit. Accessed November 15, 2015. http://topkit.com/review-post-type/grigri-2/.

1.1 Problem Statement

The goal of this project was to develop an auto belay system that replicates the flexibility provided by a manual belayer. The upgraded system will expand the features of current auto belay systems by enabling a climber to rest during difficult sections of a climb. Additionally, the enhanced system allows more interaction between the climber and the auto belay system.

Specific objectives for this project were to:

- Determine the key stakeholders involved in the climbing industry and identify system requirements
- Develop a system block diagram and system concepts
- Implement the design by integrating it with a capstone project being developed by another team

The first objective focuses on identifying the stakeholders involved in this project and determining system requirements. This sets the foundation of this project by using these needs to determine the design requirements. The second objective involves using the design requirements to develop system concepts and create block diagrams for the entire system. The third objective involves choosing a solution and implementing it to work alongside a related capstone project, which served as the final test for this capstone design experience.

1.2 Summary

This chapter introduces a problem: auto belays are missing a key feature that would enable the climber to rest. To solve this problem, my intention was to develop a system that has the capability to provide the climber with more flexibility, including a rest option, while climbing. Chapter Two contains background information including current technology about auto belay systems and their function in climbing. Chapter Three provides the methodology of the design of the upgraded auto belay system. Chapter Four focuses on the system design of the upgraded auto belay system.

2 Background

Recreational climbing has endured for hundreds of years, though little of recreational climbing history has been recorded. What is known is that the twentieth century brought about fundamental changes to the climbing sport and community. For example, in the 1930's, the first universal system for grading the intensity of climbs, the Yosemite Decimal System, was invented[7]. Later, in the 1990's, the first international climbing competition was held.[8] With the popularity of recreational climbing growing, more indoor climbing gyms and centers were opened to meet the demand for climbing facilities. According to the Climbing Business Journal, climbing gym openings increased at a rate of 9% in 2014 and 10% in 2013.[9]

2.1 Belay Devices

With this upsurge in recreational climbing, there have been continuous improvements in climbing gear and technology. The primary piece of gear associated with this project is the belay device. Before hardware versions of belay devices were invented, human belayers used a knot called a Munter hitch.[10] This knot is a simple method of belaying a climber by creating tension on the rope.

The original belay devices used in recreational climbing were Sticht plates. Sticht plates put friction on the rope through the tight angles in the system and are thus effective as belay devices. [11] However, Sticht plates are easy to jam and frequently lead to a rough descent. The next generation of belay devices were ATCs (Air Traffic Controllers), see Figure 2.2.[12] ATCs are the most common type of manual belay devices however; they must be completely controlled by a human belayer. When the ATC is locked off, the rope is immobilized and holds the climber securely so the position of the climber relative to the wall is unchanged. Evolving from ATC's were Gri-Gris, which lock automatically when the belayer pulls the rope through the system. In order to let the climber down, the belayer has to depress a small lever that releases the rope. These manual belays are shown in detail in Figures 2.1 and 2.2.

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77 "Colorado Mountaineering." A Guide to the Yosemite Decimal System. Accessed March 13, 2016. http://www.coloradomountaineering.com/2012/01/guide-to-yosemite-decimal-system.html.

8 "Climbing Competitions' History." Climbing Competitions' History. Accessed February 10, 2016. https://www.ifsc-climbing.org/index.php/about-ifsc/what-is-the-ifsc/history.

9 "Gyms and Trends of 2014." Gyms and Trends of 2014. December 29, 2014. Accessed February 10, 2016. http://www.climbingbusinessjournal.com/2014-climbing-gyms-trends/.

10 Disser, Nate. "No Belay Device? Use the Munter Hitch! - San Juan Mountain Guides." San Juan Mountain Guides. June 05, 2014. Accessed February 10, 2016. https://mtnguide.net/belay-device-use-munter-hitch/.

11 Newson, Joby. "The Beginners Guide to Belay Devices." Boulders. Accessed February 10, 2016. http://bouldersuk.com/2014/02/beginners-guide-belay-devices/.

12 "How to Choose a Belay Device." How to Choose a Belay Device. Accessed February 10, 2016. http://www.rockandice.com/gear-guide-tips/how-to-choose-a-belay-device.

Figure 2.1: Munter Hitch (left) and Sticht Plate (right)[13]

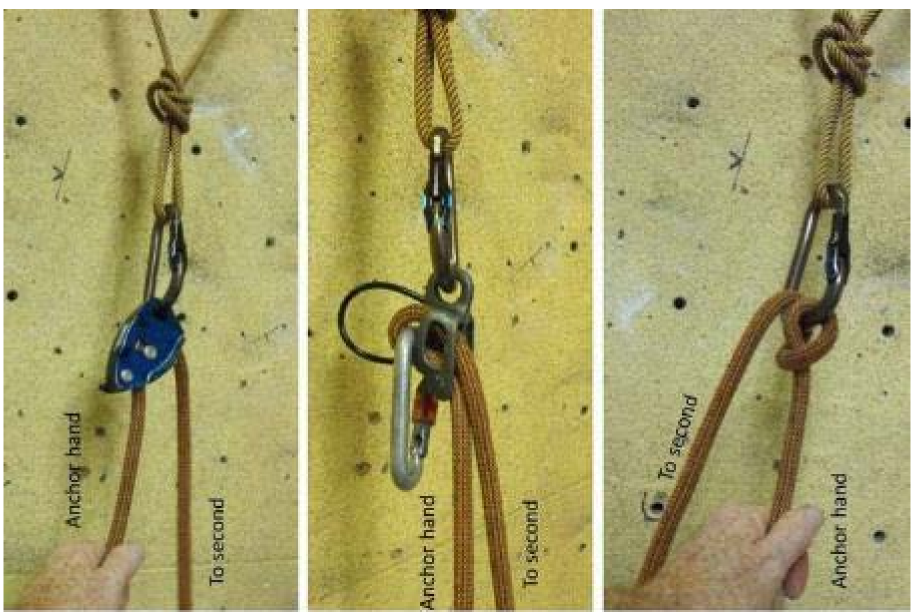

Figure 2.2: From Left to Right Gri-Gri (Auto-lock, Gear), ATC (Manual, Gear), and Munter Hitch (Knot)[14]

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[13] Newson, Joby. "The Beginners Guide to Belay Devices." Boulders. Accessed February 10, 2016. http://bouldersuk.com/2014/02/beginners-guide-belay-devices/.
"Munter Hitch." - How to Tie a. Accessed February 10, 2016. http://www.netknots.com/rope_knots/munter-hitch/.

[14] Handford, Steve. "Gear Guru Mike Law - EVERY SECOND COUNTS." Mainpeak Australia. Accessed February 10, 2016. http://www.mainpeak.com.au/blog/gear-guru-mike-law-every-second-counts/.

Another method of belaying is to use an automatic belay (auto-belay) system, shown in Figure 2.3. Auto belay systems automatically retract the rope as a climber climbs. If the climber falls, the auto belay system maintains tension on the rope while lowering the climber to the ground. A problem with auto belays is that the auto belay system is unable to hold the climber in place unless the climber manually pulls himself or herself back onto the wall. Most auto belays are manufactured and sold by two companies: TruBlue and Perfect Descent. Another company that previously made auto belays was MSA, but their Redpoint and Auto Belay descenders were all recalled in October of 2009. [15]

Figure 2.3: Auto Belay Device[16]

Typically, auto belays are missing key features that a human belayer could provide such as the ability to clamp the rope for rest during multiple attempts of a difficult climbing section. Auto belay manufacturers TruBlue and Perfect Descent, offer several different types of auto belays that wind the rope using various methods. However, none offers a clamping, resting action. A new company, BM Engineering in the United Kingdom was issued a patent in 2006 for an auto belay system that could be controlled via a remote but again has no clamping action for rest.[17] The system gave the climbers options to switch the modes of the belay system between winding up slack and letting slack out.

Most commercially available auto belay devices use 1 inch tubular webbing as a belay line rather than dynamic climbing rope. Unlike dynamic rope, tubular webbing is a static, nylon material that does not stretch. Tubular webbing and dynamic rope are shown in more detail in Figure 2.4. Auto belay devices

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[15] Cohen, Andrew. "Massive Product Recall Rocks Auto-Belay Industry - Athletic Business." Athletic Business. December 2010. Accessed February 13, 2016. http://www.athleticbusiness.com/fitness-training/massive-product-recall-rocks-auto-belay-industry.html.

[16] "Www.SpiderClimbing.com - Magnetic Climbing Wall Manufacturer." Buy Climbing Auto Belay. Accessed February 10, 2016. http://www.spiderclimbing.com/autobelay.htm.

[17] Limpet Holdings (U.K.) Limited,. 2013. "Belay Device". United States of America.

use webbing rather than rope because webbing is less expensive. Climbing rope is primarily used in outdoor environments, where the rope needs to fit through tight rocky crevices and webbing might become stuck. Since webbing stretches more than rope, if the climber falls, the webbing will allow for a gentler descent because it has more pliability.

Figure 2.4: Right Tubular Webbing[18], Left Dynamic Rope[19]

2.2 Wireless Technologies

Communication links are essential for any user interaction system. ZigBee, Wi-Fi, and Bluetooth technologies use standard IEEE wireless protocols and all share a common characteristic: they are designed for short-range wireless communications. ZigBee is typically used in home automation systems. Wi-Fi is primarily used for Internet and wireless LAN. Bluetooth is used for consumer electronics such as headsets and computer mice.

All of these networks differ in data rate, indoor range, RF line of sight, number of devices, and ease of configuration. Data rate is the speed at which data travels per second and is a significant factor to be considered. Number of devices refers to the maximum number of devices that a network can support simultaneously. RF line of sight is the maximum range for wireless devices that is typically difficult to increase because of interference. Indoor range is the approximate range of the devices inside. These are all important characteristics that are summarized for each wireless technology in Table 2.1.

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[18] "Web Source 1"(25mm) Nylon Tubular Climbing Webbing - Mountain Equipment Co-op." Mountain Equipment Co-op. Accessed February 13, 2016. http://www.mec.ca/product/5020-829/web-source-125mm-nylon-tubular-climbing-webbing/.

[19] Kha, Sajib Chandra. "ADVENTURE & MOUNTAINEERING." : MOUNTAINEERING EQUIPMENTS. September 7, 2013. Accessed February 13, 2016. http://stayhappyandcoolwithus.blogspot.com/2013/09/mountaineering-equipments.html.

Table 2.1: Comparison Table of the Three Wireless Technologies[20]

Standard	Bluetooth	ZigBee	Wi-Fi
IEEE Spec	802.15.1	802.15.4	802.11.a/b/c
Max data rate	1 Mb/s	250 Kb/s	54 Mb/s
Nominal range	10	10-100	100
Max number of nodes	8	>65,000	2007
Network topology	Piconet, scatternet	Star, cluster tree, mesh	BSS, ESS

ZigBee is a wireless standard often used in home automation and supports up to 65,000 devices on the same network that can be anything from lights and air conditioners to traffic management systems.[21] For most home applications, ZigBee devices typically transmit only a few times per day with signals that mostly turn appliances on or off. For example, a ZigBee network to turn on or off a light switch might only need to transmit ten to fifteen times a day to turn the lights on or off. In some applications, ZigBee devices can be used for continuous data transmission as well.[22] ZigBee devices typically have an indoor range from 10-100 meters ZigBee networks usually have a mesh network, star, or cluster tree architecture (shown in Figure 2.5) which can extend the range to several miles.[23] ZigBee networks ideally have low data rates and low power. All ZigBee networks must have a network coordinator as shown in red in Figure 2.5. The coordinator connects several full functioning devices that are routers for the signals to travel and several reduced function devices shown in yellow.

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[20] J. S. Lee, Y. W. Su and C. C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE*, Taipei, 2007, pp. 46-51. doi: 10.1109/IECON.2007.4460126
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4460126&isnumber=4459874

[21] Hussian, Rashid, Sandhya Sharma, Vinita Sharma, and Sandhya Sharma. "WSN Applications: Automated Intelligent Traffic Control System U Sing Sensors." *International Journal of Soft Computing and Engineering (IJSCE)*, 2013th ser., 3, no. 3 (July 2013). http://www.ijsce.org/attachments/File/v3i3/C1641073313.pdf.

[22] "RF Wireless World." ZigBee Compliance Testing. Accessed March 14, 2016. http://www.rfwireless-world.com/Articles/zigbee-compliance-test.html.

[23] Mims, Christopher. "The Wireless Network with a Mile-wide Range That the "internet of Things" Could Be Built on. "Quartz. August 31, 2013. Accessed March 14, 2016. http://qz.com/120270/a-new-alternative-to-wi-fi-has-a-range-of-nearly-a-mile-and-wont-drain-your-battery/.

