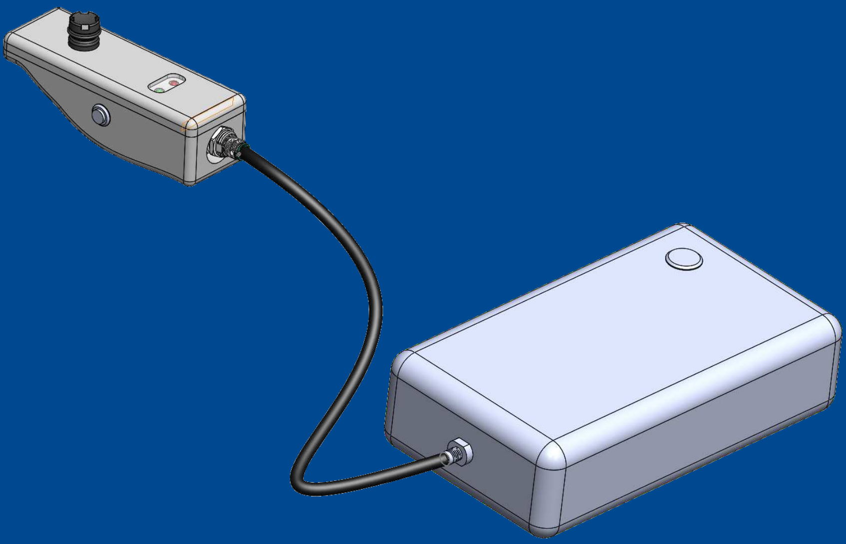
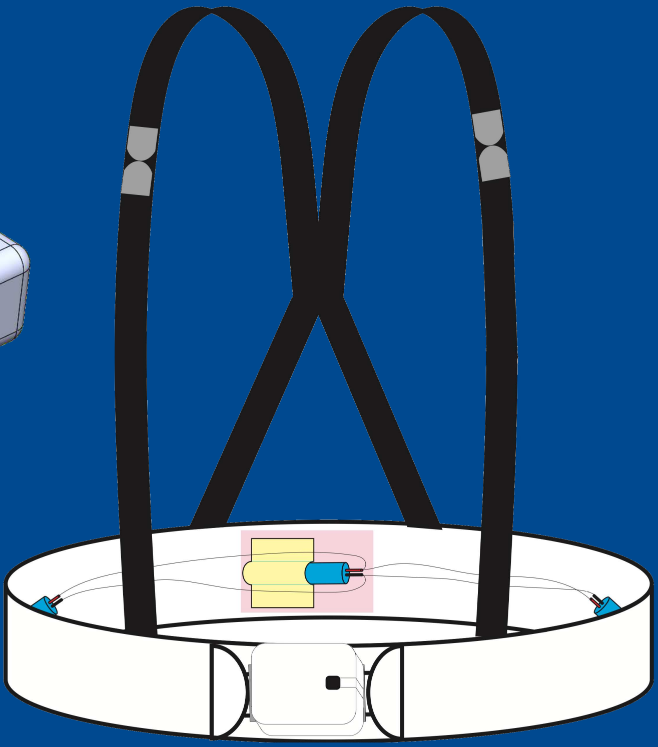
Mechanical Engineering
UNIVERSITY OF COLORADO **BOULDER**

