Mouth-Operated Assistive Device for People with Disabilities

A Major Qualifying Project Report

Submitted to the Faculty

of the

Worcester Polytechnic Institute

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

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March XX, 2021

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Abstract

Manual dexterity complications within individuals prevent ease of access to technologies and navigating those technologies including mobile devices and laptops. Diseases such as arthritis, muscular dystrophy, multiple sclerosis, and cerebral palsy are some that impair mobile dexterity. Solutions have been presented including electric wheelchairs, voice activated and controlled devices, and tongue-driven systems to help users navigate technologies essential to daily life. Puffin Innovations has presented a device, the Puffin, to allow users to connect a joystick via bluetooth to their mobile devices or computers to navigate the systems. By operating the joystick with the tongue, the individual can control the position of the mouse and what they want to select, as well as carry out functions such as pressing and holding the button for different outputs. The initial prototype utilizes an Adafruit nRF52840 to power and control the device. However, this system is not able to be brought to production due to the trademark of the Adafruit. By utilizing a STM32 microcontroller in conjunction with the Blue NRG-2, a production-level prototype is made in a more compact PCB. By utilizing CAD software as well as programming the microcontroller with an integrated development environment unlike the Arduino or Adafruit, the new device is a production-level prototype which will allow for further testing by the company to move towards the release phase of the product.

Statement of Authorship

All team members contributed to the design and implementation of the device. All members also acted as main authors and editors of this paper. Sections written by each individual are listed below:

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Acknowledgements

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2. Background

2.1 Manual Dexterity Impairments

The main audience that our project is aimed at are those individuals who have manual dexterity impairments. To understand further we must first understand what manual dexterity is. According to the ADEA, “manual dexterity is the ability to use your hands in a skillful, coordinated way to grasp and manipulate objects and demonstrate small, precise movements.” Manual dexterity is a skill most able-bodied people take for granted as it is one of the most used. Examples of this are using a computer, using a phone, opening doors, playing an instrument. That is why it is important to create systems to help those who have manual dexterity impairments use such devices. Mobility impairment is a broad term referring to any physical disability that limits the physical function of one or more limbs (Learning About Disabilities Mobility/Dexterity Impairments, 2019).

The most common associated diseases that cause mobility dexterity paralysis, arthritis, muscular dystrophy, multiple sclerosis, cerebral palsy. All of these can cause these types of impairments: congenital conditions, missing or malformed appendages, traumatic or repetitive injury to the spinal cord, and neuromuscular disorders (Learning About Disabilities Mobility/Dexterity Impairments, 2019).

2.2 Existing Assistive Devices and Programs

2.2.1 Devices

Due to the fact that there are different levels of manual dexterity impairments, we looked at different types of existing devices that assist patients in their daily lives.

To begin with is the robot based Hand Exoskeleton System (HES) prototype built by scientists at the University of Florence, Italy (Conti, 2017). It is cable driven and based on a single-phalanx mechanism. In this context, phalanx refers to one of the bones in the fingers. This robotic orthosis is a low-cost, versatile hand exoskeleton and is based on the geometrical attributes of a patient’s hand. The geometrical characteristics are used to come up with a kinematic mechanism that suits the finger trajectories. HES is a good approach because the alternative, Functional Electrical Stimulation (FES), is highly invasive, has limited usability (reduced applicability to patients with limited muscular recruitment abilities), and causes fatigue in patients fairly quickly. HES, on the other hand, is designed to assist and improve the performance of the patient's hand mobility. While focusing on portability and cost of the device, it also had to be light-weight as stated by a patient facing manual dexterity impairment (caused by Spinal Muscular Atrophy). The total cost of the preliminary prototype was less than €300, weighed about 350 g, with a maximum height of 3.5 cm from the back of the hand.

As far as the linking between hand and exoskeleton is concerned, there are two different approaches for HESs: single-phalanx devices, in which the robot exchanges forces at the fingertip, and multi-phalanx ones, where the device directly controls each joint of the hand. Multi-phalanx leads to more complex mechanisms and control strategies. The single-phalanx approach is more suitable for the application of higher forces and for the complexity reduction of the actuation system and of control algorithms, and is also portable (which was very important for this study). The device had to be adaptable to different users, so the scientists had to be vary of different hand sizes and different disabilities. This aspect was very critical due to the variability of human hands (e.g., bone positions and tissue deformations) and complicated the design of the device.

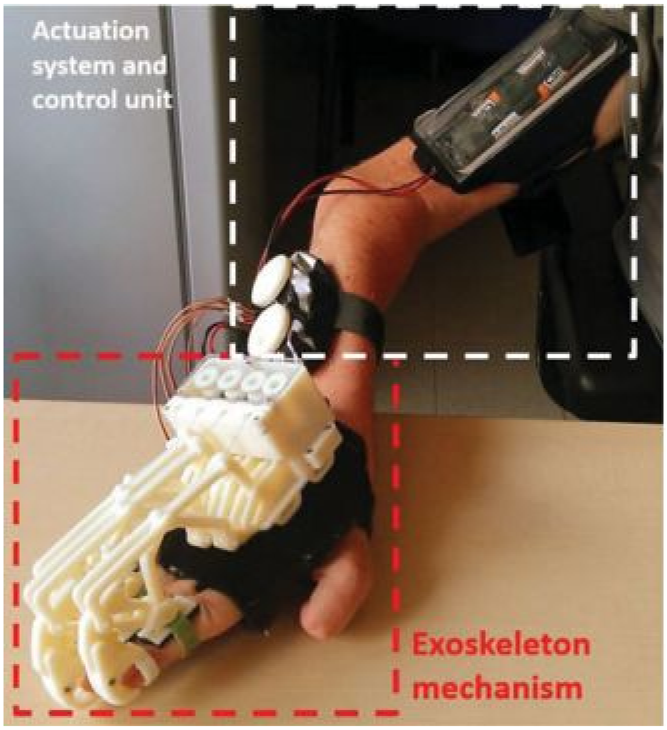


Figure 1: HES prototype: the mechanism part and the actuation and control unit one (Conti, 2017)

In the above figure, the HES prototype is shown, highlighting the two main parts of the device: the exoskeleton mechanism, the actuation system and control unit. Since the device was developed for hand opening disabilities, the HES architecture was based on a cable-driven actuation system focusing only on the fingers (thumb excluded). The mechanism developed in the proposed research paper was a rigid single-phalanx mechanism: the link between hand and exoskeleton is carried out to obtain a single Degree-of-Freedom (DOF) in the connection point. From a kinematic point of view, the mechanism always has 2 DOFs (1 DOF (residual) is the controlling DOF and 1 DOF between the hand and the exoskeleton) (Conti, 2017).

The choice of not actuating this residual DOF was made to maintain a residual mobility for the patient's hand and to keep the hand safe. It is, however, worth noting that this residual DOF did not affect the exoskeleton functionality. Through the single DOF architecture, the metacarpophalangeal (MCP) self-alignment is overcome by only considering the fingertip trajectories. Finally, the placement of the actuators was also a critical aspect for the usability of the device: to improve the portability and the simplicity of the device, the scientists proposed to place the actuators directly on the hand. The main advantages of this decision were the reliability and the effectiveness of the direct connection between fingers and actuators, but both the inertia and the obstruction of the HES increased too. The design phase has to take into account these requirements for the real prototype development: the choice of the actuators will be related to the sizes, the weight and the generated force. In the HES prototype, to maintain the exoskeleton fixed to the hand, a gym glove with some stripes of velcro has been used. Through the analysis of the forces applied to the hand, an optimised solution in terms of fixing belts is obtained. During the testing activity, the glove solution seemed to be rigid enough to not allow relative motions between the hand and the mechanism. The methodology used in this research was applied to preliminarily evaluate the kinematic and dynamic interactions between hand and exoskeleton: several 3D multibody models of the hand and the exoskeleton were developed (Conti, 2017).