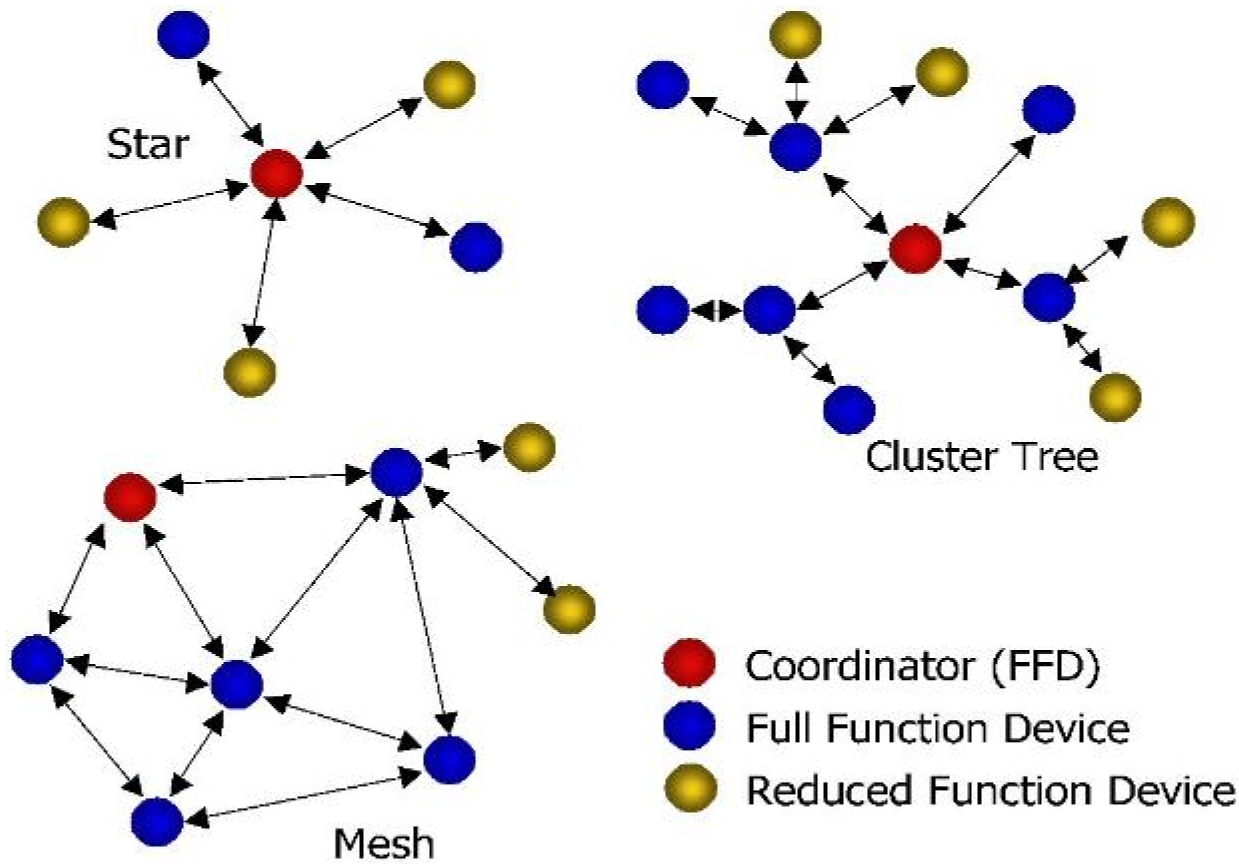

Figure 2.5: ZigBee Network Architectures[24]

The Wi-Fi standard evolved in 1997 soon after the FCC unlicensed the spectrum from 900MHz to 2.1 GHz and 5 GHz for unlicensed use in 1985.[25] Wi-Fi sends data across multiple frequencies to nodes in packets. Wi-Fi networks can support up to 2007 nodes simultaneously with several overlapping channels and a range of approximately 100 meters, thus making it ideal for use in climbing gyms, office buildings, and homes.[26] Wi-Fi networks use far fewer cables than traditional wired networks with data rates up to 54 Mb/sec, making them ideal for mobile devices. To adjust for this high data rate, most mobile devices consume large amounts of power transmitting and receiving data when compared with other wireless protocols. This is shown in detail in Figure 2.6.

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[24] "ZigBee SoCs Provide Cost-effective Solutions | EE Times." EETimes. November 5, 2005. Accessed March 13, 2016. http://www.eetimes.com/document.asp?doc_id=1273396

[25] Britannica Academic*, s. v. "Wi-Fi," accessed January 30, 2016, http://academic.eb.com/EBchecked/topic/1473553/Wi-Fi.*

[26] Jin-Shyan Lee; Yu-Wei Su; Chung-Chou Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE* , vol., no., pp.46-51, 5-8 Nov. 2007

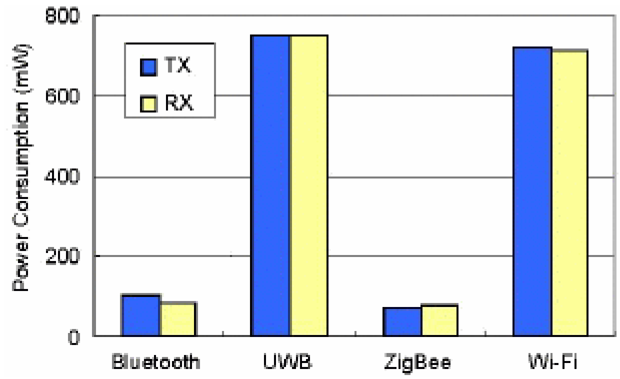

Figure 2.6: Power Supply of Various Wireless Protocols[27]

Bluetooth is used primarily for short-range wireless applications in with a range of about ten meters and low power requirements.[28] Bluetooth networks are composed of a master device, slave devices, and have network topologies of both piconets and scatternets. Piconets are Bluetooth networks that share a common channel that support a maximum of eight Bluetooth devices at once. One device acts as the master and the others as slaves. A scatternet forms by connecting two or more piconets through a common node as shown in Figure 2.7.[29] As shown in Figure 2.6, Bluetooth requires minimal device power to operate. This is due to a sleep mode that allows the Bluetooth device to minimize power use while it is inactive. Bluetooth has a high data rate (1Mb/s) which is useful for pairing peripherals with computers, smartphones, and headsets.

[27] Jin-Shyan Lee; Yu-Wei Su; Chung-Chou Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE* , vol., no., pp.46-51, 5-8 Nov. 2007
doi: 10.1109/IECON.2007.4460126

[28] Jin-Shyan Lee; Yu-Wei Su; Chung-Chou Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE* , vol., no., pp.46-51, 5-8 Nov. 2007
doi: 10.1109/IECON.2007.4460126

[29] Bhagwat, P., "Bluetooth: technology for short-range wireless apps," in *Internet Computing, IEEE* , vol.5, no.3, pp.96-103, May/Jun 2001
doi: 10.1109/4236.935183

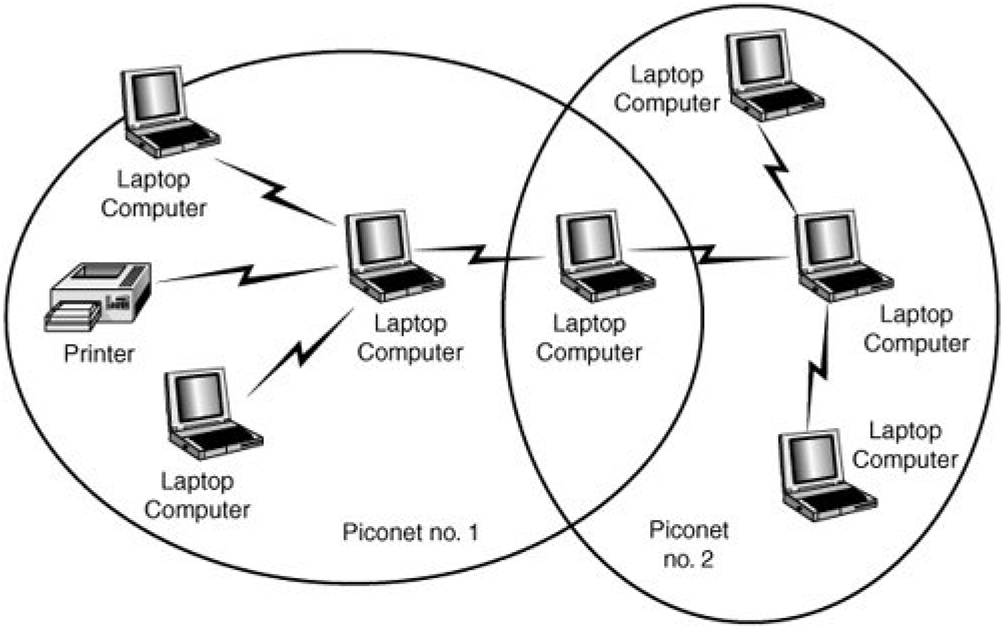

Figure 2.7: Two Piconets Together Creating a Scatternet[30]

2.3 Summary

Climbing gyms deploy both auto and manual belays to assist climbers in their gyms. Manual belay devices can utilize Munter hitches, Sticht plates or ATC's with ATC's being the most common. Auto belays are useful for climbers who want to climb without a human partner belaying them from the ground. Most belay devices use either webbing or rope connected through a carabineer to support the climber. Auto belays lack the flexibility of manual belay systems since they can only lower the climber to the ground and the climber must restart the climbing course. This section also provides background on wireless standards ZigBee, Bluetooth, and Wi-Fi standards as summarized in Table 2.1. These wireless protocols are useful for mobile applications, however, each has unique advantages and disadvantages. In order to address the challenges climbers face using auto belays, my design provides a method for users to interact with auto belays using wireless technologies.

[30] Preetham, Paul. "Bluetooth - Sharon Encyclopaedia." Sharon Encyclopaedia. 2015. Accessed January 31, 2016. http://www.sharonencyclo.com/bluetooth/.

3 Methodology

The purpose of this section is to describe the methods used to address the project goals and objectives. As described in the previous section, auto belays are at a disadvantage when compared with the versatility of a manual belay device. To develop a design to mitigate the limitations of using auto belays, the project was broken down into four main objectives:

- Identify the key stakeholders involved in the climbing industry and determine their needs
- Identify the limitations and strengths of current technology
- Identify system requirements and criteria for a successful project
- Implement design and demonstrate it working alongside with a capstone project being developed by another team

3.1 A Systems Engineering Approach

This project followed a methodology similar to the Vee diagram often used in systems engineering applications. Given the time constraints of this capstone project, the project progressed from the concept exploration phase to the implementation phase as shown in Figure 3.1. I chose this approach since it closely followed the objectives of this project.

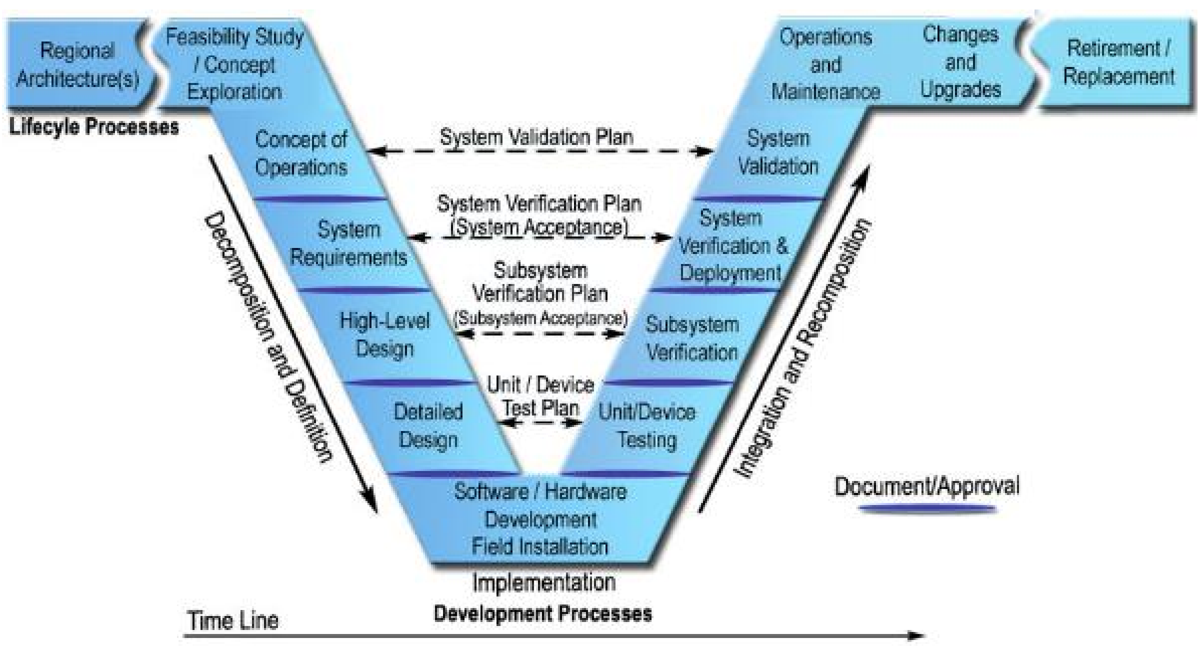

Figure 3.1: Vee Diagram[31]

[31] "What Is Systems Engineering?" Systems Engineering for ITS Handbook. Accessed January 31, 2016. http://ops.fhwa.dot.gov/publications/seitsguide/section3.htm.

3.1.1 Determining the Key Stakeholders involved in the Climbing Industry and Identify System Requirements

The first objective of the design included defining the problem and determining key stakeholders involved with the climbing industry. To meet this objective, I considered stakeholders involved both directly, such as climbing gyms and indirectly, such as the International Climbing and Mountaineering Federation (UIAA). The UIAA has expressed needs that were integral to developing system requirements as shown in Chapter Four. A thorough literature review was undertaken to determine the stakeholders involved as well as the standards set by the climbing industry for auto belay systems. After the needs analysis was completed, system requirements were developed based on the priority of the needs expressed. The requirements would later serve as criteria for assessing the success of the project.