Vibrotactile Remote Guidance System for Blind Skiers

CU Boulder Mechanical Engineering Senior Design Project 2020





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Matt Lawson | Kelly McKay | Sara Khorchidian
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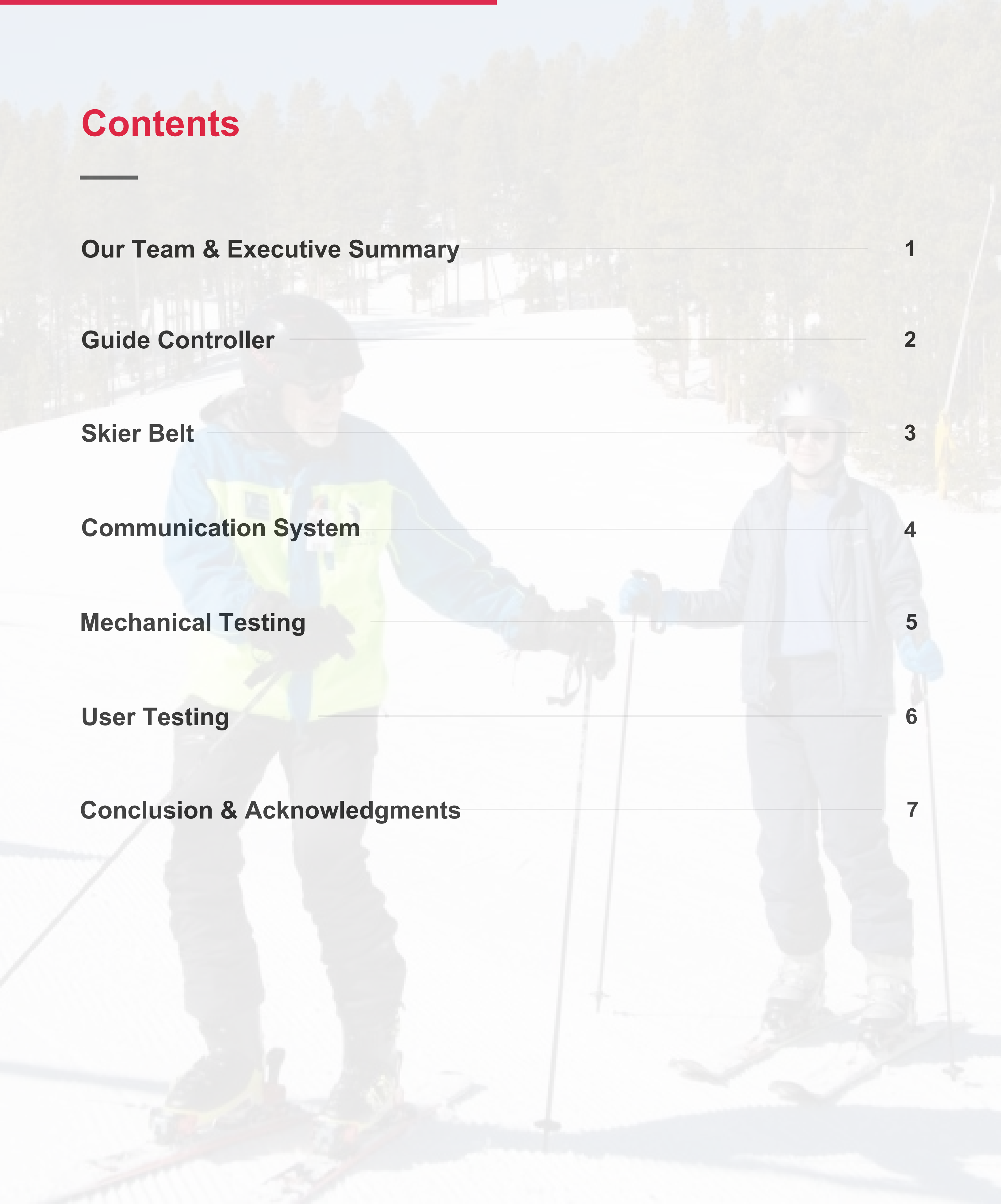

Figure 1: Team photo, from left to right: Kirsty Hodgkins, Guilherme Schulz, Kelly McKay, Nicholas Maddelone, Sara Khorchidian, Enkhlen Amarsanaa, Jarod Laroco, Matt Lawson

Our Team

Our team, as shown above in Figure 1, is composed of seven mechanical engineering students and one computer science student. We all have a fierce dedication towards helping others and serving the community. Our team members are from four different countries, including Brazil, Australia, the United States, and Mongolia. We have a combined total of six years working with disabled persons including children, adults, and Special Olympic athletes. As a collaborative team, we have used our academic and engineering skills paired with our devotion to the sport of skiing to complete the project with success.

Figure 2: a) Final design of the skier belt with the communication box centered on the front of the belt. b) Final design of the guide controller with the emergency-stop button on the side of the device.

Executive Summary

Alpine skiing allows an individual to become completely free, as they feel the wind on their face and the adrenaline rushing through their body. For a visually impaired individual, skiing can provide them with a sense of normalcy: they become independent, they gain self-confidence, and most importantly, they have fun.

The current method for blind skiers is woeful: A guide skier shouts “Left!”, “Right!”, and “Stop!” commands to the blind skier. This method can be extremely dangerous as it can be difficult to hear the commands and does not work for hearing-impaired skiers.