The second existing technology is a wireless, noncontact, unobtrusive, Tongue Drive System (TDS) (Huo, 2008). The basis of this device is a small permanent magnet secured on the tongue by implantation, piercing, or tissue adhesives is used as a tracer, the movement of which is detected by an array of magnetic field sensors mounted on a headset outside the mouth or on an orthodontic brace inside. The sensor output signals are wirelessly transmitted to an ultraportable computer carried on the user's clothing or wheelchair and are processed to extract the user's commands. The user can then use these commands to access a desktop computer, control a power wheelchair, or interact with his or her environment. This device was designed to help people suffering from traumatic brain injury and spinal cord injury (SCI) to amyotrophic lateral sclerosis and stroke. The reason why this device is based on tongue movement is because "The tongue and mouth occupy an amount of sensory and motor cortex in the human brain that rivals that of the fingers and the hand. Hence, they are inherently capable of sophisticated motor control and manipulation tasks with many degrees of freedom. The tongue is connected to the brain by the hypoglossal nerve, which generally escapes severe damage in SCI. The tongue muscle is similar to the heart muscle in that it does not fatigue easily. Further, the tongue is noninvasively accessible and not influenced by the position of the rest of the body, which can be adjusted for maximum comfort." The goal of the development project was to potentially substitute for some of the users' lost arm and hand functions.

The main advantage of the TDS is that a few magnetic sensors and a small magnetic tracer can potentially capture a large number of tongue movements, each of which can represent a particular user command. A set of specific tongue movements can be tailored for each individual user and mapped onto a set of customized functions based on his or her abilities, oral anatomy, personal preferences, and lifestyle. The user can also define a command to switch the TDS to standby mode when he or she wants to sleep, engage in a conversation, or eat.

Moving on to some of the technical aspects of the device, small, cylindrical, rare-earth permanent magnets were used as magnetic tracers. A pair of two-axis magnetic field sensor modules was mounted symmetrically at right angles on the face shield close to the user's cheeks. To minimize the effects of external magnetic field interference, including the earth magnetic field, a three-axis module was used as a reference electronic compass. The reference compass was placed on top of the face shield so as to be far from the tongue magnet and to only measure the ambient magnetic field. The compass output was then used to predict and cancel out the interfering magnetic fields.

The sensor outputs, already in digital form, were sent serially to the ultralow-power Texas Instruments MSP430 microcontroller. The MSP430 took 11 samples/s from each sensor while activating only one module at a time to reduce power consumption. After reading all sensors, the samples were arranged in a data frame and wirelessly transmitted to a personal computer (PC) across a 2.4 GHz wireless link established between two identical nRF2401 transceivers. The entire system was powered by a 3.3 V coin-sized battery.

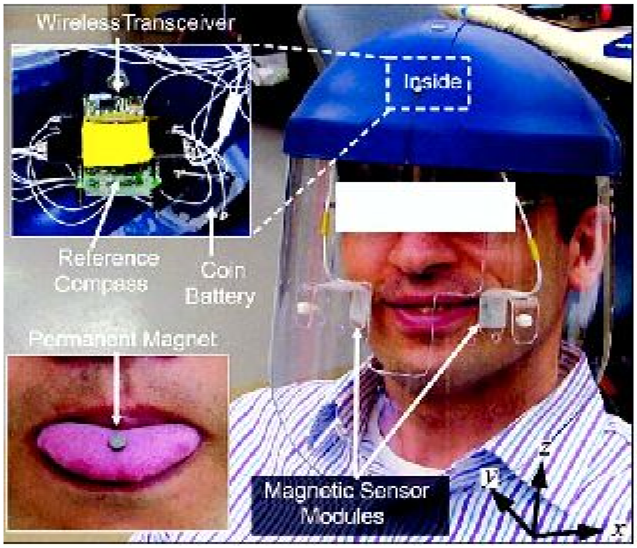


Figure 2: The TDS in operation (Huo, 2008).

Lastly, the Sensor Signal Processing (SSP) algorithm running on the PC was developed in LabVIEW and MATLAB. It operated in two phases: training and testing. The training phase used principal components analysis (PCA) to extract the most important features of the sensor output waveforms for each specific command. Future work includes improving the TDS hardware and SSP algorithms to make them smaller, faster, and more efficient. Some commands that put the TDS in standby mode and bring it back online. Another change would be to substitute the operator feedback in selecting proper tongue movements with automated visual feedback to help the users define their commands more accurately. Linking the TDS to power wheelchair (PWCs) as well as other home and/or office appliances would be a game changer. We are also working toward adding proportional control to the SSP algorithm, especially for navigation and pointing tasks. Assessing the usability and acceptability of the TDS by people with severe disabilities, who are the intended end-users of this new technology, would prove to be very helpful (Huo, 2008).

The mouth operated mouse moves the cursor by using a mouthpiece, which works like a joystick. Pushing the mouthpiece towards the case operates the right mouse button. The left mouse button is emulated by a sensor that recognizes when the user sucks air through it ("Mouth Operated Mouse", 2015). The system is controlled by an Arduino Pro Micro and can be connected to virtually any PC via USB. Open source hardware and software was used as much as possible. The system was controlled by an Arduino Pro Micro. The Firmware was written as an

Arduino sketch. Other parts were purchased from ebay or a local hardware store. This is a good inspiration for our project, with more information provided informally on a different site.

Figure 3: Mouth-operated Mouse ("Mouth Operated Mouse", 2015).

Finally, a low-cost, Do-It-Yourself alternative input device is FLipMouse. It can help people with manual dexterity impairments access their personal computer, laptops, smartphones, and other consumer electronics. Additional devices can also be controlled by attaching them to the two external switches available. An integrated universal infrared transceiver allows control of various consumer electronic devices without any additional hardware/software. An infrared receiver module and a high current infrared LED in order to support IR-remote control units for consumer electronics. Two operational modes of the FLipMouse as well as a graphical user interface for configuration give room for personalization according to a consumer's needs. Using a standardized communication protocol, raw sensor data from the device can be transferred to desired software applications for further processing and analysis. Feasibility checks of the FLipMouse in different user scenarios (gaming, desktop control, smartphone control and playing a musical instrument) with people with different limited motor capabilities confirmed a high user satisfaction. In a quantitative evaluation, the mouse cursor's sensitivity was tested. The results indicate that the FLipMouse is an affordable, fully functional alternative input device. It offers a high degree of adaptability not provided by similar assistive products available on the market (Aigner, 2016).

The target audience for the FLipMouse are people with severely reduced motor capabilities of the upper limbs, in particular persons with Duchenne Muscular Dystrophy (DMD), quadriplegia, amyotrophic lateral sclerosis (ALS) or multiple sclerosis. The design files (including hard- ware plans, firmware and configuration software) for the device are offered as open hardware / open source software. As a result, researchers have complete flexibility in changing operational characteristics and features of this special input system. A major plus point above other similar assistive devices is that DIY-communities and people who cannot afford commercially available solutions can build the device according to the documentation.

Figure 4: FLipMouse under use (Aigner, 2016).