3.1.2 Develop a System Block Diagram, System Concepts

The second objective involved developing high-level system design concepts and system block diagrams. This step included determining interface requirements as well as key components used in the system. The block diagrams were modified and refined until a final system design was reached. This involved a design overview to provide the outline of all the components functioning together in the preliminary design.

3.1.3 Demonstrating the Final Design Working with a Related Capstone Project

The third objective of this project examined the integration of a related capstone design project with this project. This integration utilized a wireless interface that would interpret specific commands correctly for the auto belay to operate properly. Testing and developing test procedures for the auto belay were vital to achieve this objective.

3.2 Summary

In summary, this project follows a systems engineering design process with three specific objectives to guide the test and design of this capstone project. This section outlines the methodology followed in this capstone project. The first objective involved determining the key stakeholders and translating their needs into system requirements. The second objective involved developing a system block diagram and assessing parts for use in the design. The final objective involved integrating the project with a related capstone project.

4 System Design

This section presents the overall system design as well as the process involved to identify and analyze system requirements, constraints, needs, and feasibility. This section opens with identifying the stakeholders and their needs. This served as the cornerstone of the project as stakeholders' needs were translated into system requirements that served as criteria for a successful design. The second step taken was to conceptualize the system by determining, the concept of operations (CONOPS) for the system. The CONOPS presents use cases, gap analysis, and risk analysis for the engineering of the auto belay system. The third step was determining a functional block diagram to serve as a guide for the detailed design. The diagram shown in Figure 4.3 presents the major components of the system design as well as specific functions of each component. This section concludes with a summary expressing the main ideas of each subsection.

4.1 Stakeholders

An important part of this project was determining the major stakeholders that would be impacted by innovations in auto belay devices. The stakeholders were identified by a thorough literature research of current auto belay systems as well as auto belay certification agencies. The major stakeholders are identified in Table 4.1. Stakeholders received a priority based on their potential impact on this project. The stakeholders with a high importance to this project received a priority of one and the lower priority stakeholders received a priority of a three.

Table 4.1: Stakeholder Analysis

ID	Title	Description	Role	Priority
SH.01	UIAA/ANSI	Inspects and certifies belay devices	Compliance with laws and regulations	1
SH.02	Climbers	Climbers and people using the auto belay device for climbing	Direct, involved, operators	1
SH.03	Climbing Gyms	Interested in implementing this technology in their gyms	Financial beneficiary	2
SH.04	Project team	Team members design auto belay system	Developer	1
SH.05	Project advisor	Scores and directs project	Director, project manager, provides technical, managerial, educational, editing and other advisor responsibilities	1
SH.06	Insurance companies	Insures belay device so climbing gyms are not liable for damages	Compliance with insurance risk management requirements and reviews	3

The first stakeholders listed are the International Climbing and Mountaineering Federation, (UIAA) and the American National Standards Institute (ANSI.) Both UIAA and ANSI are agencies that are responsible for the certification and safety of commercially available climbing equipment. Although there are no fixed safety standards for auto belays that have been adopted by the climbing industry, most auto belay manufacturers require a liability insurance standard for their product purchasers (climbing gyms). The upgraded auto belay system proposed by this MQP must be safe, inspected, and comply with UIAA and ANSI standards.

The second stakeholders listed are climbers, the end users. They are the sole operators of the belay device and therefore, are given the priority of one. For these direct operators of this device, the final product should be easy to learn and not hinder them on the climbing wall. Climbers would be the primary beneficiaries of this proposed device because it will provide them with more options while climbing. This project would enhance and provide greater flexibility for their climbing experience

Climbing gyms are likely to benefit financially from an improved auto belay system by attracting more climbers. Climbing gyms, as a stakeholder group, were given a priority of two. They would be implementing this technology in their climbing gyms. The ease of use of the proposed device and approval from UIAA and ANSI would be critical. Climbing gyms typically need to purchase insurance for liability reasons and conform to standards. Therefore, insurance companies are a stakeholder with a priority of three. Additional insurance is provided through the manufacturer, subject to the climbing gym having regular inspections and preventative maintenance.

The project team and advisors are both stakeholders with a high priority because both groups have to determine the feasibility of the needs of the other stakeholders. The project team will determine the budget of the project and the most efficient ways to implement ideas brought forward. The project advisor will have a heavy level of influence over this project. The project advisor will approve and assess any major ideas proposed and will determine if the final project meets the project proposal.

A graphical representation of the stakeholders is shown as an onion diagram below in Figure 4.1. The stakeholders closer to the center are a higher priority than the outer circles. The onion diagram shows the project in the center surrounded by our system. Our system consists of the high priority stakeholders (UIAA/ANSI, climbers, project team, and project advisor). The next layer consists of the medium priority stakeholder, climbing gyms. The wider environment consists of the lowest priority stakeholder, insurance companies.

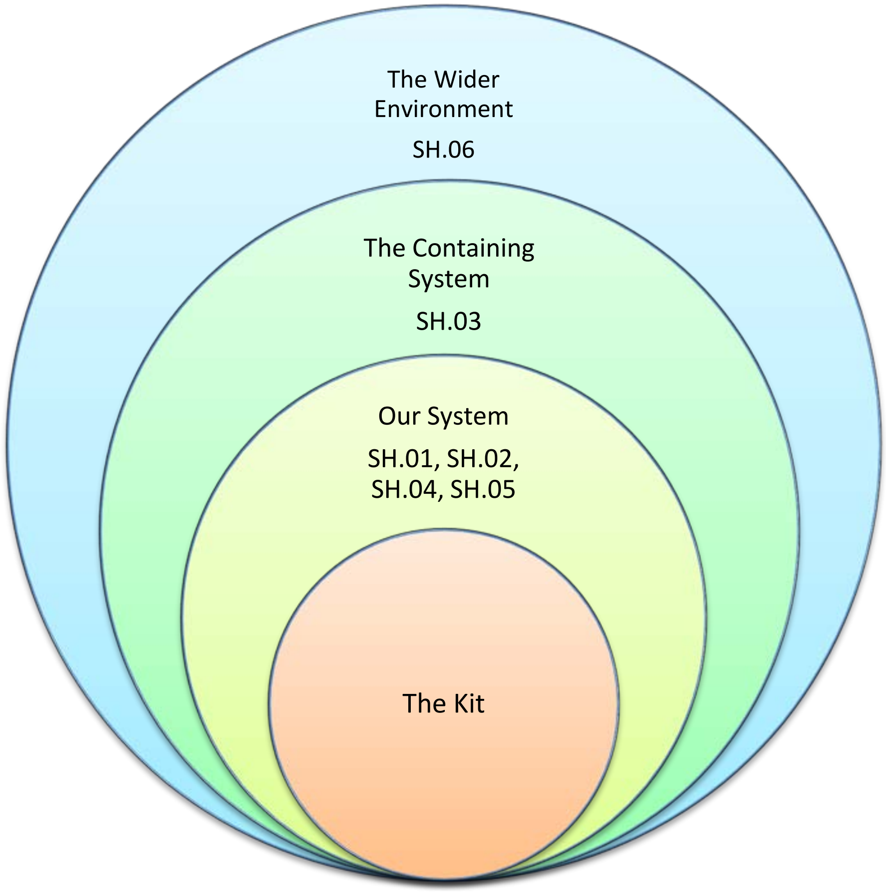

Figure 4.1: Onion Diagram of Stakeholders

4.2 Needs Analysis

The needs of each stakeholder impacted by this project were translated later into project requirements. Needs are preconceived notions of the functions of the system expressed by one or more stakeholders. Table 4.2 summarizes the needs analysis. Each need is traceable back to a stakeholder in order to determine its importance and necessity

Table 4.2: Need Analysis

ID	Title	Description	Compliance	Priority	Traceability
N.01	UIAA/ANSI	The auto belay device should conform to UIAA/ANSI standards	Test, inspect	1	SH.01, SH.02, SH.03
N.02	Climbers	The device should be easy for beginning climbers to learn	Test	1	SH.02, SH.03
N.03	Insurance companies	The device should comply with standards for insurance companies	Inspect	2	SH.06
N.04	Compatibility	The device should be backwards compatible with current belay systems	Models	2	SH.03
N.05	Wireless range	The device should have a range of at least 50 feet	Models, testing	1	SH.04, SH.05
N.06	Emergency release	The device should have a feature to release the rope in case of emergency	Models, testing	3	SH.03
N.07	User interface	The system should have a method of interaction where the user can climb with both hands and interact with the system	Test, Model	1	SH.04, SH.02

The first need was from the UIAA and ANSI expressing safety standards that auto belays should conform with. These standards are for legal and insurance purposes. This need is traceable to the stakeholders, SH.01, SH.02, SH.03. The verification procedures involve testing and inspecting the auto belays. Similarly, this project must follow the standards set by insurance companies. These standards are inspected for compliance reasons.

The second need was derived from the final end users, the climbers. The device should be easy for beginning climbers to learn. This is necessary since this project is a new invention to the market and climbers will have little experience working with it. This would be tested using surveys of patrons in climbing gyms.

Compatibility needs were expressed by climbing gyms. The auto belays should be backwards compatible with the current systems. This is important to ensure existing climbing gyms could implement this project without having a redesign. This was a lower priority need since it depends on the design chosen.

The wireless range of the upgraded system should have a range of no less than 50 feet. This was based on the maximum height of climbing walls at gyms. This is a high priority need expressed by climbing gyms. This need is later tested as a requirement in my final design.

An emergency release was expressed by climbing gyms. This need was not met in my final design based on the timing constraints of this project. This was the lowest priority need expressed by climbing gyms.

The user interface should allow for hands-free operation of the auto belay since the climber requires both hands to climb effectively. This need was expressed by climbers and climbing gyms. This is a high priority need since it is a design constraint.

4.3 CONOPS

This section covers the concept of operation for the system as well as its operational environment, constraints, and user interaction. The gap analysis presents the existing technology as well as the technology the project team is developing. The use cases are stories describing the use of the system from a user's perspective. A risk analysis was done to determine possible risks associated with the project.

4.3.1 Gap Analysis

This section explains how far the current "capabilities from the system are from meeting the identified needs, in order to prioritize development activities. This is based on both how far the current capabilities are from meeting the needs [because of insufficient functionality, capabilities, performance, or capacity] and whether the need is met in some places but not others."[32] The current capabilities were determined by assessing and examining current auto belay technologies, wireless technologies and voice recognition chips. It was determined that utilizing these technologies to add features to existing auto belay systems was feasible. The endpoint of this project was to add a rest mode to the current auto belay system. The Gap analysis is summarized in table 4.3.

[32] "California Division | Federal Highway Administration." California Division | Federal Highway Administration. April 17, 2013. Accessed March 13, 2016. http://www.fhwa.dot.gov/cadiv/segb/views/document/sections/section3/3_3_1.cfm.

Table 4.3: Gap Analysis

Future State	Current State of the Art	Current Limitations	Research Needed	Risk Assessment
Auto belay system that lowers climbers with options	Auto Belay Systems which are mostly mechanical and only descend climbers	Only lowers the climber to the bottom of the climbing structure	Research into winches and add on systems	Climbers could fall if system malfunctions
Voice recognition with 95 percent accuracy in chipsets	User interface with voice recognition in software and some chipsets	Sometimes word recognition is wrong	Better hardware for voice recognition	System hears the wrong command
Wireless technology provides a fast and reliable connection in indoor environments	Wireless technology exists and is mostly reliable in indoor environments	Not yet incorporated in climbing gyms	Incorporate wireless technology in climbing gyms	Bad connection, long network latency

4.3.2 Use Cases

Several use cases were developed that involved the upgraded auto belay systems. These use cases discuss the operation of the final system from a user's perspective as summarized in Table 4.4 and Appendix A. These were instrumental in determining whether the final design will fulfill the system requirements.

Table 4.4: Summary of Use Cases

UC ID	UC Name	Needs Ref.	Stakeholders
UC.01	Climber arrives at gym, starts climbing, and exits	N.01, N.07	SH.02, SH.03
UC.02	Climber initializes system	N.01, N.07	SH.02, SH.03
UC.03	Climber finishes climbing	N.01, N.07	SH.02, SH.03
UC.04	Voice recognition board needs to be reset	N.01, N.07	SH.02, SH.03

The first use case, UC_01 commences with the climber arriving at the gym and finishes with the climber setting the user input device into exit mode. The climber obtains the device from the front desk. Next, the climber initializes the device by holding down a button on the voice recognition board and dictating the command printed on the screen. Initially, the climber puts the device in rest mode, so that the climber can pause midway before descending to the ground. The climber then clips into the auto belay at the base of the climbing wall and starts climbing. The climber then reaches the top and chooses to descend to the ground. The climber then puts the device in exit mode. This use case presents a clear picture of a typical climb in the gym from start to finish. This use case uncovered the need for initializing and exiting procedures.

The second use case UC_02 deals with initializing the system before climbing. This use case involves the climber saying some commands and the voice recognition board recognizing the commands. This use case helped discover the commands and the respective action that should be taken for each command. Some climbers may use different vocabulary to express the same command resulting in many commands for the same action as shown in Table 4.5.