Our solution to this problem is the Non-Verbal Vibrotactile Remote Guidance System. There are two main parts to our system: the guide controller and the skier belt that communicate wirelessly with each other, shown in Figure 2. The guide uses the handheld guide controller to wirelessly send directional commands to the skier belt.

The skier belt, worn by the blind skier, will vibrate according to the command received. For example, if the guide sends a “left” signal, then the belt will vibrate on the left side. The directional vibrations of "right", "left", "forward", and "stop" are achieved by using four different vibration motors placed around the torso of the skier. The other necessary commands are a continuous forward vibration, to signal the skier that they are connected, and an emergency stop button that causes all four motors to vibrate, as the skier immediately stops. Since skiing occurs in extreme weather conditions, we needed to make our devices robust, water resistant, and have the ability to withstand freezing temperatures, all while being comfortable and easy to use.

Guide Controller

Design Process

After going through multiple design iterations, we finally landed on a handheld guide controller connected to a communication box, as shown in Figure 3. We needed the device to be able to be machined, robust, comfortable to hold and be comfortable to use with ski gloves. We designed many different designs on Solidworks and 3-D printed the prototypes to obtain user testing with the Ignite Blind Skier program guides at Eldora. More details about the user testing can be found on Page 6.

The device is a two part device that is hollow inside to house the electronic components and is connected by four screws, with an o-ring in between for water resistance, shown in Figure 3. The guide controller contains 2 LEDs to determine if the connection is adequate, a joystick to send the directional signals, an emergency stop button, and a wire connector that connects it to the box. The communication box sits inside the guide's jacket and is connected to the light-weight handheld controller by a cable that is strung through their jacket sleeve.

Manufacturing Process

Our first step was to determine the material and machining process: 3-D printing or CNC milling. 3D-Printing would be the most time, cost, and labor effective. However, we were unsure if spores that would be created in the printing process would allow water to enter inside, thus harming the electronics. Onyx material would have had a nice surface finish and has a yield strength of 36 MPa, however, we could not find data on the strength at cold temperatures. CNC milling the part would cost more in material and time, but it would be more durable and waterproof. Due to the uncertainty in the material properties, we went with CNC milling. The plastic we decided on was Ultra High Molecular Weight Polyethylene, with a yield strength of 24 MPa. UHMWPE can perform without degradation until -452 F and has an Izod Impact Strength of 18 ft-lbs/in.

If the guide happened to drop the device, we wanted to ensure that the controller would not break and potentially injure the guide. So, we needed the guide controller device to withstand the impact force even in subzero temperatures.

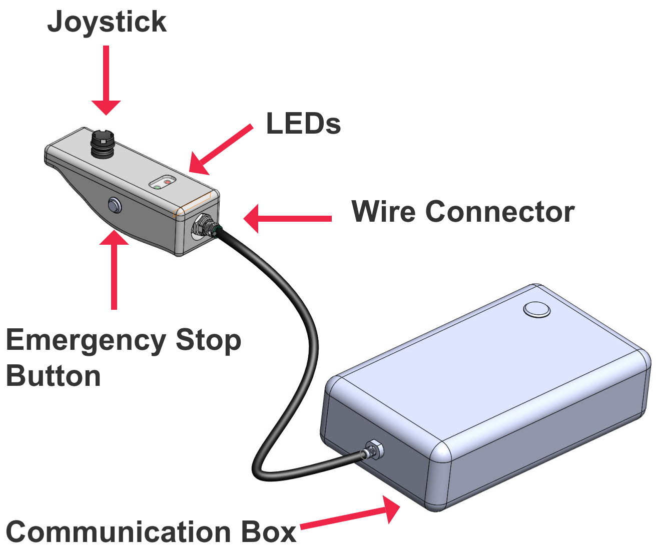

Figure 3: Handheld guide controller attached with a waterproof cable to the communication box

Calculations

To calculate the minimum wall thickness, we found the impact force if the guide weighed 200 lb, was skiing at 10 mph, and 1/4 of their weight fell on the device. The force, assuming a safety factor of 3, was 831 lb. Next, we used a 3-point beam model to determine the internal shear force to be 415.5 lb. Finally, we found the wall thickness using the following equation for the cross section of a beam.

$$\tau_{max} = \frac{Vb^2}{8I} = \frac{12Vb^2}{8b^4} = \frac{3V}{2b^2} = \frac{3 * 415.5}{2 * b^2}$$

