Overview

Maximum word count (Sections 2 and 3) – 4,300

Required Citations – 3-10

Submit technical drawings/specs/storyboard/animation/simulation/video

Submit a Gantt chart of activity for Finalist Entry prep

Submit a **detailed** budget for use of the Discovery Award

Provide team member biographies (no more than 5)

Section 2 - Idea

Title of your idea:

The Co-Chair. A collaborative navigation, steering, and fitness assistant for powered wheelchair users.

Summary: Provide a summary of your idea and the problem(s) it is addressing (150 words)

The Co-Chair is an interactive “plug and play” add-on for any powered wheelchair that augments traditional controls by **collaborating with the user** to provide intelligent, semi-autonomous functionality.

The operation powered wheelchairs (PWC) require both manual and mental dexterity. The user must avoid curbs and drop-offs, important since nearly three-fourths of wheelchair-related injuries are caused by tips and falls, while also navigating terrain and avoiding collisions. The Co-Chair will increase the users physical and mental health by avoiding these accidents and reducing the cognitive load associated with operating a powered wheelchair.

This will be accomplished by combining low cost RGB-D “3D” cameras and an IMU near the joystick with a smartwatch to have knowledge of both the environment[1][2] and the user’s physiological state[3] so that inferences about the user intent can be lead to **contextually aware** decisions allowing the Co-Chair to adaptively update the amount of shared control with the user.

How will your idea incorporate intelligent systems in a new or innovative way to support and deliver radical improvement in the personal mobility and independence to the users with lower-limb paralysis? (300 words)

Mobile autonomous systems are quickly becoming a well-studied field of research, with great strides being made towards products such as self-driving cars. This means that state-of-the-art sensing techniques, object detection and avoidance, and optimal control can be quickly implemented to create an autonomous powered wheelchair[4] (see the attached video for an example!) . The true innovation of Co-Chair is the intelligent collaboration between the user and the autonomous system.

Co-Chair will have multiple modalities of intelligence. Since it will be aware of its environment, it will track objects such as a person moving across a room or down a sidewalk, and anticipate changes, such as expecting the individual to slow down when nearing the user. It will then use this contextual knowledge in conjunction with the current control inputs to infer the user’s intended action, whether that is to coast along a hallway, navigate through a doorway, or stop to talk to a friend.

Co-Chair will measure the physiological state of the user through its smartwatch, and use an intelligent algorithm to estimate factors such as user fatigue and the impact it has on focus [3]. Once it has this information, Co-Chair will be able to best determine the amount of **collaboration** between it and the user[5]. In other words, it will know how best to scale the amount of feedback and control overrides it performs in direct relation to how much it trusts the user's ability to safely and independently operate the chair.

At a higher level, Co-Chair will learn the daily schedule of the user, including common activities, their location, and common routes taken. This means that it can then anticipate these events and prompt the user to stay on time, especially if other actions are needed prior to the task, such as charging the power chair.

How will your idea potentially respond to the wants and needs of people with lower-limb paralysis in relation to their mobility and independence? What has been the role of co-creation in developing these insights? (300)

Many common activities of daily living (ADL) have been shown to be difficult for powered wheelchair users[6][7] . These include navigating complex environments, maneuvering through tight spaces, and docking the chair in transport vehicles. Yet at the same time, user surveys[8] have shown that a fully autonomous solution is not desirable because users want to maintain as much control of their mobility as possible. Co-Chair is a natural solution to this quandary, intelligently working with the user to aid in difficult ADLs while letting them remain in control as often as possible.

The same set of surveys also indicate that users prefer a low-cost solution (obviously!). Co-Chair is planned to be affordable by using low cost RGB-D cameras instead of traditional LIDAR sensors, as well as integrating with as many off-the-shelf smartwatches as possible.

Many of these insights come from direct communication with end users through team members at Max Mobility, a leading business in power add-ons for manual chairs. End-user feedback is a crucial role in the evolution of a product, and so must be considered at every step of the development process. The opinions of clinicians, therapists, and other rehabilitation professionals paramount of importance due to their expertise and unique experiences working with those of limited mobility. Many surveys and interviews are referenced in our design process for this purpose[6]–[10].

Explain who the potential users of your idea will be and how your idea's functionality will potentially deliver measurable, radical improvements in their mobility and independence? (300)

Ideally, we believe Co-Chair will improve the quality of life of all powered wheelchair users. The most notable increase in mobility and independence, though, will be in those users with further impairments to dexterity, cognition, or awareness. Co-Chair will compensate for these impairments to bring mobility improvements in many ways:

Improved Safety – By being aware and reacting to the user's environment, Co-Chair will reduce the number of accidents experienced by users. Situations such as tipping sideways off of a curve, falling off a ramp, or sideswiping a wall can easily be avoided.

Reduced Cognitive Load – By offloading the intricacies of steering and navigation to Co-Chair, tasks that may have once required most of the user's attention are now trivial. This lets the user spend less brain power *reacting* to the environment and more *interacting* with it. More conversations can be held while traveling…

Improved Mental Health – The reduction in cognitive load combined with semi-autonomous driving means that users can be more social and active, spending more time going out into the world, independently! This has a direct impact on the user's health, reducing depression and other co-morbidities.