Table 4.5: User Input Voice Commands

Command	Action
Start	Initialization mode begins. After initialization finishes, command is inactive
Normal	Brake is disengaged, system ready to sense fall
Descend	Brake disengaged, same as normal
Stop	Brake on, enables the climber to rest
Rest	Brake on, same as stop
Go	Brake disengaged to lower climber or continue climb, same as normal
Down	Brake off to lower climber to the ground

The third use case UC_03, addresses the end of the climbing session. This use case explains the exiting procedures when either the user or climbing staff needs to erase the commands from the previous use of the device. After which, the device is rendered idle. This use case discovered the need to turn off the wireless interface in order to take the device offline. At that point, it is disconnected from the auto belay system and the braking device is released.

UC_04 deals with resetting the voice recognition board. This might happen if the board freezes or is damaged. This requires the operator to hold down both buttons to reset it. If the reset fails, then it is likely that the board will need to be replaced.

4.3.3 Risk Management

"Risk management is the process for identifying, analyzing, and communicating risk and accepting, avoiding, transferring, or controlling it to an acceptable level considering associated costs and benefits of any actions taken."[33] Good risk management ensures that a project will meet all of its requirements successfully. Risks were analyzed by ranking them according to their probability and consequence. Figure 4.2 shows the graphical approach to rate risks in this project. Analysis and testing of critical design components was done to minimize the risks associated with this project. The risk management results are tabulated in Table 4.6 and Figure 4.2. Some risks identified in this project can be minimized by transferring them to an insurance company. Other risks can be minimized through root cause elimination by identifying the cause and fixing the problem, or publicizing them by letting the user know that there is a specific risk associated with the product.

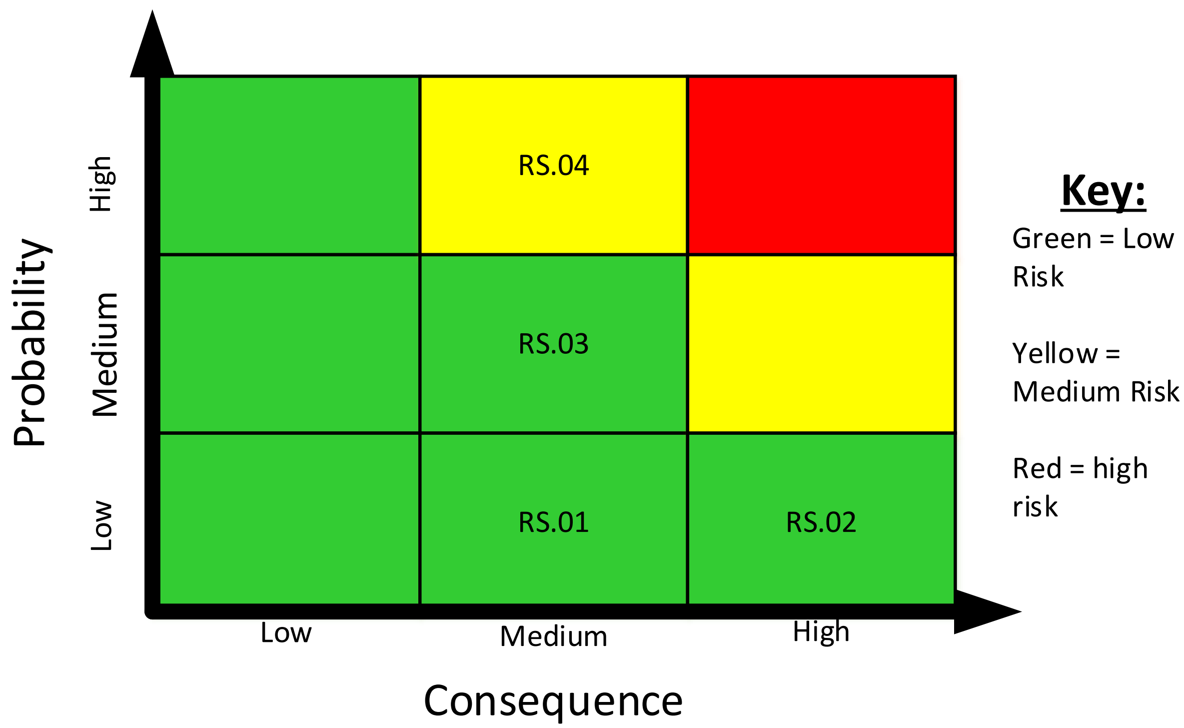

Figure 4.2: Risk Management Diagram

[33] "Risk Management Fundamentals: Homeland Security Risk Management Doctrine April 2011." April 2011. Accessed March 13, 2016. https://www.dhs.gov/xlibrary/assets/rma-risk-management-fundamentals.pdf.

Table 4.6: Risk Analysis

ID	Title	Consequence	Probability	Mitigation strategy	Priority
RS.01	User input device slips back into initialization mode	Medium	Low	Root cause elimination	1
RS.02	Climber falls and belay device not engaged	High	Low	Transference	1
RS.03	Wireless device becomes out of range	Medium	Medium	Root cause elimination	3
RS.04	User input device interprets wrong command	Medium	High	Publicize	2

The first risk identified was the user input device slipping back into initialization mode after a command was spoken. This could result from pressing the wrong buttons after initialization has been completed. This risk was mitigated through root cause elimination by implementing software that uses an exit mode to delete all commands and reprogram the device. The consequences are medium because the climber might have to initialize the device midway during a climb.

The second risk identified was the climber falling while the brake is disengaged, which could result in a hazardous situation for the climber and liability for the climbing gym. Insurance could be purchased to mitigate this risk. This risk could be due to user input device failure resulting in stopping the rope and not releasing the brake so the climber is stuck, or continuously letting rope go and not engaging the braking device so the climber drops precipitously to the ground. This risk could be resulting from a dead battery or a defective device.

Another risk is the wireless device going out of range from the transmitter. Although this risk cannot be controlled completely, the wireless protocol selected must be able to connect instantaneously if the signal is lost. This risk could be due to the building materials used in the climbing facility as well as metal objects that reflect the wireless signals. Root cause elimination was used to minimize this risk by selecting a protocol to connect quickly with slave devices.

A fourth risk is the voice recognition board interpreting the wrong command. This could result from improperly recording the command or excessive noise from other climbers in the climbing gym. The risk mitigation strategy was to publicize the risk in the climbing gym by advising climbers to record the command in a quiet place, and to vocalize it clearly, so it is audible to the device.

4.4 Requirements Analysis

For this project to be successful, six requirements were identified from the needs statements and that would define the function, purpose, and user interactions of the auto belay system. Each requirement discusses the operation of the system as a whole and addresses the needs of one or more major stakeholders. These requirements were crucial in developing the auto belay system and designing it to address the stakeholders' needs. These requirements are tabulated in Table 4.7.

Table 4.7: Requirements Analysis

ID	Title	Description	Validation	Verification	Priority
R.01	Modes of operation	The auto belay system shall have two modes of operation, descend and rest	SH.02, SH.03	Test, Model	1
R.02	Response time	The auto belay system shall activate the braking system in less than 0.1 seconds after a voice command is said	SH.02, SH.03	Model, test	2
R.03 A	Standards	The auto belay shall comply with ANSI/ASSE Z359.4-2013 "Safety Requirements for Assisted-Rescue and Self-Rescue Systems"[34]	SH.01, SH.06	Inspect	1
R.03 B	Standards	The auto belay shall comply with appropriate insurance standards	SH.01, SH.06	Discussions and meetings with insurers	1
R.04	Input commands	The user input device shall have a method for the user to input commands without the use of their hands	SH.02, SH.03, SH.04	Test, Model	2
R.05	Wireless link	The system shall have a wireless link with an indoor range 50 feet or greater	SH.03, SH.04	Test, model	2
R.06 A	Usability	The system shall be easy to operate for 80% of users who rate it a four or greater on a 1-5 Likert scale.	SH.02, SH.03	Survey climbers	2
R.06 B	Usability	The system shall interact with the user at a distance no greater than two feet.	SH.02, SH.03	Test, measure	2

The first requirement addresses the modes of operation: descend and rest. When in descend mode, the auto belay system will gently lower the climber to the ground. When in rest mode, the auto belay will stop and allow the climber to rest. This requirement involves the system receiving user input from the climber. Both climbers and climbing gyms expressed this need. The second requirement deals with the response time of the overall system. The response time from the moment when the climber loses contact with the climbing surface and the brake engages needs to be minimized for safety of the

[34] "ASSE." ANSI/ Z359.4-2013 Safety Requirements Assisted-Rescue Self-Rescue Systems, Subsystems Components. Accessed March 14, 2016. http://webstore.ansi.org/RecordDetail.aspx?sku=ANSI/ASSE Z359.4-2013.

climber. This requirement is paramount for climbers and climbing gyms. The response time of the system is crucial to the safety of the climber.

Based on the design, the auto belay remains the same as it was before the start of this project; however, a braking device is attached to the auto belay as a clip-on module. The entire system must fully comply with ANSI/ASSE Z359.4-2007 “Safety Requirements for Assisted-Rescue and Self-Rescue Systems, Subsystems and Components I” and insurance standards to ensure a system that is safe for climbers to use. Emergency releases in the control system are necessary to ensure the safety of the climber when ascending and descending, however, due to the time constraints as well as the limited budget of this project, this need was not converted into a requirement.

The interfaces among the braking device, user input device, and the control system are wireless and it is possible for one or more of these systems to be out of signal range. Therefore, it is important to minimize the time where any device would be out of range of the auto belay system. The sixth requirement deals with the user friendliness of the system. Climbers are unlikely to change their behavior because of a new device on the market. The auto belay system must be easy to learn and understand for both seasoned and new climbers. The Likert scale is a scale from one to five that can be used to assess the usability of this technology. A design constraint was that the device shall operate at a distance no greater than two feet from the climber shown as R.06B. This was to ensure that all audible and visual cues from the device will be received by the climber.

4.5 Design

After developing system requirements, the next step was designing the system functional architecture. The design of the system will be composed of five main subsystems. The functionality of each subsystem is explained briefly below and presented in the diagram in Figure 4.3. The control system and braking system are part of a related capstone project.

User Input Device - This device is carried by the user during a climbing session. The climber uses this device to input the station number they are using and to input options to engage or disengage the braking mechanism while they are climbing.

Braking System - The Braking System is used to control a servo actuator to prevent the climbing rope or webbing from slipping when a climber falls. The device is controlled by wireless inputs from the control system as well as from integrated sensors.

Control System - This system outputted climbing data such as feet climbed, calories, and a stopwatch in a graphical user interface (GUI) for the climber to see. This system also consists of a failsafe mechanism if the user input device or the braking system were to fail.

Wireless Interfacing – A wireless interface module is needed to interface the three subsystems listed above together. ZigBee was selected as the interface among the subsystems.

4.6 Summary

In summary, this section presented the system design as well as the rationale behind it. Stakeholders were identified as well as needs, CONOPS, requirements, and testing. The design consists of a user input device, wireless interface, braking device, and a control system. The braking device and control system are part of a related project. The next section describes the design of each component of the system.

5 Design

This section describes the component selection as well as the integration and design of the subsystems used in this project. Block diagrams and schematics of components are presented and described in this section. The major subsystems are listed below and shown in Figure 5.1 with a brief description of their function.

Wireless Module – This component transmits from the user input device and receives data from a braking system developed by a related capstone project using ZigBee. This component has a maximum wireless range of fifty feet.

Voice Recognition Module – Interprets voice commands from the user and converts them to a number corresponding to each command. The number is transmitted via Universal Asynchronous Receiver/Transmitter (UART) to the control processor board.

Control Processor Board – Interprets a number corresponding to a command and sends a signal to the wireless module depending on command said. The control processor board also sends a message to the LCD screen to display text corresponding to the command

LCD Screen – Displays a message to the user to communicate the mode of the system

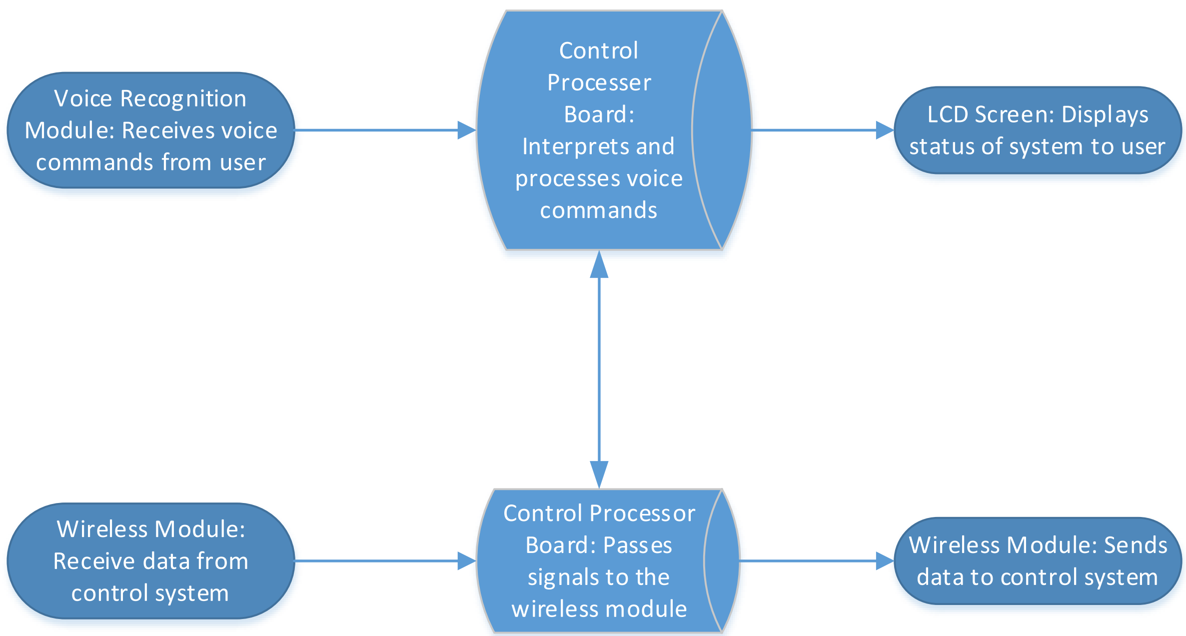

Figure 5.1: Functional Block Diagram of User Input Device

5.1 Component Selection

This section discusses the component selection for the user input device as described in Figure 5.1. Components were selected based on the system requirements stated in the system design section. The components used were an XBee 2mW PCB Antenna - Series 2 (ZigBee Mesh) for the wireless module, a Speak Up board by Mikroe for the voice recognition module, an Arduino Mega 2560 for the control processor board, and a 20 X 4 RGB character LCD by Winstar Display Corporation for the LCD.