In this calculation, V is the shear force, b is the wall thickness, I is the moment of inertia, and Tmax is the material strength. For the material, UMHW-PE, it has a maximum yield strength of 24MPa = 3480.91 psi. Substituting these numbers in the equation, the wall thickness is shown below to be 0.4". The wall thickness of the device is shown in Figure 4. The full calculations can be found here.

$$3480.91 = \frac{3 * 415.5}{2 * b^2}$$

$$b = \boxed{\mathbf{0.4\ in}}$$

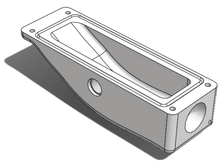

Figure 4: Bottom piece of the guide controller showing the wall thickness

Skier Belt

Design Process

The skier belt design process was completely opposite from the guide controller. It took a while to lock down a design that checked every box, but we quickly decided how we would manufacture it. The skier belt system needed to be 1) comfortable, 2) easily adjustable, 3) lightweight, and 4) easy to manufacture. A mockup of our design can be seen in Figure 5.

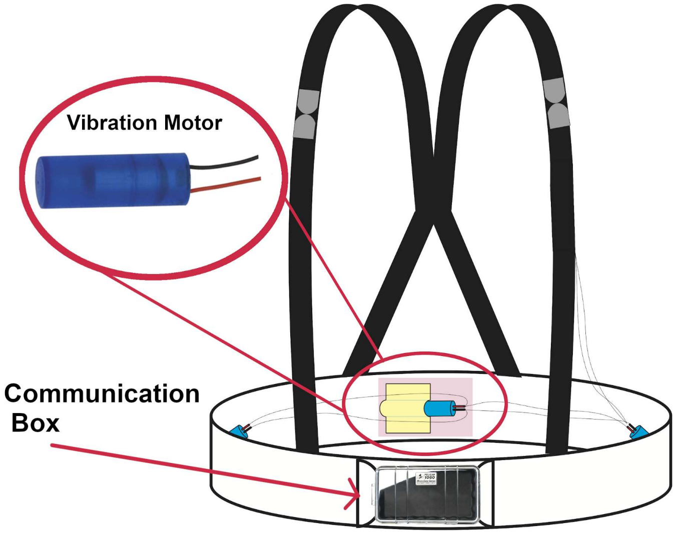

Figure 5: Mockup of the fully assembled skier belt system

We settled on using a work-belt with suspenders for the frame and wiring the vibration motors discreetly on the inside of the belt. The cost of the work-belt and suspenders came out to a total of $44.95. The entire system is adjustable to a wide range of sizes by using velcro to fasten both the vibration motors to the correct position on the belt and to secure the belt to the torso of the skier. A communication box will be attached to the front of the belt for easy access and comfort.

User feedback from the guides and blind skiers from Ignite Adaptive Sports at Eldora was essential for finalizing a design for the skier belt. They liked the idea of a belt and suspenders and after further testing, the location of the communication box was decided to be located on the front of the belt. Originally, we planned to have the box attached to the suspenders. More information on user testing can be seen on Page 6.

Manufacturing Process

The main part of the manufacturing process for the skier belt was the wiring. We used 22 gauge speaker wires to place on the inside of the belt, connecting the vibration motors to the communication box. To secure the wires on the inside of the belt, the soft side of velcro was sewn on the inside of the belt overtop the wires. Slits were also cut in the velcro in order for the wires to come out and connect to the vibration motors. The rough side of velcro can then be used to secure the vibration motors to the belt. During use, if a vibration motor were to break, we soldered wire connectors to the ends of the wires and the vibration motors, so that they can be easily detached and replaced (see Figure 6).

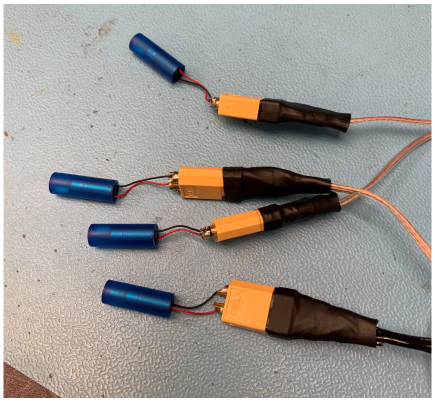

Figure 6: The vibration motors in blue are soldered to the female ends of the wire connectors and the speaker wire is soldered to the male ends of the wire connectors and wrapped in electrical wire

Determining the exact size range of the skier belt was another task. Realistically, the work-belt has specifications to fit a waist size of up to 46 inches. This was possible because the work-belt came in two pieces, but in order for the belt to be lined with wire, it had to be secured as one piece. This would ensure that any wires or motors don't overlap. We secured the belt as one piece and determined a location range for each vibration motor to fit waist sizes ranging from 26.5in to 37.5in. We used our own waist sizes to help determine this range as well. To determine the ranges at which each vibration motor could be placed, the motors had to be in the correct orientation for both the smallest and largest person our belt could fit. The motors are in a correct orientation when there is one motor on the left, right, front, and back side of the skier's waist.