Additionally, Co-Chair's utilization of smart-watch technology will bring the benefits of a fitness tracker to wheelchair users, with metrics and terminology tailored to this demographic[9]. This will allow users to be more aware of their physical health than ever before, encouraging healthy lifestyle habits.

Please upload drawings or technical specifications that explain how your idea works (Can include storyboards, animation, simulations, or video).

Have you considered what safety measures, standards, and ethical considerations are relevant to your idea and its development? (Yes/No then explanation, 300 words)

Yes

Safety – Basic, necessary fail-safes have been identified, such as stopping within a specified proximity to an obstacle or drop-off, reverting to full manual control in the case of a sensor malfunction, and an ever-present direct user override. Additional behavior is required to ensure a safe operating environment and minimize risk, such as alerting the user to perceived dangers and including appropriate responses to situations where an accident does occur. Further investigation into human factors will lead directly to a risk analysis to be presented in the Finalist application.

Standards – Co-Chair qualifies as a class one device by the FDA. As such, all relevant testing, documentation, and milestones for approval to market within the U.S. must be met. All relevant ISO Powered Wheelchair standards will be met to aid international. This includes, but is not limited to, weatherproofing that meets ISO 7176-9:2009, control specifications that meet ISO 7179-14:2008, and information disclosure methods that meet ISO 7176-15:1996. Several team members have extensive knowledge of standard's certification for medical devices through their work at Max Mobility.

Ethical - The largest ethical consideration is that this is a product that directly takes some portion of control away from the user. The responsibility of the user's well-being is then the direct responsibility of the product. All considerations must be made to ensure that an action of the product does not lead to the harm of the user or the restriction of their freedom. Additionally, the nature of this device means that personal information such as location, physiological metrics, and behavior are directly measured. All possible steps must be taken to ensure the user's privacy while still maintaining the ability to act on this information to improve the mobility and independence of the user.

Have you considered what the potential market for your idea is? (Yes/No then explanation, 300 words)

Yes

Long term, all powered wheelchair users will be the targets for our device. Near term, products will be marketed to powered wheelchair users with additional impairments to dexterity, cognition, or awareness/perception[10]. This demographic will have the most demonstrable justification of need for funding the purchase of Co-Chair. We plan to perform testing and trials to show that Co-Chair reduces the rate of injury of these users, and by extension the secondary costs of operating a powered wheelchair.

Provide a list of published articles or items from academic literature that support your entry, its feasibility, design, potential impact, and its innovative nature. (At least 3, no more than 10, 500 words)

[1] F. Endres, J. Hess, J. Sturm, D. Cremers, and W. Burgard, "3-D mapping with an rgb-d camera,"

Robot. IEEE Trans., vol. 30, no. 1, pp. 177–187, 2014.

[2] S. Kohlbrecher, O. Von Stryk, J. Meyer, and U. Klingauf, “A flexible and scalable SLAM system with full 3D motion estimation,” *9th IEEE Int. Symp. Safety, Secur. Rescue Robot. SSRR 2011*, pp. 155–160, 2011.

[3] D. McColl, A. Hong, N. Hatakeyama, G. Nejat, and B. Benhabib, “A Survey of Autonomous Human Affect Detection Methods for Social Robots Engaged in Natural HRI,” *J. Intell. Robot. Syst.*, vol. 82, no. 1, pp. 101–133, Apr. 2016.

[4] J. Leaman and H. M. La, “A Comprehensive Review of Smart Wheelchairs: Past, Present, and Future,” *IEEE Trans. Human-Machine Syst.*, vol. 47, no. 4, pp. 486–499, Aug. 2017.

[5] A. Erdogan and B. D. Argall, “The effect of robotic wheelchair control paradigm and interface on user performance, effort and preference: An experimental assessment,” *Rob. Auton. Syst.*, vol. 94, pp. 282–297, Aug. 2017.

[6] L. Fehr, W. E. Langbein, and S. B. Skaar, “Adequacy of power wheelchair control interfaces for persons with severe disabilities: a clinical survey.,” *J. Rehabil. Res. Dev.*, vol. 37, no. 3, pp. 353–60, 2000.

[7] C. Torkia *et al.*, “Power wheelchair driving challenges in the community: A users’ perspective,” *Disabil. Rehabil. Assist. Technol.*, vol. 10, no. 3, pp. 211–215, 2015.

[8] T. Padir, “Towards personalized smart wheelchairs: Lessons learned from discovery interviews,” *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS*, vol. 2015–Novem, pp. 5016–5019, 2015.

[9] P. Carrington, K. Chang, H. Mentis, and A. Hurst, “‘But, I don’t take steps,’” in *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility - ASSETS ’15*, 2015, no. To Appear, pp. 193–201.

[10] R. C. Simpson, E. F. LoPresti, and R. A. Cooper, “How many people would benefit from a smart wheelchair?,” *J. Rehabil. Res. Dev.*, vol. 45, no. 1, pp. 53–72, Dec. 2008.