5.1.1 Wireless Module

The wireless module selected for this project was the XBee 2mW PCB Antenna - Series 2 (ZigBee Mesh). The selection process included determining selection criteria based on the system requirements described in chapter four. This involved using a trade study to analyze various possible solutions and determining which one best fit the needs of this project. The criteria were ranked on a scale from one to ten, based on how well they would meet the needs of this project. Each criteria was weight-based according to its relevance for this project. The weight was multiplied by rank and summed to a total score as shown in Table 5.1.

The initial step for selecting the wireless module was determining the IEEE standard protocol that best fit the project requirements. Several alternatives were considered such as Wi-Fi, Bluetooth, and ZigBee. The selection criteria examined the characteristics of each network. More information about each of these standards is found in the background chapter. Next, the various networks were scored based on the different properties of each wireless network as shown in Table 5.1.

Data rate — Data rate describes the speed at which the device can send and receive data. This is important to minimize latency that can occur when designing networks. High data rates are most appropriate for high-speed applications such as a live video feed or using the internet.

Indoor range — The indoor range is the approximate range of the device indoors. Interference such as building materials and metal elevators can cause the range to fluctuate. This is critical to the project since it will operate in an indoor environment. Since most climbing gyms have more than one auto belay system, it is important to consider the number of devices the network can support.

Risk — Climbing is inherently a risky sport, and it is important to consider the risks to the end users (climbers) and purchasers (climbing gyms) the device would engender.

Configurability — This is a qualitative measure of the ease of setting up the network from a developer's point of view. Since Wi-Fi is the most difficult to set up, it received a score of a one. Wi-Fi is difficult to configure since multiple Wi-Fi networks often exist in the same bandwidth. Based upon the rankings, ZigBee was the network selected to use for this project. ZigBee requires little time to connect to the network, so it is the lowest risk. It also has the slowest data rate, which reduces the speed of the network.

Table 5.1: Selection of the Wireless Protocol for the User Input Module

Criteria	Data Rate	Indoor range	Number of devices	Risk	Device Power	Ease of Configurability	Totals
Weight	0.15	0.2	0.3	0.1	0.15	0.1	1
Bluetooth	10	10	4	6	10	8	7.6
ZigBee	9	10	10	8	10	9	9.55
Wi-Fi	10	10	10	4	7	1	8.05

The second characteristic evaluated was ZigBee vs ZigBee Pro, shown in Table 5.2. ZigBee Pro allows for more configuration settings such as the mapping of memory addresses as well as further security when compared with ZigBee. The criteria for this trade study were the following: security, speed, ease of configurability, reliability, and cost with ease of configurability having the most weight. Since this is only a prototype, ease of configurability was the most highly ranked and security was the lowest ranked. As explained previously, ease of configurability is the ease of setting up the network from a developer's point of view. This is significant when considering the time constraints of this project. ZigBee was the protocol selected.

Table 5.2: Selection of the Wireless Standard for the User Input Module

Criteria	Security	Speed	Ease of Configurability	Reliability	Cost	Totals
Weight	0.10	0.15	0.3	0.25	0.2	1
ZigBee	8	9	9	8	10	8.85
ZigBee Pro	10	10	7	9	8	8.45

Next selection criteria was deciding on which ZigBee module to use, shown in Table 5.3. The two most widely used modules are XBee and XBee Pro. XBee Pro offers more range, but consumes more power, and is more expensive. XBee Pro uses about 63mW of power and has an outdoor range of about one mile. For this project, the extra range is unnecessary for this application. Based on the results of this trade study, XBee was selected.

Table 5.3: Selection of the Wireless Module for the User Input Module

Criteria	Range	Cost	Module Power	Configurability	Totals
Weight	0.25	0.4	0.15	0.2	1
Xbee	10	8	9	9	7.65
Xbee Pro	10	7	7	8	6.85

ZigBee modules typically can have three different types of antennae for use on XBee boards: a whip antenna, chip antenna, and a PCB antenna.[35] Whip antennas use a wire extending from the XBee module with less attenuation when compared with the other two antennas. Two problems associated with whip antennas are that they can snap off if the radio is dropped and the larger form factor it uses on the XBee board. A second type of antenna is the chip antenna. Chip antennas are small chips that attach to the XBee module. One problem associated with chip antennas is the attenuation of the signal. However, these antennas are the least expensive. A third antenna used on XBee modules is the PCB antenna. This type is similar to the chip antenna, except with less attenuation of the signal and is slightly more expensive. The selection for the antenna was the PCB antenna as shown in Table 5.4.

Table 5.4: Selection of the Antenna on the Wireless Module for the User input Module

Criteria	Size	Durability	Internal or External	Performance	Cost	Totals
Weight	0.3	0.2	0.1	0.3	0.1	1
Whip	7	6	1	10	6	7
Chip	9	8	10	7	10	8.4
PCB	10	10	10	8	8	9.2

5.1.2 Voice Recognition Board

The primary function of the voice recognition board is to process spoken commands from the user. The voice recognition board transmits signals corresponding to commands using a wired interface such as UART to a control processor board. The voice recognition board selected for this project was the Speak Up board by Mikroe based on the selection process shown in Table 5.5 and Figure 5.2. For selection

[35] Faludi, Robert. *Building Wireless Sensor Networks*. North, Sebastopol, CA: O'Reilly, 2011.

of the voice recognition board, four alternative solutions were evaluated including software and integrated circuit solutions.

Dragon speech recognition software provides text to speech applications for computers.[36] This solution although is the most expensive, yet it would be the easiest to implement. The cost for Dragon Speech Recognition software was approximately $100, far beyond the budget for this project. Dragon software needs an OS such as windows to process commands and increase the complexity of the project.

A second alternative was the VS 1053 chip is a chip often used in speech recognition applications. The VS 1053 decodes audio signals into a command signal to send to another board. The VS 1053 is included in the MP3 Click board by Mikroe. This board interfaces using SPI and supports multiple audio formats.

Sensory Technology markets chips involved in speech recognition with one of their leading products is the NLP5x natural language processor.[37] This chip is often used in robotic controls which include speech synthesis . This chip supports USB, SPI, UART, and I2C interfaces, which meet the interface requirements of this project. This chip serves more digital signal processing applications which are often more complex than a typical microcontroller.

The last option considered by this project was the Speak Up board by Milkroe. The Speak Up board uses software as well as push buttons to listen, record, and delete voice commands. This enables the operator's voice to map voice commands directly to the Speak Up board. A key feature of the Speak Up board is to configure the voice recognition board without a computer. The Speak Up board interfaces using one UART port to as well as SPI. This device has limitations as far as customization; however, the ease of configurability makes this board ideal for this capstone project.

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[36] "Dragon NaturallySpeaking Home Edition." Dragon NaturallySpeaking Home Edition. Accessed March 19, 2016. http://www.nuance.com/for-individuals/by-product/dragon-for-pc/home-version/index.htm#!other.

[37] "NLP-5x Natural Language Processor | Sensory." Sensory. Accessed March 14, 2016. http://www.sensory.com/products/integrated-circuits/nlp-5x-natural-language-processor/.

Table 5.5: Trade Study for Voice Recognition Board

Criteria	Ease of integration	Cost	Need for Supplemental Materials	Size	Accuracy	Resources	Totals
Weight	4	4	2	1	4	3	
Software	5	1	4	2	2	4	54
VS 1053 Chip	4	2	3	1	2	3	48
Sensory Technology	2	5	1	2	1	2	42
Speak Up Board	2	2	1	4	2	2	36

Figure 5.2: Speak Up Board[38]

5.1.3 Control Processor Board Selection

The control processor board functions as the hub to interface the XBee module to the voice recognition board and LCD Screen. The device selected for the control processor board was the Arduino

[38] "MikroElektronika MIKROE-1534 SpeakUp Click Board." MikroElektronika MIKROE-1534 SpeakUp Click Board. Accessed March 14, 2016. http://www.rapidonline.com/electronic-components/mikroelektronika-mikroe-1534-speakup-click-board-73-5244.

Mega 2560. The XBee module uses an XBee shield to interface with Arduino boards through a UART port. The Speak Up board also uses a UART port to interface with other peripherals, therefore the control processor board must have two UART ports and be able to interface with an LCD screen. The LCD screen uses a parallel interface through IO ports. The Arduino Mega 2560, the Arduino Zero, and the Arduino Due all fit the interface requirements for this capstone.

The Arduino Mega 2560 (shown in Figure 5.3) operates at 5V with 54 digital IO pins, 16 analog inputs, 4 UARTS. This board fits the minimum of fourteen IO ports for the LCD as well as having the two UART ports required to interface with the voice recognition board and the wireless module. Since the Arduino Mega 2560 operates at 5V, a level shifter is not needed to convert the 5V from the Arduino to the 3.3 V required for the voice recognition board. Thus, the Arduino Mega 2560 is the preferred selection for the control processor board.

The Arduino Zero operates at 3.3 V with 20 IO pins, 2 UARTs, fitting the specifications for this project; however, the LCD display needs a level shifter since it operates at 5V. The Arduino Due presents a similar problem since it also operates at 3.3 V. From a designer's perspective, level shifting 14 IO ports for the LCD requires more materials as opposed to no level shifting (fewer materials and lower cost) required with the Arduino Mega 2560. The Arduino Mega 2560 was the final selection for this project since it meets the interface requirements for this capstone project. Since the focus of this capstone design experience is to design a working prototype, the extra power consumption of the Mega was not considered for this project.

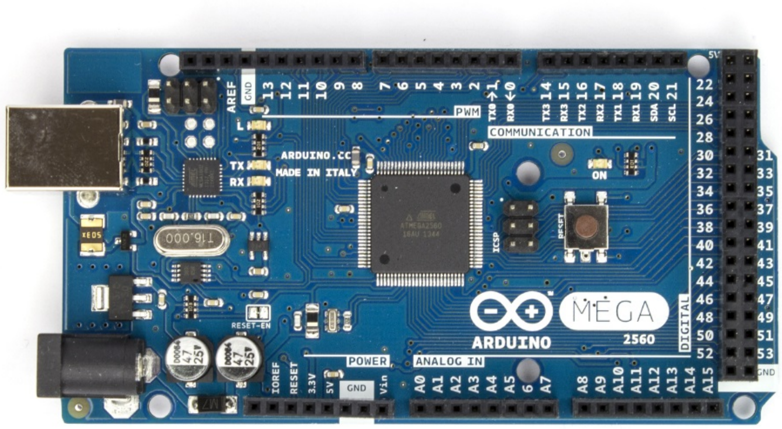

Figure 5.3: Arduino Mega 2560[39]

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[39] "Arduino Mega 2560 - Elite Innovations." Elite Innovations. Accessed March 14, 2016. http://eliteinnovationsllc.com/product/arduino-mega-2560/.

5.1.4 LCD Screen

The LCD screen was the last component chosen. The LCD was selected based upon the control processor board selection. Different boards support different types of LCD screens. It was necessary for the LCD screen to display a menu with instructions for the climber to select among the different modes of operation. One of the requirements for the LCD screen was that it must be readable from a distance of 2 feet. A 20 X 4 RGB character LCD was chosen. The multiple colors allow the user to easily differentiate between the modes of operation as well as provide greater visibility to the display. This LCD interfaces through eight digital I/O ports and three PWM ports on the Arduino Mega 2560 board. The display is shown in Figure 5.4.

Figure 5.4: RGB Backlight Negative LCD 20x4[40]

5.2 Interfaces among Components

This section includes a context diagram as well as a wiring diagram to show the relationships among the different system components as well as their environment. The context diagram, shown in Figure 5.5 shows the user input device interacting with climbers, gym staff, and a braking device from a related capstone design project, as well as functional elements such as power for the device. The climber operates the device by programming the user input device to match the climber's voice. Either the climber or the gym staff will reset the device to clear commands from the previous user.