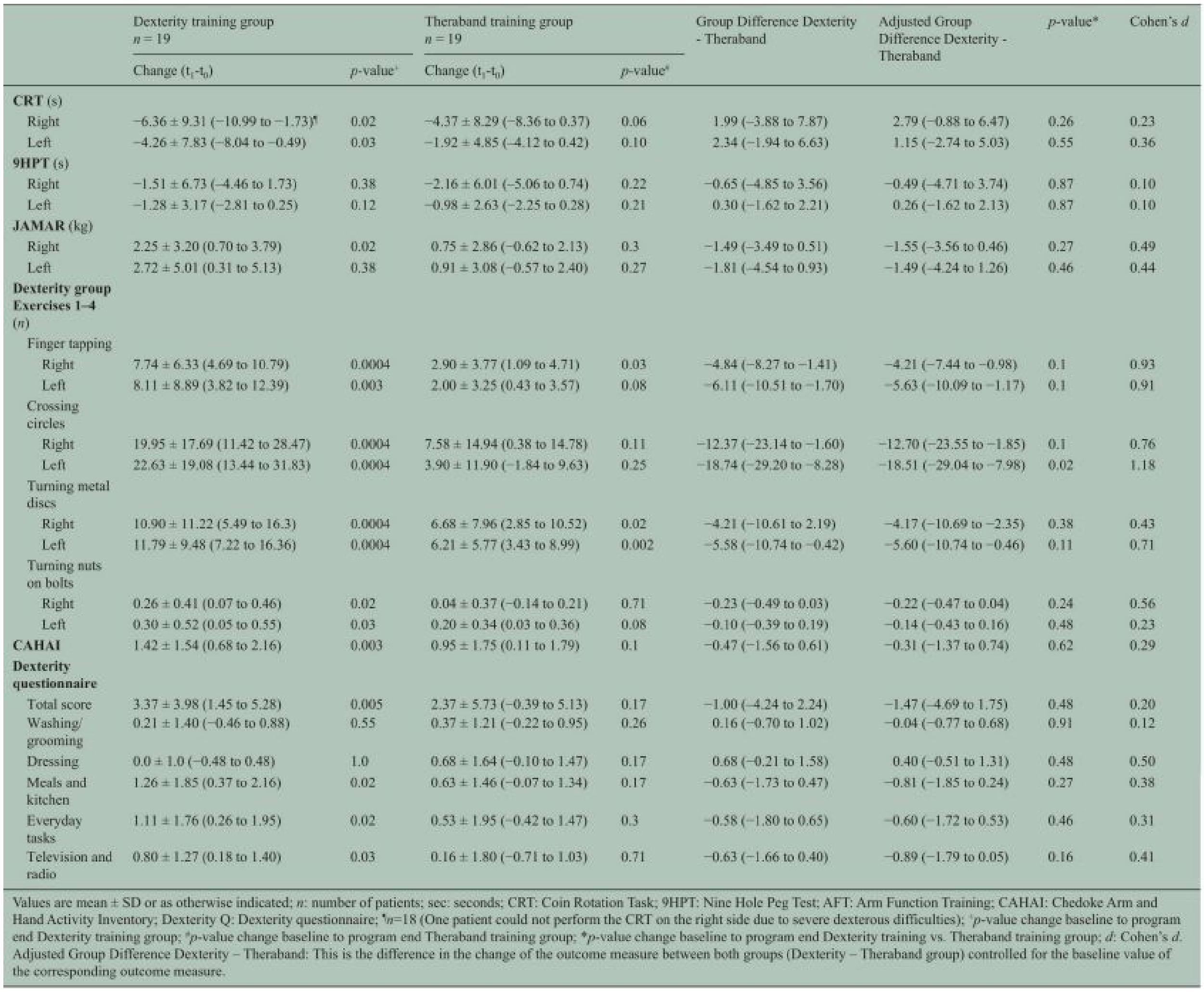
2.2.2 Programs

First, we are going to discuss results from a home-based training to improve manual dexterity in patients with multiple sclerosis. A randomized, rater-blinded, controlled trial comparing two standardized 4-week home-based training programs were performed. These focused on different aspects of manual dexterity. The dexterity training program predominantly consisted of fine motor dexterity exercises with in-hand manipulation of objects, whereas the theraband training program predominantly consisted of hand and arm strength-training exercises. Both groups were well matched with regard to baseline characteristics and baseline measurements. After 4 weeks of training, the dexterity training program resulted in significant improvements in almost all outcome measures, compared with baseline. The Coin Rotation Task (CRT) and JAMAR (hand-held dynamometer) improved, indicating increased dexterous skills and grip strength, respectively, with a meaningful improvement over 15% for the CRT.

Furthermore, the CAHAI-8 as real-life upper limb functional tests and the dexterity questionnaire improved significantly. The CAHAI-8 is a performance-based test containing eight real-life upper limb functional tests ("pour a glass of water" etc.) rated on a 7-point quantitative scale, with higher scores indicating better performance (Kamm, 2015).

The dexterity training program was superior to the theraband training program with regard to higher absolute improvements in almost all endpoints that reached significance in one trained exercise, however in none of the primary and secondary endpoints. This lack of significance is due to mostly non-significant improvements of manual dexterity and dexterity-related activities of daily living (ADL) in the theraband training group as well, and in this regard the low number of patients. This is not surprising because the theraband training program is an established arm and hand function training program. Impaired manual dexterity in MS results from several neurological deficits such as ataxia, spasticity, paresis, sensory deficits or apraxia alone or in combination with each other, as well as de-conditioning. Despite focusing on different aspects of arm and hand function, both programs train several causes of impaired manual dexterity and aspects of its counterpart. This explains the positive effect of the theraband training program on manual dexterity with regard to fine motor dexterity, as well as the superior effect of the dexterity training program on grip strength measured by the JAMAR. The latter is probably due to exercises 5 and 6 of the dexterity training program that contain kneading tasks that strengthen hand-grip. Furthermore, both programs probably improved physical deconditioning of less-used upper extremities, explaining the strong effects in a very short time in some patients (Kamm, 2015).

The results are in favor of the dexterity program (manual dexterity and fine motor dexterity) compared with the theraband training program. This is underlined by the calculated effect sizes (Cohen's d) which were in favor of the dexterity training program (Table 3). The effectiveness of the training program is remarkable, especially with regard to its practicability (Kamm, 2015).