Section 3 – Proposal

At what level of development is your idea currently and what is the TRL (Technology Readiness Level) rating of your idea? (0-9)

4

4- Basic technological components are integrated – Basic technological components are integrated to establish that the pieces will work together.

Why do you need a Discovery Award to continue its development as part of your entry for a Finalist Development Grant?

A competitive Finalist entry should include a well-done initial proof of concept (scale model) and feasibility analysis. In Co-Chair's case, this requires an accurate testbed in which to validate functionality. A powered wheelchair must be purchased and modified to create such a testbed. Additional high fidelity "Ground Truth" sensors such as a 3D LIDAR are required to evaluate Co-Chair's performance.

The primary team member for this entry is a graduate student at Vanderbilt University. No grant currently supports this work, meaning that the acquisition of capital assets is currently impossible. The Discovery Award will provide the funds to realize the development of our Finalist entry.

What is your plan for the development and submission of your entry for a Finalist Development Grant? (Your answer can include diagrams such as solid models, flow diagrams, and/or block diagrams)(1000)

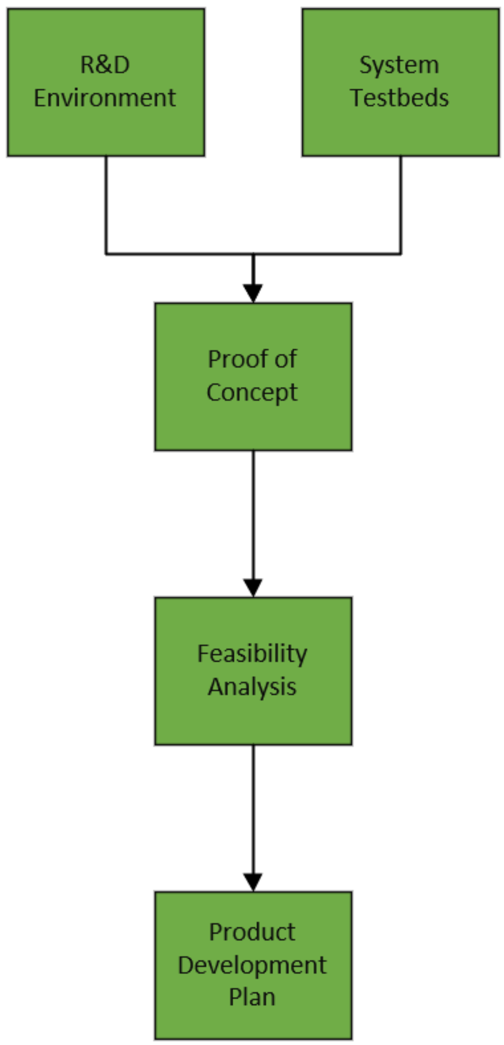

Figure 1 Discovery Development Plan

Our Finalist entry must meet a minimum standard of quality. It must accurately demonstrate not only the thought and consideration put into Co-Chair, but that we have the expertise and capabilities to bring it to a receptive market. Our work starts with the acquisition and design of a sufficient research and development space while initial testbeds for individual systems and capabilities are conducted. Once these two steps have been completed, an initial working model to serve as a proof-of-concept can be fabricated. This model will then be the basis for building an initial feasibility analysis for the Finalist entry, the results of which will be used to present our Finalist entry's Product Development Plan.