Communication System

System Outline

We used Digi's Xbee radio frequency (RF) communication modules, Atmel Atmega328p microcontrollers, and 3.7 Volt 2000 mAh batteries in both communication boxes. Additionally, a joystick, stop button, and LEDs were used in the Guide Controller communication system and vibration motors were used in the Skier Belt communication system. The Xbee modules are ideal because of their low-latency, low-power, nearby communication centered design and their range of 90 meters.

We planned to use a printed circuit board (PCB) to professionally and reliably integrate each device's components to its respective communication box components. Due to COVID-19, we were unable to produce our PCBs and instead downgraded to a perfboard. The perfboard achieves the same functionality as the PCB, but it is less reproducible and professional-looking.

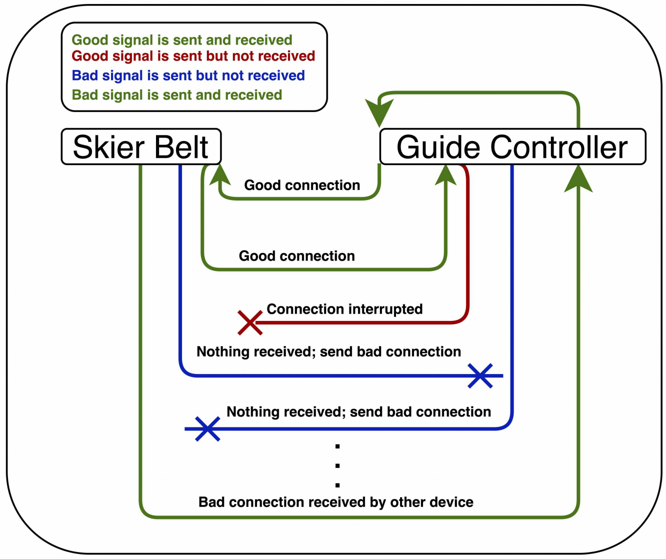

Figure 7: Model of the communication system

Figure 8: XBee wireless communication module used in both the Guide Controller and the Skier Belt communication box.

Critical Features

The Xbees are set up to automatically pair to each other when turned on. This is a facile and safe method for users, allowing multiple guide/skier systems to be used at once. We achieved this by setting both devices to the same channel and the same PANID.

As recommended by skier guides at Ignite Adaptive Sports, the skier will receive a forward pulse at a frequency of 0.5 Hz as long as both devices are connected. This reassures the skier, reminding them that the communication system is working properly. The guide device will display a solid blue status light when connected to the skier system, and will flash as confirmation with every command the guide sends.

A connection issue could lead to serious injury if not handled properly. If the skier and guide device get disconnected somehow, the skier device will instantly send the emergency stop signal to the skier while the guide device will instantly flash a red light. When the devices are reconnected, the skier device will cycle through all vibrations to let the skier know that the device is connected again and the guide device will display the green status light again.

This idea is implemented in the code by having the devices send a "good connection" signal back and forth (see Figure 7). The guide device sends the first signal to the skier device. When the skier device receives it, it sends it right back to the guide device and the process repeats. Keep in mind that these are different from the commands initiated by the guide from the joystick. Directional commands are sent manually by the guide while the "good connection" commands are sent automatically by the devices at a frequency of 10Hz. With this system, it will take a maximum of two cycles (0.2 seconds) for both devices to recognize a connection issue and activate bad-connection mode.