[40] "RGB Backlight Negative LCD 20x4 Extras." Adafruit Industries. Accessed March 12, 2016. https://www.adafruit.com/products/498.

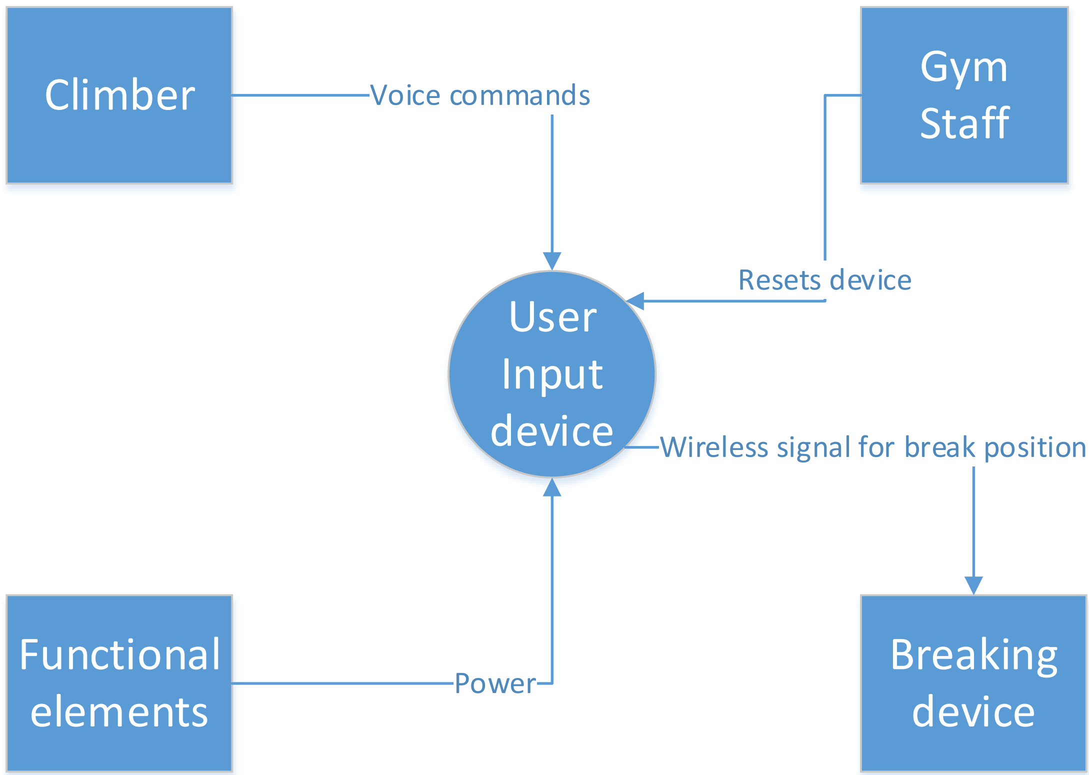

Figure 5.5: Context Diagram

A wiring diagram is shown in Figure 5.6. This depicts a detailed drawing of the wiring for the Arduino Mega connected to the LCD display and the Speak Up board. The XBee module was mounted on the Arduino using an XBee shield. The XBee used pins 2 and 3 for UART by utilizing a software serial. The software serial held the pins high and when they were pulled low for the UART data, they were read in the Arduino. For the LCD, Pins 18, 17, 16 were connected to Pins 13, 5, 6, and 7 on the Arduino. These were used to control the colors of the LCD display. Pins 4, 6, 11, 12, 13, 15 are the data lines used for the LCD screen. A 10 K Ω potentiometer was used to regulate the brightness of the screen. The Arduino was connected to the Speak Up board via UART. The TX pin on the Speak Up board was connected to the Rx pin on the Arduino (pin 17). The TX pin on the Arduino (pin 18) was connected to the Rx pin on the Speak Up board.

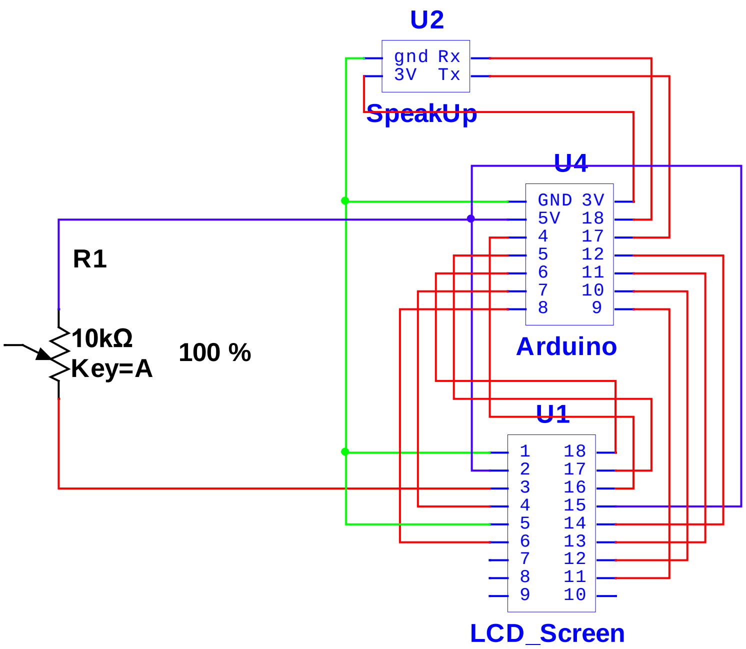

Figure 5.6: Wiring Diagram for Arduino and Speak Up Board

5.3 Design Criteria to be met

This design meets the requirements for developing a user input device to facilitate a brake for the climber during a climb. The user input device takes an input from the climber using the voice recognition board, prints a corresponding message on the LCD display, and sends the message via ZigBee to a control station. This design satisfies the requirements by allowing the climber to use both hands while climbing while still changing the mode of the device.

5.4 Summary

In summary, the components for the user input device were selected based upon trade studies and flow down requirements. The Arduino Mega was selected as the control processor board for this project. The XBee module selected for this project was the XBee 2mW PCB Antenna - Series 2 (ZigBee Mesh). The Speak Up board was selected as the voice recognition board for this project. The LCD screen selected for this project was a 20 X 4 RGB LCD screen. Together, these components integrate to form the user input module. In subsequent sections, the results and testing of the user input module will be explored.

6 Results and Testing

Testing involved verifying each component of the system to ensure it integrates properly with other system components. There were a series of four tests conducted during the course of this capstone project. The first test conducted was component testing, which involves testing each component of the system with the Arduino board. The second test conducted verified the entire user input system and helped fix any bugs associated with combining the components tested in the first test. The third test involved testing whether the device operates with the braking system designed by a related capstone project.

6.1 Component Testing

The focus of these tests was to ensure each component interfaces properly with the Arduino. Each component was tested individually to ensure the interface requirements for both the Arduino and the component were met. The first component tested was the LCD screen. The LCD screen was wired to the Arduino and configured to display a menu with text that loops to change the screen. The menu was configured to display text with a color signifying each voice command.

The second component tested was the voice recognition module. The goal of this test was to ensure that the UART connecting the Speak Up board to the Arduino functioned properly and transferred the data correctly. This test involved the operator configuring the Speak Up board using the software provided with the Speak Up board. An audible command was vocalized to the Speak up board. The LCD was configured to change depending on the type of command vocalized to analyze whether this portion of the test worked. This test helped determine the need for an initializing procedure to match the voice of the climber to the Speak Up board.

The XBee module was tested by sending a signal from the serial monitor on the Arduino application and checking whether it had been received through an XBee module connected to the computer in XCTU, an application used to configure the XBee modules. The computer confirmed the signal received. The next step was configuring the XBee to send commands rather than echoing commands from a computer. This task was accomplished by adding "else" statements to the program on the Arduino.

6.2 Full System Test

The full system test determined whether all the parts of the user input device functioned together and the device worked as designed. This test was conducted by analyzing the use cases described in Appendix A and determining if the device worked as designed. This test ensured that the entire system functioned properly and identified any design adjustments required. This test analyzed the entire system from initializing the device to setting up commands for climbing. Some problems discovered in this test occurred during the initializing mode, when the device would slip into the operating mode. An outline of the software development procedure is shown in Figure 6.1. This was used as a test case to evaluate the modes of the user input device.

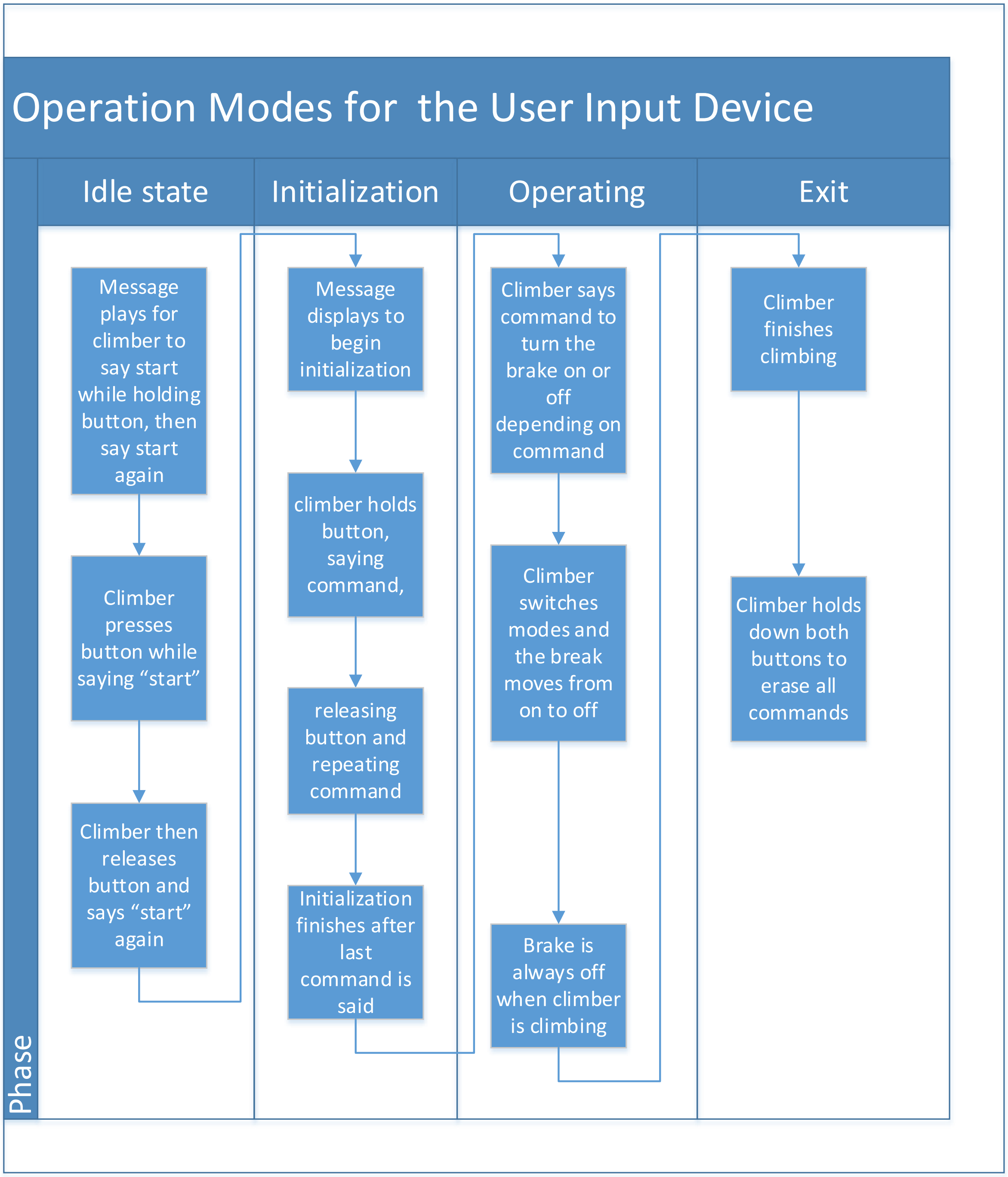

Figure 6.1: Operating Modes for User Input Device

6.3 Communication Test with Braking System

A final test with the braking system was done to confirm communication between the user input device and the braking device. This test was done in two phases: the first was setting up a wireless link between the computer and the user input device; the second was setting up a wireless link between the braking device and the user input device. The goal of the first phase was to ensure that the user input device was in fact transmitting and receiving signals. The goal of the second phase was communication between the two devices. This communication test was critical to ensure the wireless link worked between the user input device and the braking device and that communication was established.

The initial phase included testing the user input in a long hallway in the first floor of Atwater Kent. The hallway was greater than 50 feet long to ensure a clear line of sight for communication. The purpose of this phase was to demonstrate a range greater than 50 feet for the ZigBee network. The user input device was placed at one end of the hallway and a computer was placed on the other end. The computer ran a range test function using XCTU software to send packets of data to the user input device. The XCTU software measured the number of packets sent to the user input device and the number of packets received from the device to determine the quality of the signal.

This test confirmed the need to transmit multiple messages to ensure that the signal would be received even if one or more of the packets dropped. During the test, Out of 50 packets data sent, 1 was dropped. The design was modified to transmit eight messages from the user input device so that the braking device would receive at least one correct command if the signal was dropped and the device was still in range. This test ensured that when a voice command was spoken after initialization, it would be received by the braking system. This significant test served as one of the criteria for a successful project.