	Dexterity training group *n* = 19		Theraband training group *n* = 19		Group Difference Dexterity - Theraband	Adjusted Group Difference Dexterity - Theraband	*p*-value*	Cohen's *d*
	Change (t_1-t_0)	*p*-value[†]	Change (t_1-t_0)	*p*-value[‡]				
CRT (s)								
Right	−6.36 ± 9.31 (−10.99 to −1.73)[¶]	0.02	−4.37 ± 8.29 (−8.36 to 0.37)	0.06	1.99 (−3.88 to 7.87)	2.79 (−0.88 to 6.47)	0.26	0.23
Left	−4.26 ± 7.83 (−8.04 to −0.49)	0.03	−1.92 ± 4.85 (−4.12 to 0.42)	0.10	2.34 (−1.94 to 6.63)	1.15 (−2.74 to 5.03)	0.55	0.36
9HPT (s)								
Right	−1.51 ± 6.73 (−4.46 to 1.73)	0.38	−2.16 ± 6.01 (−5.06 to 0.74)	0.22	−0.65 (−4.85 to 3.56)	−0.49 (−4.71 to 3.74)	0.87	0.10
Left	−1.28 ± 3.17 (−2.81 to 0.25)	0.12	−0.98 ± 2.63 (−2.25 to 0.28)	0.21	0.30 (−1.62 to 2.21)	0.26 (−1.62 to 2.13)	0.87	0.10
JAMAR (kg)								
Right	2.25 ± 3.20 (0.70 to 3.79)	0.02	0.75 ± 2.86 (−0.62 to 2.13)	0.3	−1.49 (−3.49 to 0.51)	−1.55 (−3.56 to 0.46)	0.27	0.49
Left	2.72 ± 5.01 (0.31 to 5.13)	0.38	0.91 ± 3.08 (−0.57 to 2.40)	0.27	−1.81 (−4.54 to 0.93)	−1.49 (−4.24 to 1.26)	0.46	0.44
Dexterity group Exercises 1–4 (*n*)								
Finger tapping								
Right	7.74 ± 6.33 (4.69 to 10.79)	0.0004	2.90 ± 3.77 (1.09 to 4.71)	0.03	−4.84 (−8.27 to −1.41)	−4.21 (−7.44 to −0.98)	0.1	0.93
Left	8.11 ± 8.89 (3.82 to 12.39)	0.003	2.00 ± 3.25 (0.43 to 3.57)	0.08	−6.11 (−10.51 to −1.70)	−5.63 (−10.09 to −1.17)	0.1	0.91
Crossing circles								
Right	19.95 ± 17.69 (11.42 to 28.47)	0.0004	7.58 ± 14.94 (0.38 to 14.78)	0.11	−12.37 (−23.14 to −1.60)	−12.70 (−23.55 to −1.85)	0.1	0.76
Left	22.63 ± 19.08 (13.44 to 31.83)	0.0004	3.90 ± 11.90 (−1.84 to 9.63)	0.25	−18.74 (−29.20 to −8.28)	−18.51 (−29.04 to −7.98)	0.02	1.18
Turning metal discs								
Right	10.90 ± 11.22 (5.49 to 16.3)	0.0004	6.68 ± 7.96 (2.85 to 10.52)	0.02	−4.21 (−10.61 to 2.19)	−4.17 (−10.69 to −2.35)	0.38	0.43
Left	11.79 ± 9.48 (7.22 to 16.36)	0.0004	6.21 ± 5.77 (3.43 to 8.99)	0.002	−5.58 (−10.74 to −0.42)	−5.60 (−10.74 to −0.46)	0.11	0.71
Turning nuts on bolts								
Right	0.26 ± 0.41 (0.07 to 0.46)	0.02	0.04 ± 0.37 (−0.14 to 0.21)	0.71	−0.23 (−0.49 to 0.03)	−0.22 (−0.47 to 0.04)	0.24	0.56
Left	0.30 ± 0.52 (0.05 to 0.55)	0.03	0.20 ± 0.34 (0.03 to 0.36)	0.08	−0.10 (−0.39 to 0.19)	−0.14 (−0.43 to 0.16)	0.48	0.23
CAHAI	1.42 ± 1.54 (0.68 to 2.16)	0.003	0.95 ± 1.75 (0.11 to 1.79)	0.1	−0.47 (−1.56 to 0.61)	−0.31 (−1.37 to 0.74)	0.62	0.29
Dexterity questionnaire								
Total score	3.37 ± 3.98 (1.45 to 5.28)	0.005	2.37 ± 5.73 (−0.39 to 5.13)	0.17	−1.00 (−4.24 to 2.24)	−1.47 (−4.69 to 1.75)	0.48	0.20
Washing/ grooming	0.21 ± 1.40 (−0.46 to 0.88)	0.55	0.37 ± 1.21 (−0.22 to 0.95)	0.26	0.16 (−0.70 to 1.02)	−0.04 (−0.77 to 0.68)	0.91	0.12
Dressing	0.0 ± 1.0 (−0.48 to 0.48)	1.0	0.68 ± 1.64 (−0.10 to 1.47)	0.17	0.68 (−0.21 to 1.58)	0.40 (−0.51 to 1.31)	0.48	0.50
Meals and kitchen	1.26 ± 1.85 (0.37 to 2.16)	0.02	0.63 ± 1.46 (−0.07 to 1.34)	0.17	−0.63 (−1.73 to 0.47)	−0.81 (−1.85 to 0.24)	0.27	0.38
Everyday tasks	1.11 ± 1.76 (0.26 to 1.95)	0.02	0.53 ± 1.95 (−0.42 to 1.47)	0.3	−0.58 (−1.80 to 0.65)	−0.60 (−1.72 to 0.53)	0.46	0.31
Television and radio	0.80 ± 1.27 (0.18 to 1.40)	0.03	0.16 ± 1.80 (−0.71 to 1.03)	0.71	−0.63 (−1.66 to 0.40)	−0.89 (−1.79 to 0.05)	0.16	0.41

Values are mean ± SD or as otherwise indicated; *n*: number of patients; sec: seconds; CRT: Coin Rotation Task; 9HPT: Nine Hole Peg Test; AFT: Arm Function Training; CAHAI: Chedoke Arm and Hand Activity Inventory; Dexterity Q: Dexterity questionnaire; [¶]*n*=18 (One patient could not perform the CRT on the right side due to severe dexterous difficulties); [†]*p*-value change baseline to program end Dexterity training group; [‡]*p*-value change baseline to program end Theraband training group; **p*-value change baseline to program end Dexterity training vs. Theraband training group; *d*: Cohen's *d*. Adjusted Group Difference Dexterity – Theraband: This is the difference in the change of the outcome measure between both groups (Dexterity – Theraband group) controlled for the baseline value of the corresponding outcome measure.

Figure 5: "Table 3" mentioned in the article and the above paragraph (Kamm, 2015).

Another program of interest is Rehab-let. The results of this program are not available but the strategy and methodology is there. It is a touchscreen tablet helping self-train against impaired dexterity post stroke. For the most part, stroke rehabilitation methods do not achieve the required intensity to be effective. Touchscreen tablet technology may be used as a motivating tool for self-training impaired dexterity of the weaker upper extremity post stroke. A self-training protocol utilizing the Apple iPad touchscreen tablet with a variety of game-like apps will be used. Apps that encourage finger movement, could be motivating for adults, are not restricted in time and are not too fast will be used (Rand, 2015).

The primary outcome measure is improved dexterity, which will be assessed by The Nine Hole Peg Test (NHPT). This test is a valid and reliable test to assess dexterity in individuals with stroke and the time to insert and remove 9 pegs is measured. The following secondary outcome measures will be used; grip and pinch strength will be assessed by the Jamar and pinch dynamometer. The Fugl-Meyer Motor Assessment will assess the motor impairment of the upper extremity. The Action Research Arm Test will assess the functional ability of the upper extremity by grasping and moving objects of different size and weight. The Visual Analogue Scale, which quantifies the perceived level of pain intensity on a scale of 0–10 cm, will also be used. Self-training time will be used to assess adherence to the self-training protocol and will be taken from the daily logs. Satisfaction from the self-training program will be determined by a Satisfaction Questionnaire, developed for the study. The questionnaire will query the participant's satisfaction with the self-training intervention and his or her perceived benefit of the intervention to improve upper extremity's function. Responses will be rated on a scale of 1–5. The System Usability Scale will be filled in by individuals in the Rehab-let group – to assess their subjective usability of the tablet for rehabilitation. Each of the 10 items is rated on a 5-point scale from 1 (disagree totally) to 5 (agree totally), an overall score is calculated ranging from 10 (low usability) to 100 (high usability) points. Demographic and stroke characteristics will also be collected at baseline as well as information regarding prior tablet experience. In addition, independence in basic activities of daily living of this population will be characterized using the Functional Independence Measure (Rand, 2015).

The findings of this program will help design a fully powered randomized controlled trial (RCT) to determine the effectiveness of Rehab-let for improving impaired dexterity of the weaker upper extremity post stroke. Furthermore, it will help determine the profile of individuals who can benefit from this protocol and provide guidelines for developing apps that are tailored for people with strokes (Rand, 2015).