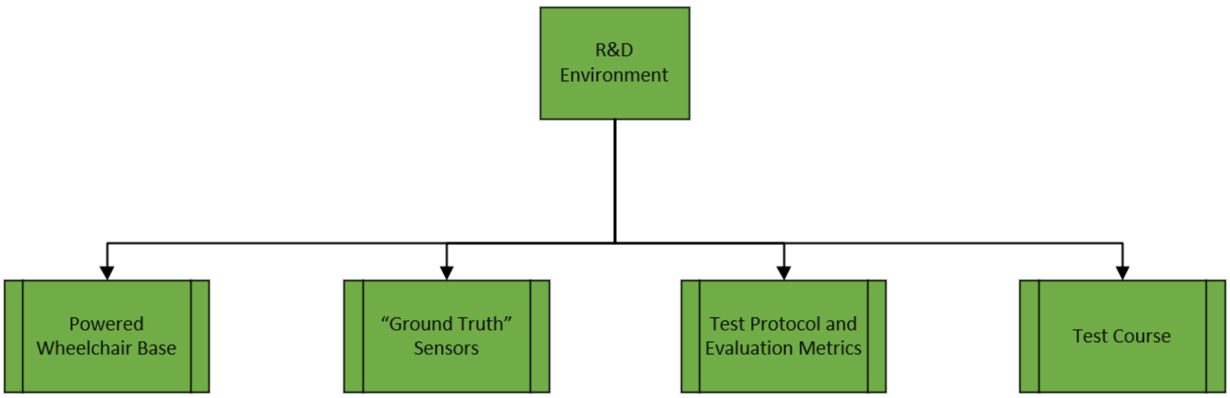

Figure 2 Research and Development Enviroment

We want to hit the road running, and to do so we need a great R&D environment to work in. This will be our priority and will include the acquisition of assets such as a powered wheelchair and relevant "Ground Truth" sensors, and the construction of a realistic obstacle course and the testing protocols necessary to ensure we get the most value out of our work. A powered wheelchair will serve as the core to our development, allowing us to have a real-world controllable mobile platform for systems testing and serve as the target platform for our initial proof of concept. To measure the performance of our tests, accurate position and tracking must happen. To do this, we will use a suite of sensors external to our test platform to serve as an absolute "Ground Truth" to compare against. A high-end 3D Laser positioning system, known as LIDAR, will be mounted onto our test platform to serve as an independent system for simultaneous localization and mapping (SLAM). External to the test platform itself, an overhead camera system will be used to track the mobile platform within the environment. A modest test course will be constructed containing obstacles commonly encountered in daily life, such as walls, a small ramp, curbs, and drop-offs. It is then of utmost importance to then develop a rigorous set of testing protocols and evaluation metrics to easily measure the viability of our designs. We want to show as clearly as possible that our new, low-cost RGB-D mapping system achieves functional parity with the higher fidelity and more expensive ground truth sensors.

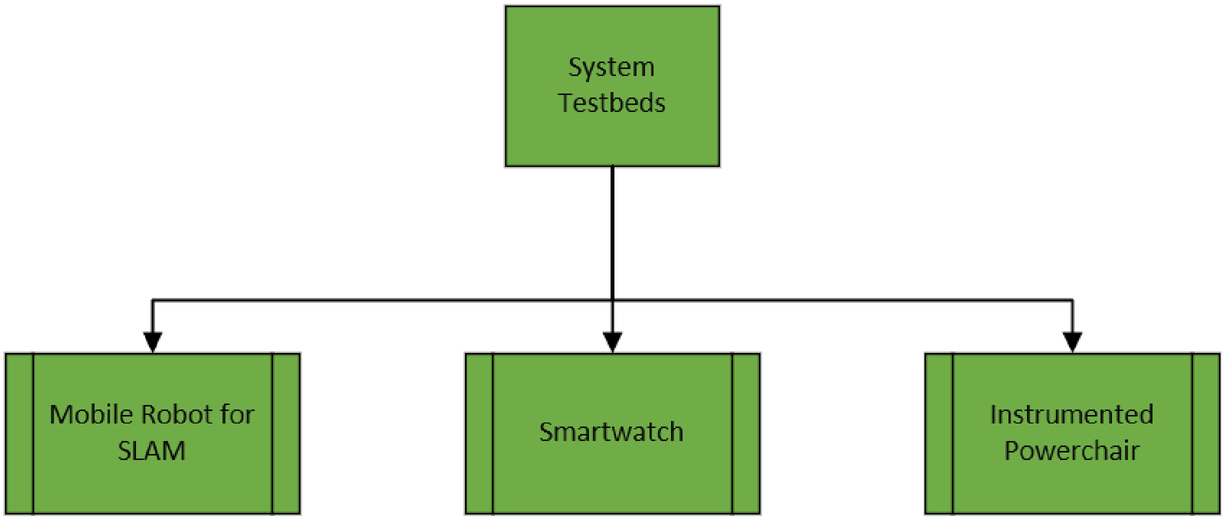

Figure 3 System Testbeds

Concurrent with the R&D environment evolution is the construction of preliminary testbeds for each separate subsystem. A small mobile robot as depicted in “SLAM-Platform.png” will be used in developing our vision-based SLAM algorithms for environmental mapping. This smaller unit will provide quicker turnaround, implementation, and testing than if we went straight to working on powered wheelchair development. Alongside this mobile platform will be application development for a smartwatch. This will include preliminary implementations of our fitness tracking functionality, algorithms for determining user focus, and recognition and tracking of daily activities and locations for the user. Finally, an instrumented power wheelchair will be used for data gathering on typical usage by users, user interactions with the environment, and preliminary intent recognition algorithms.