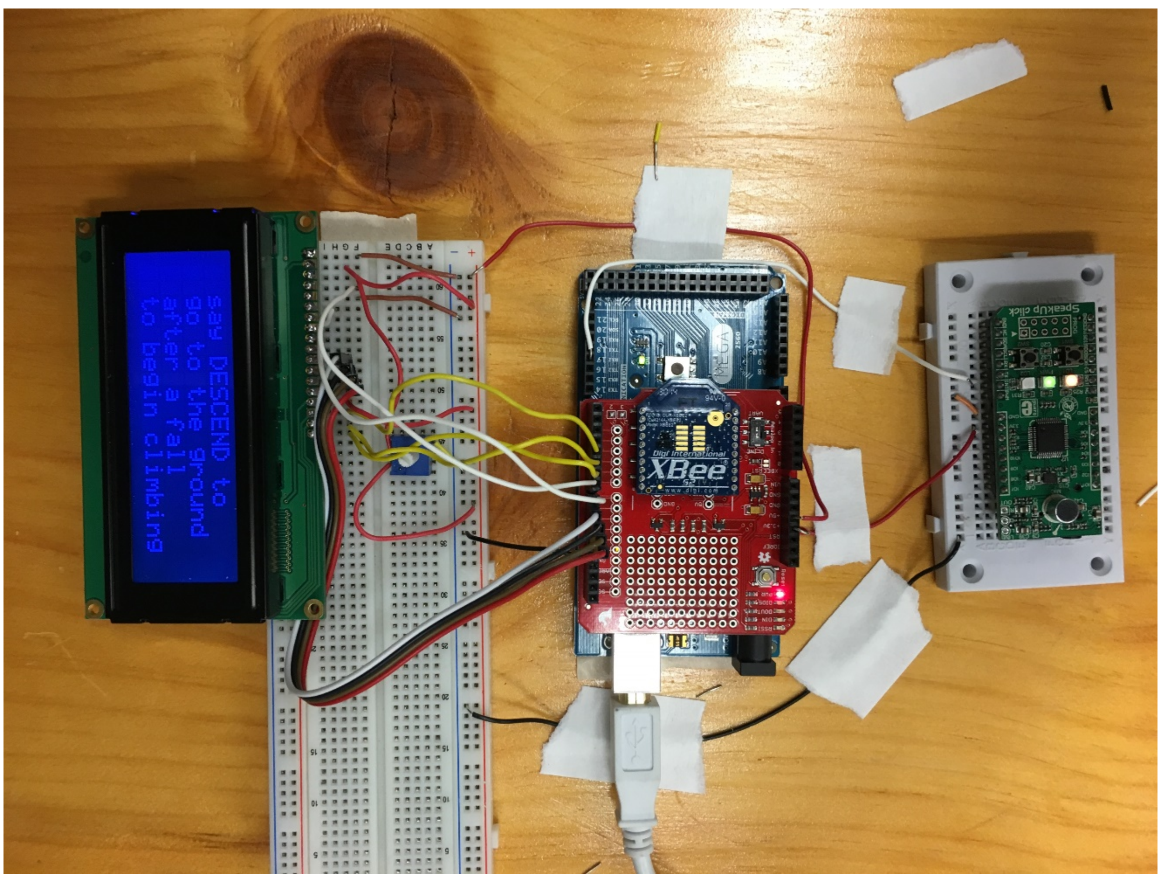

Figure 6.2: View of User Input Device

The second phase of this test tested the wireless link with the braking system. This was done in the basement of Atwater Kent on a table about three feet in length. The braking device was positioned at one end of the table and the user input device at the other. The user input device transmitted a signal and the braking device confirmed that it was received. Although the wireless link could go farther than three feet, the purpose of this phase was to demonstrate communication between the two devices.

6.4 Results Summary

These tests helped refine the project and determine successful criteria for the project. The tests helped uncover problems associated with the design of this project as well as resolutions for the problems. A component test, a full system test, and a communication test with a related capstone design project were conducted as part of the testing phase of this project.

7 Discussion and Future Work

This section reviews project goals and possible future development plans for increasing the versatility of auto belay systems used in indoor climbing. This section discusses the requirements met by this project as well as lessons learned and conclusions.

7.1 Summary of Project

In summary, this project created a user input device to interact with a braking system from a related capstone project to increase the versatility of auto belays for indoor climbing. This capstone project collaborated with another related capstone project that developed a braking device as well as a control panel. In order to develop the user input device, the following were produced:

- A functioning prototype of a user input device which allows the climber to rest midway during a climb
- A wireless network that allows the user input device to transmit messages to the braking system designed by a related capstone project
- A display to enable the climber to see whether the brake is on or off

7.1.1 Requirements Met

This project met the requirements outlined in the system design section. There were six requirements met in the design, which served as criteria for a successful project.

1. Modes of operation –The auto belay system shall have two modes of operation, descend and rest.

My design has two basic modes of operation: descend and rest. Rest corresponds to placing the brake on whereas descend places the brake off. The braking device receives messages based on the different commands spoken by the user. The messages are sent using XBee modules on the user input device and received on the braking device.

2. Response time - The auto belay system will activate the braking system in less than 0.1 seconds after a voice command is spoken.

This requirement tested the approximate response time between the spoken command and the application of the brake. This requirement could be met with a future implementation of the system. A command was spoken and the time was calculated by measuring the distance the rope fell for a weight of 20 kg and by solving Equation 3.1 below for time. The time measured was less than 0.1 seconds for the brake to engage. As shown in Equation 3.1, *x* refers to the distance traveled, v_0 refers to the original velocity, the acceleration is represented by *a* and the time by *t*.

$$\Delta x = v_0 t + \frac{1}{2} a t^2$$

Equation 3.1: Kinematic equation for finding time

3. Standards, insurance and ANSI - The auto belay shall comply with ANSI/ASSE Z359.4-2013 “Safety Requirements for Assisted-Rescue and Self-Rescue Systems”[41] The auto belay shall comply with appropriate insurance standards

There are no standards for climbing devices adopted within the climbing industry, however, most climbing gyms are required to have insurance on their auto belay systems. Most auto belays follow ANSI standards because of this. A literature review was conducted to examine the guidelines that a prototype would follow. Future implementation of the device would require additional research and testing to comply with ANSI standards as well as for certification and insurance purposes.

Input commands - The user input device shall have a method for the user to input commands without the use of their hands.

This requirement was met by using a voice recognition board with a built in microphone to listen to voice commands. This enables the climber to use both hands for climbing and set the mode of the user input device.

4. Wireless link - The system shall have a wireless link with an indoor range 50 feet or greater

This requirement was met by selecting an XBee module with a range greater than fifty feet. This was the approximate maximum distance between the ground and the peak of the climbing structure. This was tested in the first floor of Atwater Kent in a hallway greater than fifty feet long. This allowed for a straight path similar to an indoor climbing gym.

5. Usability - The system shall be easy to operate for 80% of users who rate it a four or greater on a 1-5 Likert scale.

This requirement was addressed through discussions with climbers and the project advisor. Since design was the primary focus of this project and due to the timing constraints, this requirement was secondary to the others. A formal survey was not accomplished however; this could be done in the future through another project. It is unknown if this requirement was met during the duration of this project

7.2 Next Steps

Should the climbing industry move forward with integrating my project with the current auto belay systems, a more robust system would be needed. I have provided the following recommendations for an effective solution:

- Control processor board with lower power consumption – Since I did not factor the power of the device in determining which control processor board to use, this would have to be considered to

[41] "ASSE." ANSI/ Z359.4-2013 Safety Requirements Assisted-Rescue Self-Rescue Systems, Subsystems Components. Accessed March 14, 2016. http://webstore.ansi.org/RecordDetail.aspx?sku=ANSI/ASSE Z359.4-2013.

determine optimal battery selection and usage times. This would ensure a small light-weight portable device for climbers.

- Speaker to play back recording – The addition of a speaker would enable the climber to play back commands recorded during the initiation phase. Although climbing gyms can be very loud at times, a speaker would ensure a better match between the climber's voice and the message recorded on the user input device.
- Discussing standards for auto belay systems insurance agencies – This would allow a discussion to determine whether all guidelines were followed during the development of the device. A third party would be needed to test and certify the device for use.
- Survey climbers interested in testing the device – A survey could be performed to determine whether this device would in fact help climbers and clarify whether the requirement was met regarding ease of use.
- Test on climbing gyms – Although every climbing gym is inherently different, this would test all the features of the user input device as well as the braking system in a practical setting, necessary for the device to function.

7.3 Conclusions

In conclusion, this project intends to upgrade current auto belay systems with more versatility to replicate more closely a manual belay system. Due to timing constraints for this capstone project, I created a functioning prototype rather than a production model of a user input device for an indoor climbing application.

A few major challenges were undertaken such as determining the proper system based on a wide variety of components on the market as well as learning how to use software applications such as Multisim, XCTU, and Arduino v1.1.6. Through practice and online tutorials, these software tools were learned. Another major challenge was interfacing over the UART connection between the Arduino and the Speak Up boards. This proved to be tricky and difficult to debug since it used the Software serial library on the Arduino. This involved researching documentation for the Arduino Mega, Speak up boards and UART connections. A third challenge presented by this project was determining which wireless protocol to follow. This proved to be challenging for someone with little experience with communication systems and served as an excellent lesson to seek out knowledgeable professors experienced in wireless communication systems.

Some lessons learned from working on this project included an overall perspective on the design process from starting with a preliminary design to finishing by completing a prototype. This project taught me that it more feasible for capstone design projects to be done in groups of two or more to allow for more diverse skillsets. This project provided an invaluable experience in report writing as well as guiding me through the engineering design process.

Appendix A

In this section, a detailed overview of each use case is presented.

Use Case identifier: SS_01

Use case name: Climber arrives at gym, starts climbing, finishes climb, and exits gym

Participating actors: Climber, system

Initializing Conditions: Climber arrives at the gym

UC description:

1. Climber arrives at climbing gym
2. Climber obtains a user input device from front desk
3. User input device instructs climber to initialize system
    a. Instructions display on the LCD prompting the climber to say a word
    b. The climber dictates the word so the user input device recognizes the voice pattern for that word
    c. climber repeats A⇨B until all words have been entered
4. The climber initializes the user input device to rest mode using voice commands as described in SS_02
5. Climber clips into auto belay on the ground
6. Climber starts ascending the climbing wall
7. Climber stops to rest
8. The auto belay stops the rope when it senses the climber stopped climbing
9. The climber rests while still on the climbing wall
10. The climber then chooses to keep climbing
11. The auto belay retracts the rope as the climber ascends
12. The climber reaches the maximum height of the climbing wall
13. The climber switches the user input device into descend mode
14. The auto belay gently lowers the climber to the ground
15. The climber arrives on the ground
16. The climber unclips from the auto belay
17. The climber puts the user input device in exit mode

Alternatives:

Exit Conditions:

- Climber puts the user input device in exit mode

Needs/requirements discovered:

1. The user input device shall have an initializing procedure
2. The user input device shall have exit procedures

3. The auto belay shall have sensors at the ground to make sure the climber is clipped in properly, the auto belay is functioning properly

Models/studies needed:

Use Case identifier: SS_02

Use case name: Initialization Procedure

Participating actors: Climber, system

Initializing Conditions: Climber obtains user input device from staff at the climbing gym. Climber goes through the initialization procedure from start to finish.