Mechanical Testing

Water Resistance

The purpose of this test would have been to meet the IPX4 specification for the guide controller because we wanted to ensure electronics were housed safely from moisture. The case possesses multiple custom holes and it would be possible for a guide to drop the device in snow. The test would have been very straightforward. We were going to remove all electronics from the inside of the guide controller, leaving the joystick, emergency stop button, wire connector, and LED pane. Next, a humidity indicator would be placed inside the case. This would have been a generic moisture indicator that measured relative humidity in 5 percent increments. The case would be shut by external screws at each corner. The case would be immersed in a shower of water from all directions until the case had been covered at all angles. Then it would be removed and the exterior would be quickly dried with a cloth. Then the case would be reopened to inspect for leakage or a change in humidity. We wanted to repeat the same test, but try for IPX7 rating by immersing the controller in 1m of water for one hour, given the first test passed. If the device did not pass the first waterproofing test, we would have reevaluated our "waterproof" components and decided if controller material needed to be changed or better sealed components would need to be purchased.

Device Robustness

This test was imperative to ensure devices would not fail due to the rugged nature of skiing. The controller could be subject to a free-fall onto ice, sat or stepped on, or collide with a stationary or moving object. We decided that the worst-case scenario would be someone stepping on the controller with all their weight because it would exert the greatest force on the device (see Figure 9). This force turned out to be approximately 275 lbf with a factor of safety of 3 (831 lbf). You may refer to the calculations on page 2 for more information on how we came to this value. If the device were to deform plastically after this load was applied, a new material may have needed to be chosen or wall thickness of the device may have needed to increase.

Figure 9: Testing the response of the strain gauge to a realistic force. The gauge did not produce useful data because it was not calibrated.

To simulate this worst case scenario, we determined a 3-point flexure test would suffice. This test allows the specimen to be supported from underneath at both ends by two anvils, while the third anvil applies a force to the top face in the center. This test is particularly useful in comparison to a basic uniaxial compression or tensile test because it can evaluate the reaction of the material in a realistic loading situation (like being stepped on).

The device would be placed in the Instron machine such that it would be fixed on both ends by two of the anvils, eliminating translational or rotational motion. The device would be oriented such that the joystick would be facing up, to induce the largest stress. Strain measurements would be taken while the sample was applied the 3-point load. This strain would be measured near the joystick hole by a CEA-13-240UZ-120 strain gauge. Shunt calibration would be used to calibrate the strain gauge. A large resistor (15kΩ, 50kΩ, and then 100kΩ) would be placed in parallel with one of the arms of the Wheatstone bridge and the voltage would be measured at each resistance. These values would then be used to construct a calibration curve so the strain of the sample could be measured. Finally, stress would have been calculated given the known elastic modulus of the material.

User Testing

Guide Controller

While iteratively designing 3D prototypes (see Figure 10) for the handheld controller, we created a survey to gather information about people's thoughts on the current design. Ten people, both peers and instructors, were interviewed regarding the current controller prototype.

They were asked to rank characteristics like comfort and ease of use, and provide subjective feedback. There were two common suggestions gathered from this survey. First, the controller felt too bulky and was difficult for people with smaller hands to use. Next, moving one's thumb from the joystick to the emergency stop button (then located on the top face of the controller) felt cumbersome and awkward.

The second suggestion echoed an Ignite Ski Guide's suggestion of placing a gross-movement emergency-stop button on the side of the controller. This would allow for a more reflexive activation of the emergency stop protocol. Both of these suggestions were taken into consideration and incorporated into the final design of the controller (see Figure 2b).