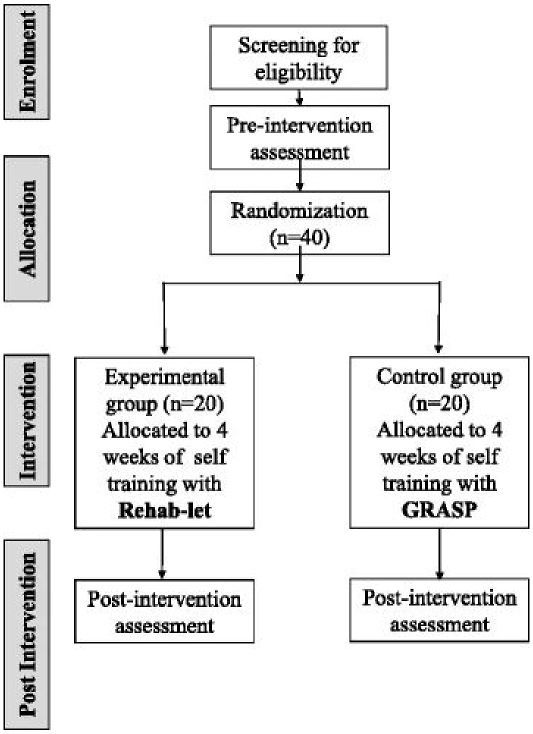


Figure 6: Overview of Rehab-let Program (Rand, 2015).

2.3 Innovation Programs

2.3.1 Internationally

Creating assistive technologies has been a societal norm for many years. The Dutch people were among the pioneers in developing assistive technology for disabled people. In the absence of today's impressive sensors and processing units, the Dutch developed lifts on staircases to ferry people who can not traverse the stairs on their own. The Dutch even overhauled their urban design standards to accommodate people with disabilities. An example of this is how they raise their floor blocks to meet the levels of their homes, allowing for easier access for disabled people. In modern times, the Dutch emphasize quality in all of their assistive technology devices. For instance, each municipality possesses a “senior council” that speaks for the needs of the elderly population and even labels products and technology as “senior friendly.” As most seniors have movement impairments, among other disabilities, these products can also be used by younger people with disabilities. This ensures that assistive technology producers are creating quality products and Dutch citizens can be aware of what fits their needs best.

As one of the fastest-growing technology leaders in the world, Israel's Innovation Authority possesses a research and development program that encourages research "in industrial products that provide technological solutions for the disabled to enable them to integrate into society and the labor market." Companies and nonprofits can have upwards of 85% of their budget funded (up to 900,000 NIS or $262,048.94 USD over 12 months) for developing an active technology device. The Israeli Innovation Authority supports these projects at a higher rate and supports such products as touch-free devices, a mountain climbing wheelchair, and robotic skeletons to help disabled people live normal lives. By providing government funding, Israel is actively creating a culture that not only wants to assist the disabled but promotes understanding and empathy for these individuals. Other governments can use this model as a way of assisting and providing for the disabled population.

The World Health Organization (WHO), a collection of medical experts from around the world, seeks to promote cooperation on assistive technology research to "improve access to [them] as a part of Universal Health Coverage." Recognizing only about 10% of people who need assistive technology devices currently have access to them, WHO developed the Global Cooperation on Assistive Technology (GATE) program in 2013. WHO expects that more than 1 billion people need one or more assistive products, with that number ballooning to 2 billion by 2050. In the GATE program, WHO creates a user-centric approach that provides tools and guidance for creating assistive technology programs in countries. The GATE program also provides a list of at least 50 assistive technology products, such as hearing aids, wheelchairs, atrichia limbs, and memory aids, that are selected based on the need for them globally and the impact these assistive technology devices have on people's lives. These lists have been adopted by Tajikistan and Nepal for use. GATE provides additional servicing and provision guidance in the form of e-modules that were piloted by Bangalore in 2018. The GATE program is an excellent initiative to bring assistive technologies to developing countries. This will raise the standard of life in these countries and provide a better, healthier life for their citizens, as well as continuing to foster a culture of understanding and acceptance for people with disabilities.

2.3.2 Domestically

In the United States, there are many individual states that take the initiative for providing assistance to the disabled. Two examples of these states are Massachusetts and Kentucky. These are geographically and culturally different states with different populations. However, both states do a significant amount for their respective disabled communities. In Massachusetts, the Massachusetts Rehabilitation Commission uses regional vendors to provide assistive technology devices to financially-struggling disabled people. While these people may have to wait on a wait list, Massachusetts still takes steps to provide for the disabled community, especially those with financial hardships. Kentucky, on the other hand, has state laws that govern the service and provision of assistive technology devices to ensure that the devices are safe and installed correctly. Kentucky also has the Kentucky Assistive Technology Services Network to connect and provide people with assistive technology devices and providers, as well as the Kentucky Assistive Technology Loan program (privately and publicly funded) to help people acquire assistive technologies. These two states serve as excellent examples of states with very different backgrounds and cultures that can provide for the disabled community. All states can model their own programs off of what other states like Massachusetts and Kentucky did.

Education and technical acumen is a key component of any assistive technology provider. The best way to get this is through experience at a place of higher education. There are several American colleges that offer education in assistive technology development. One college is George Mason University in Virginia. George Mason University offers an undergraduate, masters, and doctorate education in assistive technologies. This program was "designed to develop professionals who can effectively implement, assess, and research applications of Assistive Technology (AT) devices and services that provide greater independence for those with disabilities." These courses are also offered entirely online, so they are fully accessible to anyone who wants to become educated in the field. Another college that provides a graduate level certificate in assistive technology is the University of Illinois-Chicago. The goal of this certificate is to, "learn how to analyze a person's interaction with their environment, help them select effective technology, and support their use of tools through implementation and follow-up training." While this education is available only to graduate students, it is also entirely online. These two schools are pioneers in the assistive technology education field and other schools can look to these colleges for examples on how to design their own programs to create the next generation of assistive technology providers.

There are also several American organizations that provide grants to companies or organizations trying to develop or acquire assistive technologies. These organizations include the Janki Saye Foundation, the National Deaf Children Society, and The Aidis Trust. The Administration for Community Living (ACL) in the United States Government sponsors two grants as well. One grant is the State Grant for Assistive Technology Program, which is awarded to states in an amount that is based upon that state's population. The goal of this grant is to "support state efforts to improve the provision of assistive technology to individuals with disabilities of all ages through comprehensive, statewide programs that are consumer-responsive." The ACL also sponsors a competitive grant for individuals, service providers, states, protection and advocacy entities, and others to support and improve the implementation of the Assistive Technology Act of 2004. This program, called the Assistive Technology National Activities Program, is designed to award money to the best idea or service that can be offered to help disabled people.

2.4 Puffin Innovations

Puffin Innovations is an assistive technology startup that develops solutions for people with disabilities to be more independent. Their flagship product, the Puffin, is a wireless mouth-operated input device that can interface with smart devices (Puffin Innovations, 2020).

2.4.1 History

Creator of the Puffin and Founder and CEO of Puffin Innovations, Adriana Mallozzi, has made it her goal to use assistive technology to empower people with disabilities (Ability Tools, 2018). At a young age, Adriana was diagnosed with cerebral palsy, and by the time she was seven, she had been introduced to computers. The ability to use a computer on her own gave her a newfound freedom, the ability to do something on her own (Anderson, 2019). Now, she is on a mission to make technology more accessible, thus allowing people with disabilities to become more independent through smart technology.