UC description:

1. Climber picks up user input device to initialize system
2. User input device prints a message on the LCD “press and hold button 1 and say START to select mode”
3. The climber holds down button 1 and says start
4. A message displays on the LCD “Initializing system, please hold button 1” The message disappears and rotates with “and say the following commands” since the character screen can only display 60 characters at once
5. A message on the LCD displays “ Say NORMAL”
6. The climber says “normal”
7. The red LED flashes on the Speak Up board
8. A message displays on the LCD “command received, next command is “DESCEND, say DESCEND””
9. The climber says “descend”
10. The red LED flashes on the Speak Up board
11. A message displays on the LCD “command received, next command is “STOP, say STOP””
12. The climber says “stop”
13. The red LED flashes on the Speak Up board
14. A message displays on the LCD “command received, next command is “REST, say REST””
15. The climber says “rest”
16. The red LED flashes on the Speak Up board
17. A message displays on the LCD “command received, next command is “GO”, say GO”
18. The climber says “go”
19. The red LED flashes on the Speak Up board
20. A message displays on the LCD “command received, next command is “Down”, say DOWN”
21. The climber says “down”
22. A message displays on the LCD “done initializing system, please select mode, say REST to engage a brake on the rope, say DESCEND to release the brake”
23. A message displays confirming the initializing procedure has completed

Alternatives:

Exit Conditions:

- Initialization procedure is done

Needs/requirements discovered:

1. The LCD screen shall display a maximum of 60 characters at one time, so the screen must switch to show full commands

Models/studies needed:

1. Research specific commands climbers say during belaying

Use Case identifier: SS_03

Use case name: Climber finishes climbing

Participating actors: Climber exits gym

Initializing Conditions: Climber finishes climbing

UC description:

1. Climber is done climbing
2. User input device prompts climber to press and hold button two as labeled on the Speak UP board for more than 2 seconds
3. Climber holds on button two to reset user input device
4. The wireless interface is turned off
5. User input device prints a message on the LCD " Pleas program device, press and hold button 1 and say START to select mode"

Alternatives:

Exit Conditions:

- User input device is de-initialized

Needs/requirements discovered:

1. Thank you message at end
2. De-initialize state
3. The user input device shall turn off its wireless interface to release braking system

Models/studies needed:

Use Case identifier: SS_04

Use case name: Speak up board needs to be reset

Participating actors: system

Initializing Conditions: Speak Up board needs to be reset

UC description:

1. Speak up board is malfunctioning and needs to be reset
2. Operator holds down both button one and button two as labeled on the Speak Up board to reset the speak up board
3. The board is reset

Alternatives:

Exit Conditions:

- Board is reset and works properly

Needs/requirements discovered:

Models/studies needed:

1. Testing the reset procedure on a Speak Up board

Appendix B

This section presents the code used by the Arduino Mega 2560 running in Windows 10 on Arduino 1.6.6 software. The final design included a library `<utility/Adafruit_MCP23017.h>` linked from the AdaFruit website[42]. The other three libraries utilized in this design (`<LiquidCrystal.h>`, `<Wire.h>`, and `<SoftwareSerial.h>` were included with the Arduino 1.6.6 software downloaded from the Arduino website.[43] The code was written to support the Arduino Mega 2560 board.

```
// include the library code:

#include <LiquidCrystal.h>

#include <Wire.h>

#include <SoftwareSerial.h>

#include <Adafruit_RGBLCDShield.h>

#include <utility/Adafruit_MCP23017.h>


//PWM Ports for light`   anodes

#define REDLITE 4

#define GREENLITE 5

#define BLUELITE 6


#define RED 0x1

#define YELLOW 0x3

#define GREEN 0x2

#define TEAL 0x6

#define BLUE 0x4

#define VIOLET 0x5

#define WHITE 0x7

enum State {WELCOME, CAPTURE_CLIMB,
CAPTURE_REST,  CAPTURE_NORMAL,
CAPTURE_GO, CAPTURE_DOWN, CAPTURE_STOP,
BREAK_ON, BREAK_OFF, THANKYOU};

enum Command {START, DESCEND, NORMAL,
GO, DOWN, REST, STOP};

// initialize the library with the
numbers of the interface pins

LiquidCrystal lcd(7, 8, 9, 10, 11, 12);

// XBee's DOUT (TX) is connected to pin
2 (Arduino's Software RX)

// XBee's DIN (RX) is connected to pin
3 (Arduino's Software TX)

SoftwareSerial XBee(2, 3); // RX, TX


// you can change the overall
brightness by range 0 -> 255

int brightness = 255;

int incomingbyte = 0;

int i;

State systemState = WELCOME;

bool initialized = false;

void setup() {
```

[42] "Adafruit/Adafruit-MCP23017-Arduino-Library." GitHub. Accessed March 23, 2016. https://github.com/adafruit/Adafruit-MCP23017-Arduino-Library/blob/master/Adafruit_MCP23017.h.
[43] "Arduino - ArduinoBoardMega2560." Arduino - ArduinoBoardMega2560. Accessed March 23, 2016. https://www.arduino.cc/en/Main/ArduinoBoardMega2560.

```
  Serial2.begin(115200);

  // set up the LCD's number of rows
and columns:

  lcd.begin(20, 4);



  pinMode(REDLITE, OUTPUT);

  pinMode(GREENLITE, OUTPUT);

  pinMode(BLUELITE, OUTPUT);


  brightness = 255;

  // Set up both ports at 9600 baud.
This value is most important

  // for the XBee. Make sure the baud
rate matches the config

  // setting of your XBee.

  XBee.begin(9600);

  Serial.begin(9600);

  showWelcomeScreen();


}



void loop() {




  if (Serial2.available() > 0)

  {

    Serial.println("SerialAvailable");

    Command command = serialEvent1();

    runState(command);




  }



  //  Serial.print("Wrong place");

  //XBee stuff

  while (Serial.available())

  { // If data comes in from serial
monitor, send it out to XBee

    char mySend = Serial.read();

    XBee.write(mySend);

    Serial.print("sent: ");

    Serial.println(mySend);

  }

  while (XBee.available() > 0)

  { // If data comes in from XBee, send
it out to serial monitor

    Serial.print(XBee.read());

    Serial.println("Recieved message");

  }

}



void setBacklight(uint8_t r, uint8_t g,
uint8_t b) {

  // normalize the red LED - its
brighter than the rest!


  r = map(r, 0, 255, 0, brightness);
```

```
  g = map(g, 0, 255, 0, brightness);

  b = map(b, 0, 255, 0, brightness);


  // common anode so invert!

  r = map(r, 0, 255, 255, 0);

  g = map(g, 0, 255, 255, 0);

  b = map(b, 0, 255, 255, 0);

  //  Serial.print("R = ");
Serial.print(r, DEC);

  //  Serial.print(" G = ");
Serial.print(g, DEC);

  //  Serial.print(" B = ");
Serial.println(b, DEC);

  analogWrite(REDLITE, r);

  analogWrite(GREENLITE, g);

  analogWrite(BLUELITE, b);

}


Command serialEvent1() {

  Serial.println("Reading");

  Command command = (Command)
Serial2.read();

  Serial.print("command: ");

  Serial.println(command);

  //  XBee.write(command);

  return command;

}


void runState(Command command)

{

  switch (command)

  {

    case START: {

        if (systemState == WELCOME)

        {

          showClimbScreen();

          systemState = CAPTURE_CLIMB;

        }


        break;

      }

    case DESCEND: {

        if (systemState ==
CAPTURE_CLIMB)

        {

          Serial.println("go");

          showNormalScreen();

          systemState = CAPTURE_NORMAL;

        }

        else if (initialized == true)

        {

          //put code for Send signal

          showBreakOffScreen();

          systemState = BREAK_OFF;

        }

        break;

      }

    case NORMAL: {

        if (systemState ==
CAPTURE_NORMAL)

        {
```

```
          Serial.println("normal");
          showGoScreen();
          systemState = CAPTURE_GO;
        }
        else if (initialized == true)
        {
          showBreakOffScreen();
          systemState = BREAK_OFF;
        }
        break;
      }

    case GO: {
        if (systemState == CAPTURE_GO)
        {
          showDownScreen();
          systemState = CAPTURE_DOWN;
        }
        else if (initialized == true)
        {
          showBreakOffScreen();
          systemState = BREAK_OFF;
        }
        break;
      }

    case DOWN: {
        if (systemState ==
CAPTURE_DOWN)
        {
          showRestScreen();
          systemState = CAPTURE_REST;
        }
        else if (initialized == true)
        {
          showBreakOffScreen();
          systemState = BREAK_OFF;
        }
        break;
      }
    case REST: {
        if (systemState ==
CAPTURE_REST)
        {
          showStopScreen();
          systemState = CAPTURE_STOP;
        }
        else if (initialized == true)
        {
          showBreakOnScreen();
          systemState = BREAK_ON;
        }
        break;
      }
    case STOP: {
        if (systemState ==
CAPTURE_STOP)
        {
          showDoneInitializingScreen();
          systemState = BREAK_OFF;
```

```
          initialized = true;

          XBee.write("Initialization
Done");

          delay (2000);

          showModeScreen();

          initialized == true;

        }

        else if (initialized == true)

        {

          showBreakOnScreen();

          systemState = BREAK_ON;

        }

        break;

      }

  }

}

void showWelcomeScreen()

{

  lcd.clear();

  lcd.setCursor(0, 0);

  lcd.print("  Welcome to the");

  lcd.setCursor(0, 1);

  lcd.print("  climbing gym!");

  lcd.setCursor(0, 2);

  lcd.print("  Please say START");

  lcd.setCursor(0, 3);

  lcd.print("  to begin climbing");

  setBacklight(255, 255, 255);

}

void showClimbScreen()

{

  lcd.clear();

  lcd.setCursor(0, 0);

  lcd.print("  say DESCEND to");

  lcd.setCursor(0, 1);

  lcd.print("  go to the ground");

  lcd.setCursor(0, 2);

  lcd.print("  after a fall");

  lcd.setCursor(0, 3);

  lcd.print("  to begin climbing");

  setBacklight(0, 0, 255);

}

void showRestScreen()

{

  lcd.clear();

  lcd.setCursor(0, 0);

  lcd.print("   say REST");

  lcd.setCursor(0, 1);

  lcd.print("   to rest after");

  lcd.setCursor(0, 2);

  lcd.print("   a fall");

  lcd.setCursor(0, 3);

  lcd.print(" ");

  setBacklight(255, 0, 255);

}


void showThankYouScreen()

{
```

```
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("  THANK YOU for ");
  lcd.setCursor(0, 1);
  lcd.print(" coming to our gym!");
  lcd.setCursor(0, 2);
  lcd.print("  have a great day");
  lcd.setCursor(0, 3);
  lcd.print(" ");
  setBacklight(0, 255, 0);
}

void showNormalScreen()
{
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("  say NORMAL to");
  lcd.setCursor(0, 1);
  lcd.print("  go to the ground");
  lcd.setCursor(0, 2);
  lcd.print("  after a fall");
  lcd.setCursor(0, 3);
  lcd.print("  to begin climbing");
  setBacklight(0, 0, 255);
}

void showGoScreen()
{
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("  say GO to");
  lcd.setCursor(0, 1);
  lcd.print("  go to the ground");
  lcd.setCursor(0, 2);
  lcd.print("  after a fall");
  lcd.setCursor(0, 3);
  lcd.print("  to begin climbing");
  setBacklight(0, 0, 255);
}

void showDownScreen()
{
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("  say DOWN to");
  lcd.setCursor(0, 1);
  lcd.print("  go to the ground");
  lcd.setCursor(0, 2);
  lcd.print("  after a fall");
  lcd.setCursor(0, 3);
  lcd.print("  to begin climbing");
  setBacklight(0, 0, 255);
}

void showStopScreen()
{
  lcd.clear();
```

```
  lcd.setCursor(0, 0);
  lcd.print("   say STOP");
  lcd.setCursor(0, 1);
  lcd.print("   to rest after");
  lcd.setCursor(0, 2);
  lcd.print("   a fall");
  lcd.setCursor(0, 3);
  lcd.print(" ");
  setBacklight(255, 0, 255);
}
void showDoneInitializingScreen()
{
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("done");
  lcd.setCursor(0, 1);
  lcd.print(" initializing");
  lcd.setCursor(0, 2);
  lcd.print("device");
  lcd.setCursor(0, 3);
  lcd.print(" ");
  setBacklight(255, 255, 255);
}

void showModeScreen()
{
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Please choose a");
  lcd.setCursor(0, 1);
  lcd.print("mode");
  lcd.setCursor(0, 2);
  lcd.print(" ");
  lcd.setCursor(0, 3);
  lcd.print(" ");
  setBacklight(255, 255, 255);
}

void showBreakOnScreen()
{
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Break is on");
  lcd.setCursor(0, 1);
  lcd.print("in rest mode");
  lcd.setCursor(0, 2);
  lcd.print(" ");
  lcd.setCursor(0, 3);
  lcd.print(" ");
  setBacklight(255, 0, 255);
  for (i = 0; i <8; i++){
  XBee.write(" break on \n");
  }
}
void showBreakOffScreen()
{
  lcd.clear();
  lcd.setCursor(0, 0);
```

```
lcd.print("Break is off");
lcd.setCursor(0, 1);
lcd.print("in descend mode");
lcd.setCursor(0, 2);
lcd.print(" ");
lcd.setCursor(0, 3);
lcd.print(" ");
setBacklight(0, 0, 255);
  for (i = 0; i <8; i++){
XBee.write(" break off \n" );
  }
```

Appendix C

This section presents the configuration settings for the XBee module in XCTU. The version of software used was XCTU 6.3.0[44] on a Windows 10 machine. The configuration settings are summarized in Tables C.1 and C.2. The default settings on the firmware were used for both the user input device and braking device.

Table C.1: X-CTU Configuration Settings

	Router XBee Settings	Braking Device XBee Settings
Product Family	XB24-ZB	XB24-ZB
Function Set	ZigBee Router AT	ZigBee Coordinator AT
Firmware Version	22A7	22A7

The firmware selected sets the braking device as the network coordinator and the user input device as a router. Application transfer (AT) mode was selected to allow commands to be sent verbatim from the user input device to the braking system[45]. The newest firmware (as of March 23, 2016) implemented on both boards was 22A7.

[44] "XCTU." Next Generation Configuration Platform for XBee® RF Solutions. Accessed March 23, 2016. http://www.digi.com/products/xbee-rf-solutions/xctu-software/xctu#productsupport.
[45] Faludi, Robert. *Building Wireless Sensor Networks*. North, Sebastopol, CA: O'Reilly, 2011.

Appendix D

This section presents the configuration settings for the Speak Up board. The Speak Up board can be configured using either downloadable software on the computer or by pressing buttons. The Speak up board had built in software; however, it also had its own software. An index corresponding to each command was recorded and passed using UART to control processor board. As outlined in the system design section, there are seven commands. The first command, “start” has an index of zero and the last “rest has an index of six. The software records the command, allows for playback, and sends it to the device. An alternative approach was configuring the Speak Up board using click mode. Click mode involves holding push buttons to record commands as outlined in the use cases in appendix A.

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