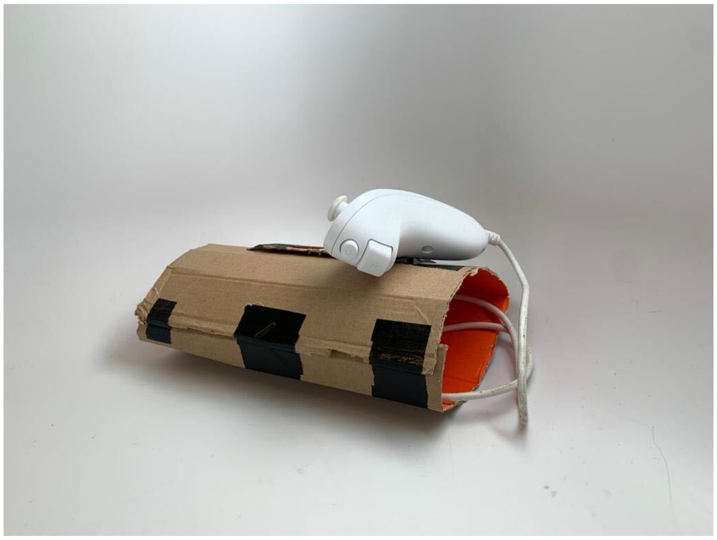

Figure 10: Our first prototype of the guide controller

Skier Belt

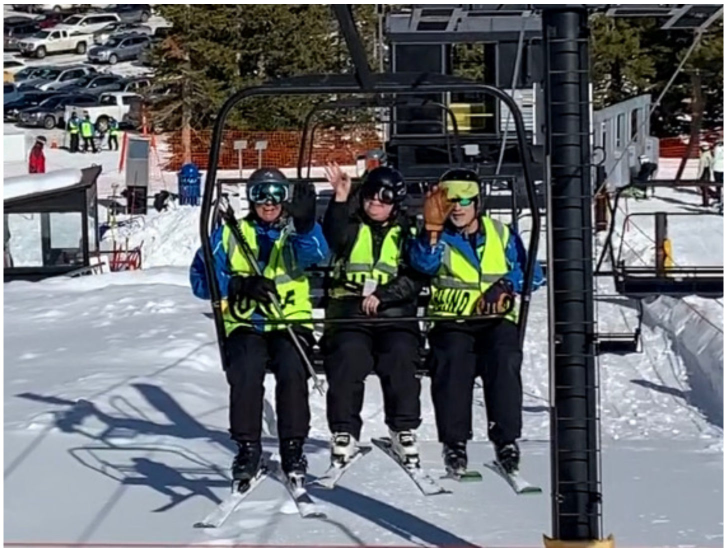

Figure 11: Blind skier Holly (middle) and two blind skier guides (left, right) wave as they ride the ski lift up.

Following a testing session at Eldora ski resort, blind skier Holly and her ski guides gave us some useful feedback (see Figure 11). They had two major suggestions. First, having the communication box on her shoulder felt a bit cumbersome and awkward. Without a central chest strap connecting the two shoulder straps, the weight of the box caused the strap to feel loose and swing while skiing. She suggested we have the communication box centered on the body to balance the weight and keep it more secure.

Secondly, the guides believed that placing the box on the skier's back would reduce the risk of accidentally knocking it off themselves. The idea of centering the communication box was useful, though, placing it on the back of the skier is less functional and introduces problems with falling and riding chairlifts, so it was not incorporated into the final design. The updated design, as seen in Figure 2a, was tested with new ski guides who found it far more comfortable.

Conclusion

We designed a vibrotactile remote guidance system to assist blind-deaf skiers. Our design focused on functionality and versatility. We wanted the controls to be intuitive for guides that already work with challengers and the guiding pulses to be recognizable and effective. For the guide device, this turned into something that resembles a video game controller. We concurrently thought about its comfort and durability; it was built to be ergonomic and withstand the harsh winter climate. The challenger system consists of original hardware on a pre-fabricated belt. We made the decision that current market belt design is more than adequate, which let us focus on improving motor configuration and recognition.

With so much effort going into design, we wanted to test both devices to see how their performance compared to specifications. Unfortunately, due to the consequential limitations resulting from COVID-19, we were unable to test our devices' mechanical properties comprehensively. However, prior to this, we were able to conduct equipment functionality testing with guides and challengers. Footage of this can be found in our team video. If given the opportunity, we would like to conduct all planned tests to ensure the quality of our product.

Figure 12: The team visiting Ignite Adaptive Sports at Eldora Ski Resort.

Acknowledgments

This project would not have been possible without the kind support and help of many individuals and organizations. We would like to express special gratitude to Scott Huyvaert and Court Allen at QL+ for their continued support and guidance of our project. We would also like to extend our gratitude to our director Christoph Keplinger for giving our team invaluable advice and professional management that helped guide us through unforeseen obstacles throughout the life of our project; John Humbrecht at Ignite Adaptive sports for providing us with valuable feedback from his connection with guides and blind skiers; Jim Riley at Team River Runner for lettings us pick apart his device; Pat Maguire and Lauren Darling for sharing their extensive electronic manufacturing and PCB knowledge with us; Cameron Micksch and others at the ITLL for spending hours programming and overseeing the quality CNC milling of our guide device; Daria Kotys-Schwartz, Julie Steinbrenner, Sean Sundberg, Gabe Rodriguez, and Danny Straub for working tirelessly to ensure that our team succeeds in every way possible; Victoria Lanaghan, Lauren Wheeler, Greg Potts, Chase Logsdon, Josh Colyer, and the rest of the Idea Forge staff for providing knowledge and advice in their areas of expertise.

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