As an accessibility solution, Adriana had come up with the Puffin, whose key features are portability, wireless connectivity, and affordability. Portability allows a user to use the Puffin anywhere, without being tethered to a power source. Wireless connectivity allows a user to connect to any of their Bluetooth-enabled devices on their own. Most importantly, the Puffin must be affordable, reducing the financial barrier to independence.

In 2015, Adriana Mallozzi had the opportunity to compete in the MIT Assistive Technology Hackathon (Not Impossible, 2019). At the hackathon, she was paired with students who were tasked with creating an assistive technology solution that would help her in her daily life (El Dandachi, 2020). Adriana was finally able to bring her idea to fruition. With the help of four students — Ned Burnell, a doctoral student in mechanical engineering; Esther Jang, a graduate student in electrical engineering and computer science; Shirlene Liew, a graduate student in systems design and management; and Kate Tatar, an undergraduate student in mechanical engineering — the first prototype of the Puffin was built in the form of a sip-and-puff joystick. The Puffin won the 2015 MIT Hackathon (Sampson, 2015).

Figure 7: The team working on the Puffin at the 2015 MIT Hackathon (ATHack, 2015)

Since then, Adriana has founded Puffin Innovations, a free-flowing company where people come in and out and continue working on the device. One goal of the Puffin is to be able to adapt to future technologies like smart cities and cars. This allows for a new level of freedom for people with disabilities (Not Impossible, 2019).

Now it is our turn to improve upon the Puffin. Our goal is to transform the Puffin from a prototype device to a production device.

2.4.2 Device Concept

The Puffin is a battery-powered, Bluetooth-enabled joystick controller featuring both a physical button and an optical button. It can be charged using Micro USB-B, and includes LEDs to indicate battery life and Bluetooth status. In addition to the lights, there is also a small speaker for auditory cues. In addition to this, the device has a power switch.

The joystick contains a PCB within a 3D printed housing and a protective sheath. The PCB has a physical button that can be triggered by biting the joystick, a joystick button which can be triggered by pushing toward the center of the joystick, and an optical button that can be triggered by hovering one's mouth over the photosensor. As seen in the photo below, the optical button consists of one LED and two photosensors. The purpose of the two photosensors is to measure the difference in light between them to trigger a click when one becomes covered. The purpose of the LED is to emit light when the device is in the dark, so the user can still trigger the optical button.

Figure 8:

(a) Top view of the Puffin (b) Joystick PCB

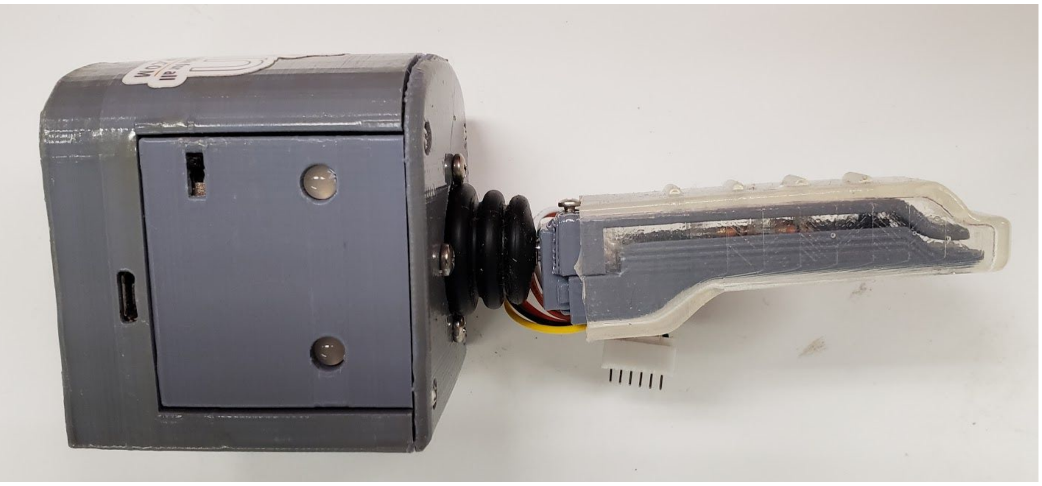


Figure 9: Side view of the Puffin showing switch, LEDs, and charging port

On the side of the chassis, there are 2 LEDs, one indicating battery level and one indicating Bluetooth mode, a power switch and a USB charging port.

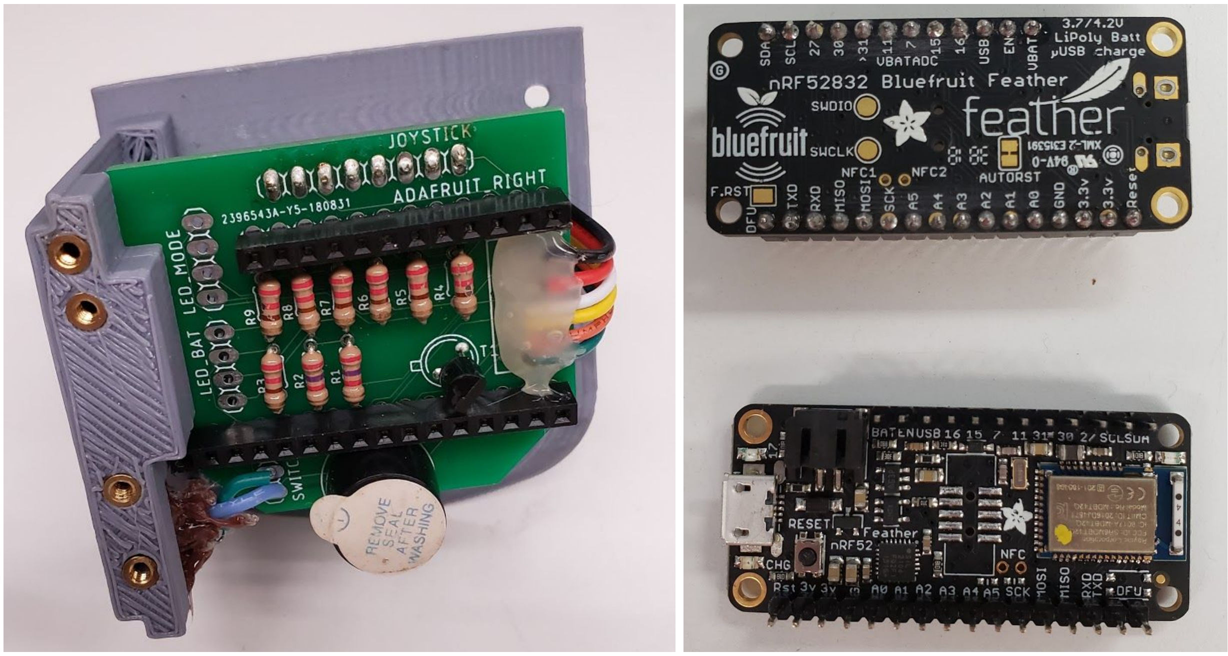


Figure 10:

(a) The main PCB (b) Adafruit Feather nRF52840

Inside the chassis, the Adafruit Feather connects to the main PCB. The main PCB acts as a hub for all of the I/O, including the joystick, LEDs, switch, and speaker.

2.4.3 Improvements Needed

One necessary improvement is to the optical button. There is currently a problem where fluorescent lighting can trigger the optical button. We plan to investigate the cause of this to determine if it needs to be fixed either in hardware or software. The optical button may also be reimplemented to be more robust.

Another improvement is to replace the Adafruit board with a Bluetooth-enabled board or a custom microprocessor/Bluetooth board that can be used in a commercial product. The Bluetooth module must be pre-certified for use in commercial products.