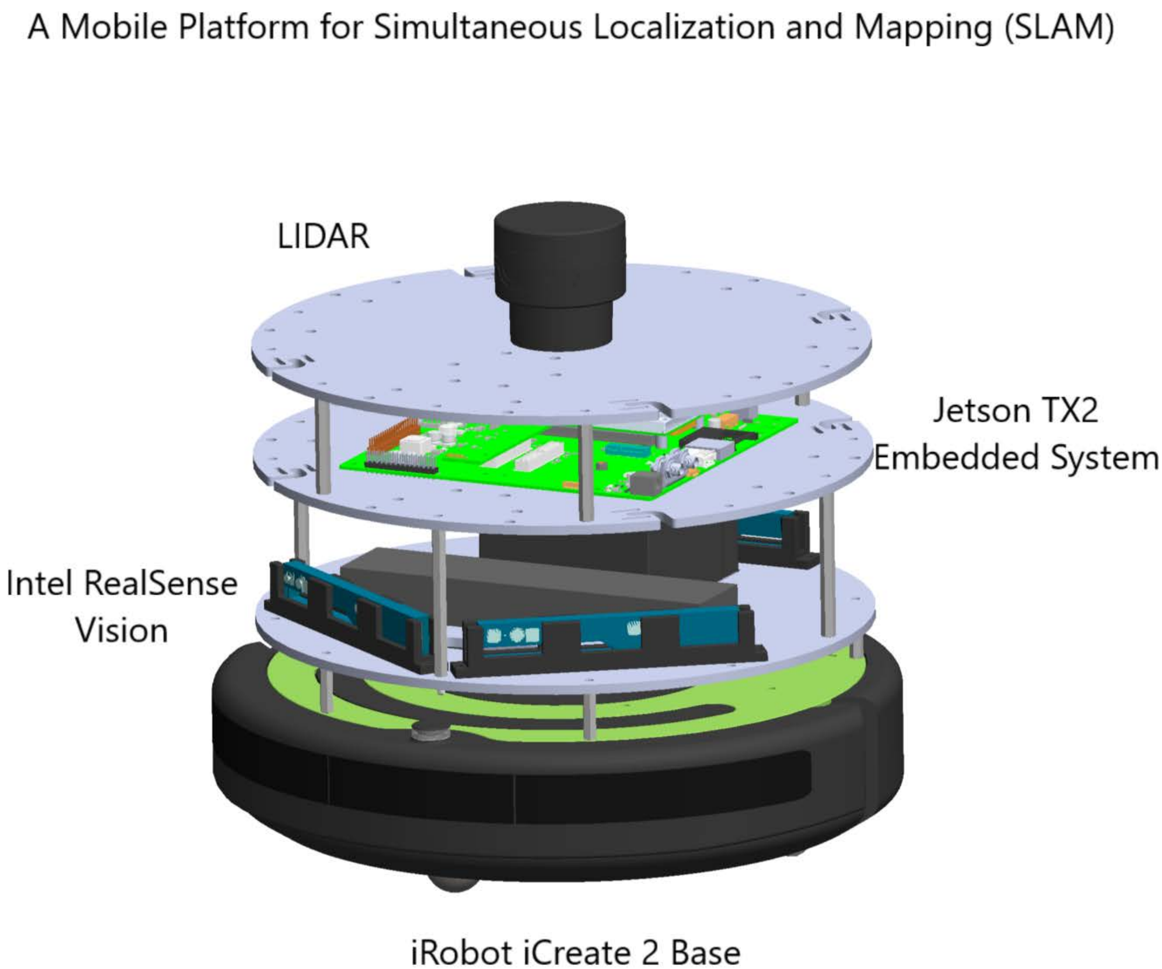

Figure 4 SLAM-Platform

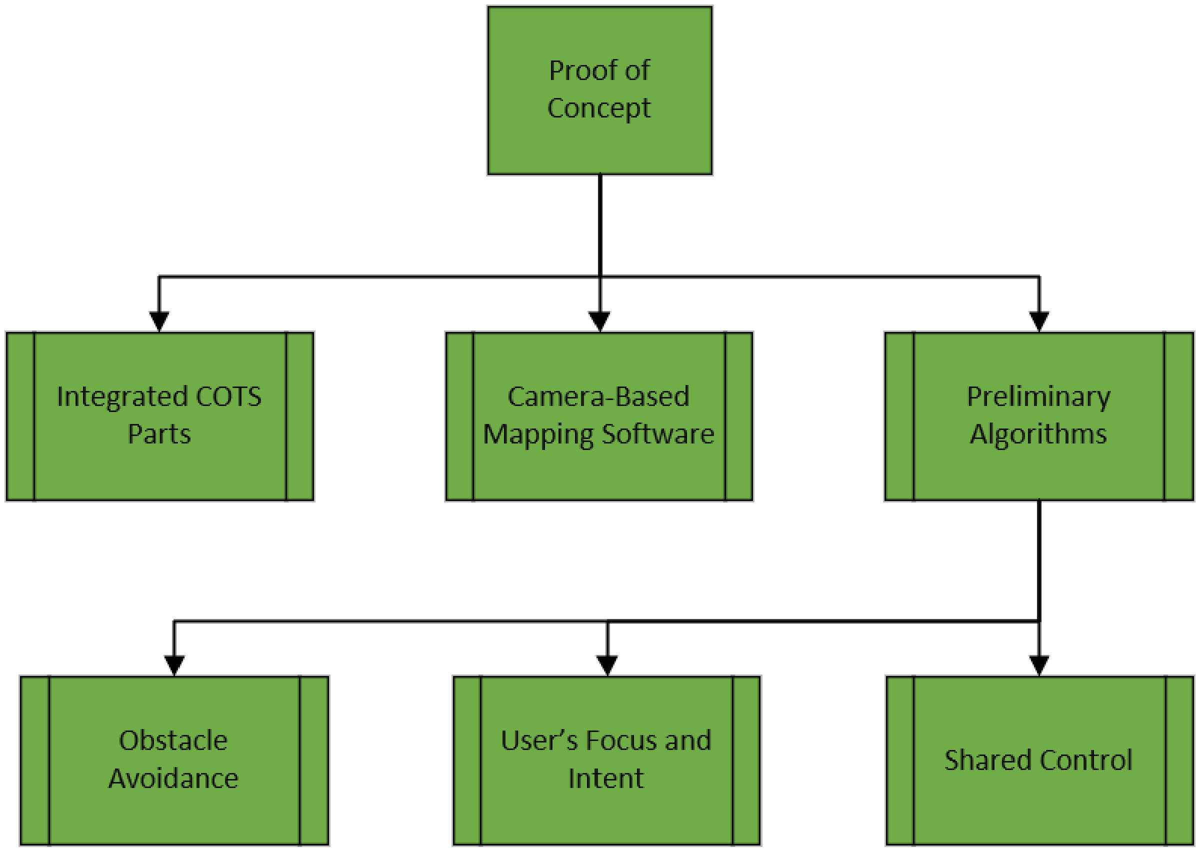

Figure 5 Proof of Concept

After these two steps have been met, work can be made to integrate each subsystem to produce a prototype working model of Co-Chair. This initial working model will be based purely on commercial off-the-shelf (COTS) parts integrated with custom software. The real demonstration at this point is the ability to use pre-existing technology along with our novel intelligent software and algorithms to prove the viability of Co-Chair. This software component of this working model is split into two main components: the camera-based SLAM software and the suite of algorithms used for obstacle avoidance, determination of the user's focus and intent, and how best to share control of the system between the user and Co-Chair.