The battery and charging system must also be improved. The original power system is unreliable and results in damage to the Adafruit boards. This appears to be a problem with Adafruit boards.

Another improvement needed is the design of the chassis. The original design makes it very difficult to get to the battery in case it needs to be replaced. An improved design will offer easy access to the battery.

Finally, improvements will be made to the code that runs on the Adafruit. The original code lacks organization and documentation. The plan to improve this is to separate functionality into well documented classes. This will make the code easier to understand for future developers, and it will make it easier to implement new features in the future.

2.5 Interfacing

There is a large diversity of disability among users of assistive technology, even among those with the same type of injury or disease. Therefore, the design of a device interface must include flexible and varied options for inputs and outputs to serve a variety of users.

In order for a device to be useful and efficient, the input methods of the system must serve the limitations of the user, and the output methods of the system must serve both their limitations (e.g. simplified displays for the visually impaired) and their needs (e.g. controlling an electric wheelchair). Because people with spinal cord injuries represent Puffin’s target demographic for their device, the device should be designed around the following limitations: varying degrees of paralysis, diminished fine or gross motor control, spasticity, limitations of speech, and loss of the sensations of touch and temperature (Hagen, 2015).

2.5.1 Physical Devices

In order to adapt physical input methods to users with the aforementioned impairments, areas of the body where mobility is preserved should be used. Because spinal cord injuries usually preserve mobility above the neck, systems that rely on movement of the eyes, neck, or mouth are popular for assistive devices. Mouth-based controls in particular are a good choice for these systems because the lips, tongue, and cheeks of most people are capable of high-precision motion on multiple axes.

Among these mouth-based controls, joysticks and buttons offer flexible solutions for interfacing with a device. While both can be positioned in multiple ways to maximize comfort and usability, joysticks provide two or more axes of precise control for muscle groups with sufficient fine motor control (often the lips or tongue) while simple buttons and switches can be activated by a single muscle or simple movement. Stephen Hawking, whose degenerative disease (amyotrophic lateral sclerosis) was very high-profile, used an infrared switch which detected movement in a cheek muscle to move, talk, and use a computer (Godlewski, 2018).

In users with limited to full manual dexterity, joysticks and buttons are also excellent options for similar reasons. There are many ways to utilize the various muscle groups of the hands and arms for joystick control, and again buttons can be positioned anywhere a simple movement can be made.

Many more specialized controls exist for people with disabilities, especially for those with greatly diminished motor control above the neck. These include sip-and-puff tubes, eye and head trackers, and neural interfaces. These systems are often expensive and represent little utility to most users; this makes them impractical to ship with a more generalized device, but worthwhile to design devices for users to supply their own.

Input devices may also be used to passively collect metrics rather than acting as controls. Ambient noise and light may be recorded to adjust control sensitivity, and metrics such as body temperature and heart rate may be gathered for the benefit of a user monitoring their health.

2.5.2 Software

In addition to providing a variety of controls, a system can improve its interface through software. The role of software in a system's interface includes processing inputs, providing graphical displays, and maintaining configuration settings.

Processing raw inputs to a system can be quite trivial or highly complex. It may be desirable to prioritize some inputs over others due to a device's physical configuration, such as a button which should be ignored while a joystick is in use. Other ways to process inputs include applying acceleration to a virtual cursor, translating a set of movements to a particular selection in a GUI, and requiring button presses to exceed a minimum duration to prevent unintentional activation.

Applications such as web browsers and word processors often require inputs too precise for someone with diminished fine motor control to use, requiring the use of specialized interfaces for accessibility. These interfaces often use larger buttons, deeply nested menus, and error-tolerant features such as an “Are you sure?” dialog box (WebAIM, 2012). While very useful, these designs increase the amount of interaction required by the user, slowing down their use of some software significantly.

This trade-off between efficient interfaces requiring high precision and inefficient interfaces requiring low precision can be mitigated through the use of machine learning. A user’s errant movement from spasticity and tremors can be subtracted from a joystick, effectively augmenting a user’s precision and reducing the need for a simplified interface (Mack, 2018). Additionally, predictive text and predictive menu selection can significantly speed up usage by reducing the amount of interaction required from the user (Bridle and McCreath, 2005). By implementing both precision-augmenting and interaction-reducing algorithms, motion-impaired users can interface with technology faster, with fewer errors, and with less fatigue.

2.6 Controller Circuitry

Puffin Innovations had developed a prototype of the Puffin device utilizing an Adafruit Feather nRF52840 microcontroller. To move the device closer to the production stage, the team identified options to replace the single-board microcontroller with a single-chip microcontroller and Bluetooth system on a chip (SoC). The firmware of the Puffin device had been developed based on the Adafruit microcontroller and an Arduino integrated development environment (IDE). Utilizing the same microcontrollers which are used to develop single-board microcontrollers, such as the Arduino Uno, allows for the transition to the prototype of the production-level device to be simpler in terms of hardware and software development.

The original prototype of the Puffin is built around an Adafruit microcontroller. The microcontroller used in the prototype in Figure x receives input from the joystick, part 67B-JA-3C-S-P, to control the x-y position of the pointer by using magnets and its Hall Effect sensor to detect movement. The Hall Effect is known as a phenomenon where voltage is perpendicular to the magnetic field and flowing current when the current through the conductor is exposed to a magnetic field. The sensor detects the strength of the magnetic field relative to the movement of the joystick and outputs an amplified voltage measurement. This data is then outputted using I2C.

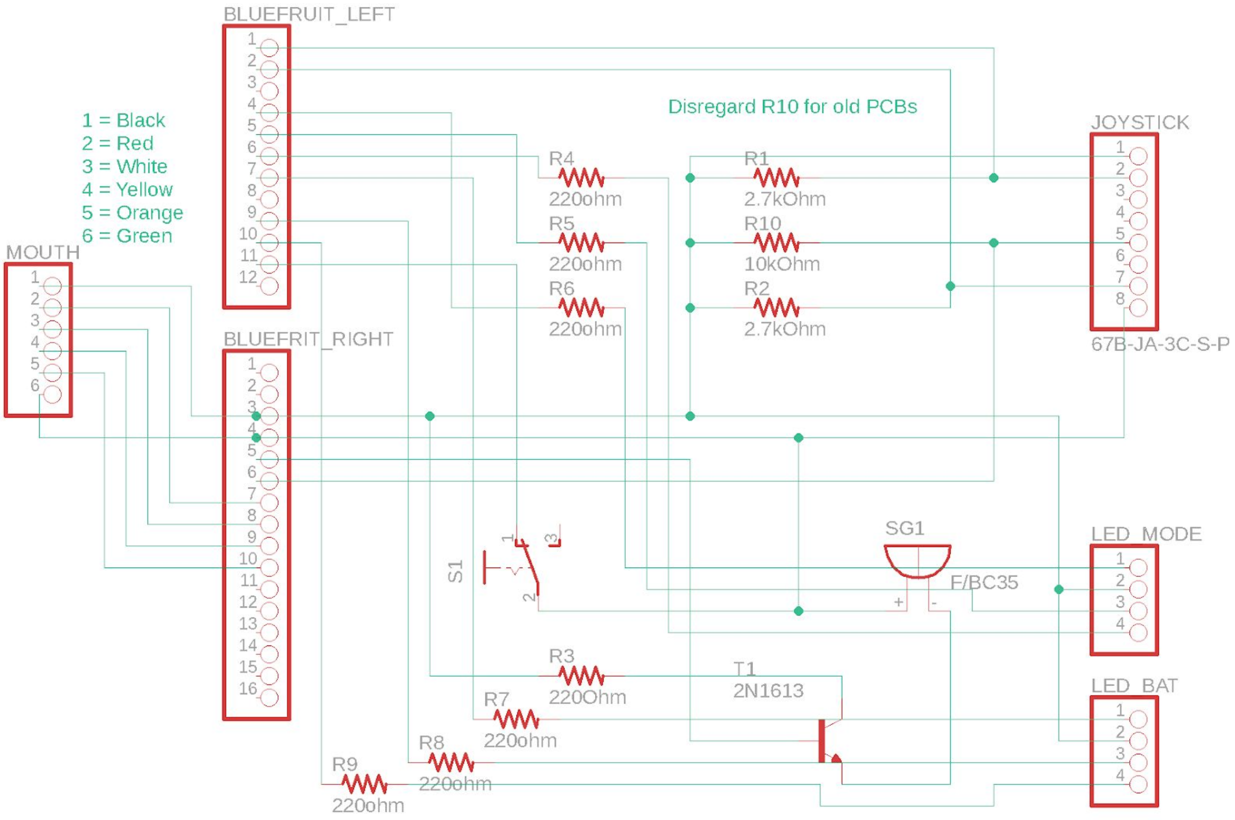


Figure 11: Schematic of AdaFruit Puffin Device Housing connections

The 67B joystick is an I2C slave and utilizes its pins for supply voltage, ground, and I2C interface pins including SCL (I2C clock line), SDA (I2C data line), and the push-button (active when low). Pins 2 and 7 are the SCL and SDA signals which utilize 2.7kΩ resistors as pull-up resistors. These values were chosen based on the datasheet of the manufacturer to maintain a 100kHz SCL Standard mode. A pull-up system allows the microcontroller to recognize a change in the x-y position by recognizing the change from a high voltage level to a low voltage level and constantly sampling the data based on SCL.

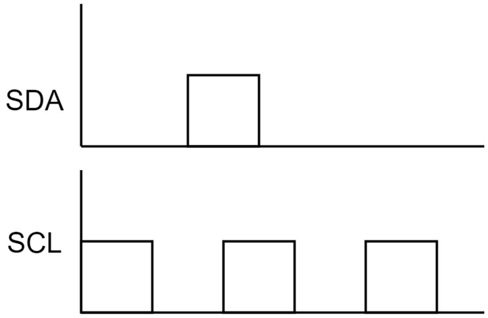


Figure 12: I2C Communication SCL and SDA Signals

When the SCL is high and the SDA switches from high to low, transmission of data starts as the SDA reads or writes data to the microcontroller. Transmission of data ends when the SDA switches from its low state to high while the SCL is high. The joystick uses bytes to determine the x-y position of the joystick as well as when to start and stop transmitting data.

The circuit also includes a status buzzer. This is operated using a BJT to drive current through the load and force it to sound. The analog pin on the microcontroller turns on the BJT to drive current from 3.3V to ground (GND) through the load.

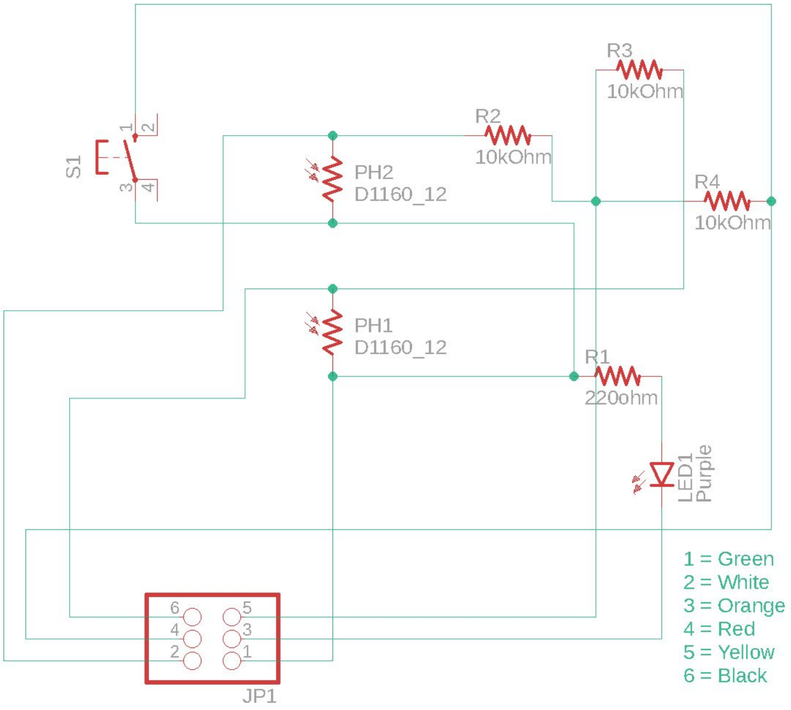


Figure 13: Schematic of Joystick PCB

In Figure x, the circuitry shows the connections in the tip of the Puffin. R2, R3, and R4 are present as to not short any of the connector pins together when the photoresistors are detecting maximum light and act as a short. However, when the photoresistors detect low light, their resistances increase to become a resistor with a large value. The voltage between the photoresistor and the subsequent resistor is then used as an input for the tip to detect activation.

The two photoresistors, PH1 and PH2, form two different voltage dividers, modeled in Figure x. The voltage found between PH2 and R2 is used as one reference value. It is found as some fraction of the source voltage as shown in the following equation:

$$V = IR = \frac{V(R)}{(R+PH)}$$

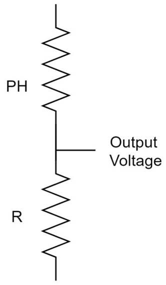


Figure 14: Voltage-divider concept

This value is then compared to the voltage between PH1 and R3, a second reference value. If the voltage between PH1 and R3 is 10% of the value of PH2 and R2, the Puffin can detect if the tip button, S1, is pressed to execute a command.

The production-level device required a system with a low-powered, low-cost microcontroller, Bluetooth module, and a USB to serial converter. The circuitry must be translated over using production-level components.

2.7 Summary

In order to invent new and more advanced assistive technologies, one must understand dexterity impairments and the modern assistive devices used to help people with disabilities become more independent. Through an innovation program at MIT, Puffin Innovations' CEO and founder, Adriana Mallozzi, was able to create the Puffin; however, significant improvements are needed in order to bring the Puffin to production. The company plans to redesign the hardware to create a more stable, durable, and effective device. By working closely with the company, investigating mouth-based controls and processing softwares, and implementing a new microcontroller, we can deliver a mass-producible Puffin for Puffin Innovations.

3. Methodology

3.1 Client Statements

3.2 Design Objectives and Constraints

3.3 General Architecture

3.3.1 Input Hardware

3.3.2 Microcontroller

System Requirements

Based on the inputs, outputs, and software of the Puffin, the requirements for the microcontroller can be determined to narrow down which microcontrollers are viable for use. The requirements for our system are listed below.

Puffin Component	MCU Hardware	Minimum Requirement
Physical Button, Battery LED, Bluetooth LED, Buzzer, Optical Button, Joystick	Digital I/O Pins	11
Optical Button	Analog I/O Pins	2
Joystick	I2C	1
BlueNRG-2	SPI	1
	Digital	
Original Puffin Firmware	Flash Memory	70 kB
	SRAM	>6 kB

3.3.3 Software Architecture

3.3.4 Output Hardware

3.3.5 Bluetooth

3.3.6 Mobile Application

3.3.7 Power

3.4 Summary

4. Implementation and Results

5. Discussion

6. Conclusion

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Appendix A