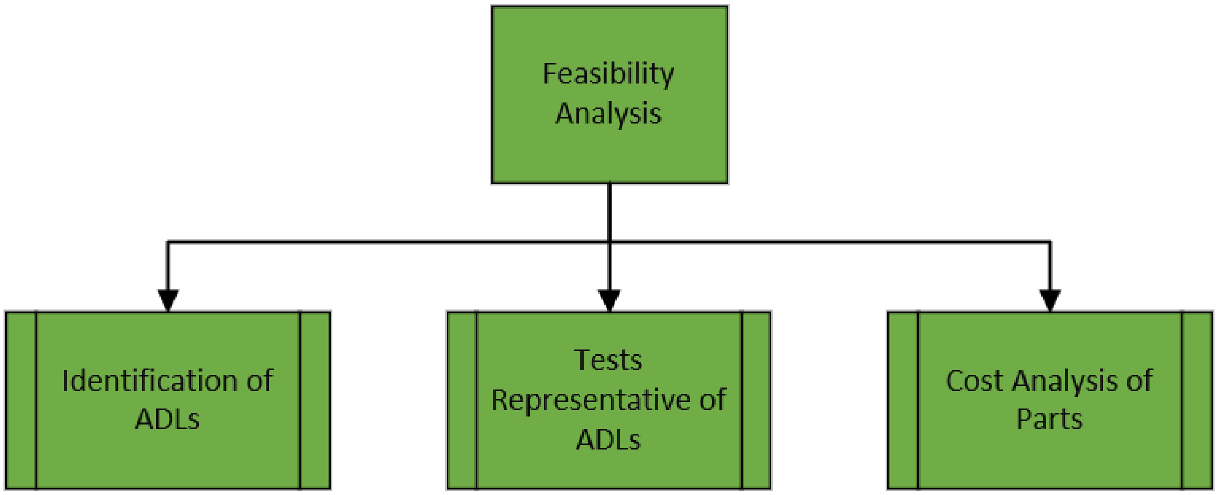

Figure 6 Feasibility Analysis

The availability of a working model then means that a multitude of tests can be performed to generate a preliminary feasibility report. First, common Activities of Daily Living (ADL) will be identified that are relevant to Co-Chair. Using the testing protocols and metrics developed as part of the R&D environment, tests will be generated for each of these ADLs to measure the impact of Co-Chair. Independent of this, team members will generate cost reports for both the as-built prototype using COTS products and our planned final product consisting of custom, integrated parts. This information will allow us to gauge the current standing of Co-Chair and leads directly to the development plan we will present as part of our Finalist entry.

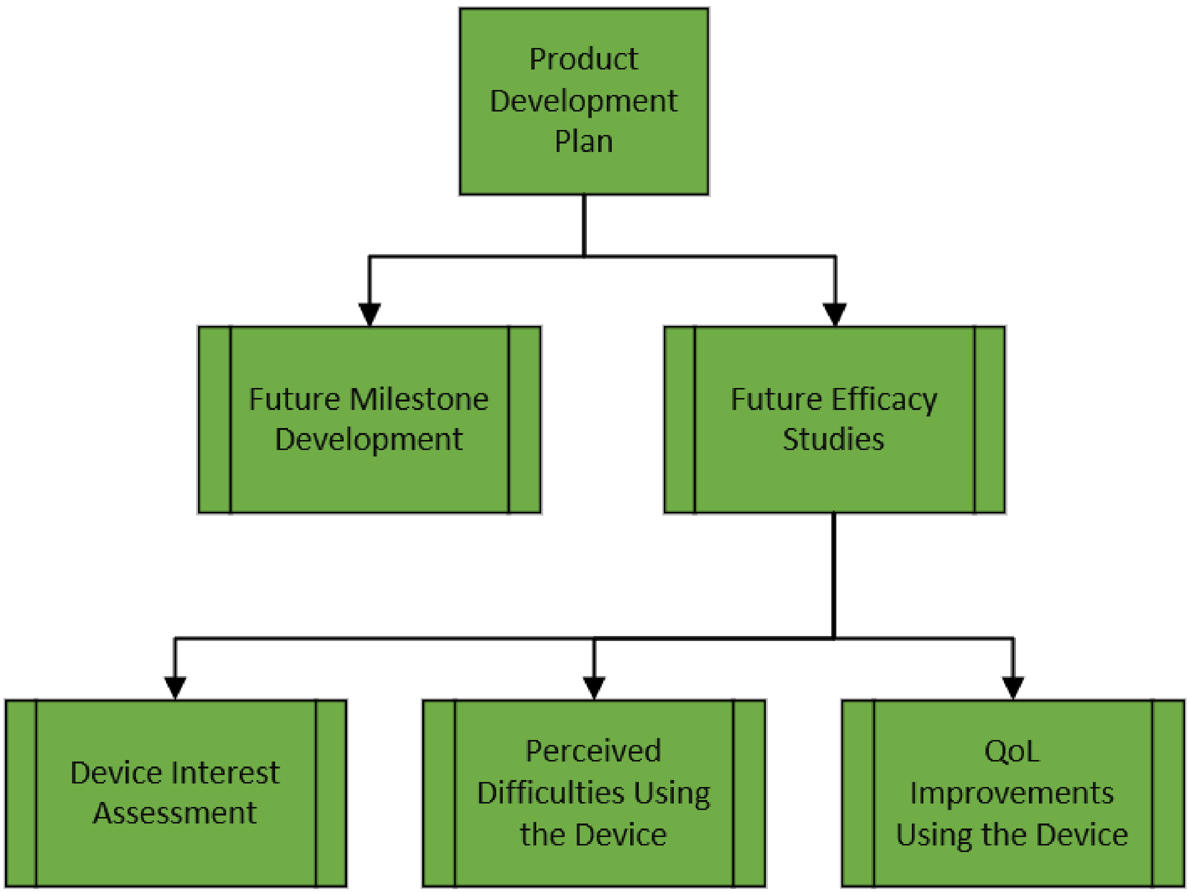

Figure 7 Finalist Development Plan

The Finalist product development plan will detail specific milestones and deadlines for both product design and function, and potential users and market. Each milestone will be backed up by efficacy studies that will be developed as part of the Finalist application. These will include device interest assessments, perceived difficulties using the device, and quality of life improvements due to the device. All of these assessments will be done with direct interaction with end-users through the design of trials, demos, and end-user interviews.

Upload a PDF version of your Gantt chart for activity to be conducted between the receipt of the Discovery Award and the submission of your entry for a Finalist Development Grant.

Has

Upload your budget setting out how you will use the Discovery Award. Include other sources of funding, budget justifications, and accounting practices. If relevant, the in-direct rate should not exceed 25%.

Has

What resources will you require to develop and submit your entry for a Finalist Development Grant and how will you secure them? (For example, team members, partners, expertise, space, equipment, software, etc.) (500)

The primary requirement for semi-autonomous control systems for powered wheelchairs (PWC) is that they work under a multitude of environmental conditions and that if they fail it is in a safe manner that falls back to full-manual control. As such, the primary resource that needs to be developed is the testbed environment for which we must test all the edge conditions in lighting, sensor obstruction, sensor / computation / communications failure, material interactions, kinematics, and obstacle configurations. Such a robust testbed requires enough space for full systems-integration testing as well as multiple channels of data capture from both the chair system as well as externally to the chair to be able to investigate any potential performance or behavioral issues that may crop up while testing. Such a test environment would require multiple, movable obstacles of differing materials, multiple PWC bases, a remote sensing / motion capture system, and be large enough to accommodate iterative test sequencing.

We plan to utilize the existing space we have at Vanderbilt University and our affiliated company Max Mobility for initial testing and integration. We will make use of the various terrain of the university at large and the office spaces at Max Mobility for performance tests of our prototype system. The necessary equipment and instrumentation will be purchased using the Discovery grant.

Alongside the required testing infrastructure is an associated expertise that must be developed and expanded. By consulting with industry specialists at Max Mobility, LLC. and Permobil Inc., we can leverage their decades of experience in the PWC industry to expedite bringing our product to market and performing market analyses and forecasts for the expected user-base and sales of the Co-Chair.

From a software standpoint, we will be building upon the open-source community's work and contributing back to the open source community as much as we can through the development of our project. However, there are certain licenses that we must pay to integrate with existing systems, such as the standard CAN protocols found on many PWC (i.e. R-net) as well as other proprietary control interfaces, especially related to powered seating controls. Acquiring licenses for these may be required depending on whether the existing licenses held by our affiliated companies can cover this development and use.

What activities do you plan to carry out using the Discovery Award? Explain why these will be essential to developing and submitting your entry for a Finalist Development Grant and why you would not be able to complete them without an award. (1000)

As stated in earlier answers, the development of a high-fidelity research environment and testbeds with which we can perform meaningful, repeatable tests is of utmost importance. The data we collect from these initial tests serve as both a driving factor for refinement of our design idea and as a clear demonstration that we have the technical capabilities to bring this idea to reality. Without these assets and testbeds, we would not have the ability to produce a competitive Finalist application. While the rest of our Finalist entry development plan can be completed without further financial assistance, a quick look at our activity Gantt chart shows that all other tasks rely on the completion of these initial testbeds.

With the Discovery Award, we will carry out the following activities:

Mobile Robot Testbed – An iRobot iCreate 2 robot base will be purchased and integrated with Intel RealSense cameras and a Velodyne LIDAR to create a small, portable, easy to use robot that implements state-of-the-art simultaneous localization and mapping (SLAM) algorithms. This lets us work on semi-autonomy and collision avoidance algorithms on a platform that poses no danger risks as it is 1) not large, 2) cannot move quickly, and 3) does not carry a person, yet can still interact with the environment and the user. This is a very quickly made device, as opposed to the acquisition of a powered chair and the development of a ground-truth testbed. The iCreate 2 also has much simpler kinematics than a PWC since it does not have to deal with heavy, high friction casters. This offloads the complexities related with PWC control until after we have base-line algorithms running for obstacle avoidance and user interaction.

Smartwatch Testbed – Multiple COTS smartwatches of various manufacture and capabilities will be purchased as the base for our fitness tracker, interaction, and schedule tracking software. This will be implemented as an application on the smartwatch, running on its native operating system. It is important to use multiple smartwatches as software testbeds because of the variety of such operating systems for smartwatches. An android or android wear-based watch will behave very differently than an Apple Watch – and along these lines we will need to evaluate the efficacy of the different sensor solutions on the smartwatches to determine the quality of their data streams, e.g. the IMU orientation filtering and the heart-rate monitoring. Along these lines, we will need to develop the software to accept multiple different types of sensor input and analyze the resultant fused data to determine the minimum sensing capabilities for the smartwatch and the minimum data quality that we can accept with respect to signal-to-noise ratio (SNR), accuracy, and precision.

Ground-Truth Position Tracking – High fidelity LIDAR sensors such as the Velodyne VLP-16 "Puck" will be used to provide accurate position updates and mapping. As stated earlier, the development of this system is vital so that we can compare the performance of our system that will use lower cost RGB-D "3D" cameras to achieve the same functionality.

Processing Board Integration – We will use the Jetson TX2 development board as the base for all non-smartwatch software development. All intelligent systems will reside here, including our mapping, obstacle avoidance, and user interaction algorithms. It will serve as the brains of our system for all testing and prototyping during the development of our Finalist application.

Powered Wheelchair – As our entire product idea revolves around integrating with commercial power wheelchairs, we need to acquire multiple PWCs, both to act as initial instrumented testbeds for controllability and performance and as the base for our scale model. For the initial testbed, we will integrate our Velodyne LIDAR sensors and the Jetson TX2 to observe the chair's kinematic/dynamic behavior and how it responds to the user. The current efficacy of the chair in performing common Activities of Daily Living will be measured as part of our feasibility analysis to compare against our scale model product. Once we have a proof-of-concept from COTS parts constructed, we will integrate it with the powered wheelchair base to perform the other half of our feasibility analysis.

What is the IP status of your idea? (150)

Preliminary analysis of the IP in this space indicates that there is a lot of prior art and patents related to the primary concepts of autonomous driving, environmental sensing, obstacle avoidance, and human-machine interaction. Because of all this prior art, we feel there may not be room left in the space for new patents stemming from this work except possibly in a very narrow scope within a small sub-domain of one of these fields. It is our intention to continue investigating in this space and as our design reaches maturity continue to discuss with our counsel what aspects of our solution may indeed be novel and worthy of patent application. At such a time as that may be required, we will discuss with the Technology Transfer Center at Vanderbilt University and the Counsel at Max Mobility / Permobil as well as any other affiliated parties.

Team make up – please provide up to 5 biographies for members of your team. Each biography should be no more than 150 words

Dexter Watkins

Dexter Watkins is a graduate student at Vanderbilt University, where he is pursuing his Ph.D. in Mechanical Engineering under Dr. Nilanjan Sarkar. His interests are in human-robot interactions, and the modeling/integration of system dynamics and their impact on the behavior and decision making of intelligent systems. Throughout his undergraduate and graduate career, Dexter has been involved in research projects ranging from robot-assisted steerable needles, to eye trauma from IED-like explosions, to his current work in human-centric intelligent mobility. While at Vanderbilt, Dexter has been involved as a team leader and mentor to the Vanderbilt Aerospace Design Laboratory, where he has learned to quickly develop working prototypes of advanced systems. Dexter interned at Max Mobility in 2017, where he worked on the application of autonomy to existing wheelchair systems. Dexter received his B.E. in Mechanical engineering from Vanderbilt University in 2013.

Nilanjan Sarkar

Nilanjan Sarkar has a dual appointment as Professor of Mechanical Engineering and Computer Engineering at Vanderbilt University, where he also serves as the Chair of the Mechanical Engineering Department. He is interested in the analysis, design, and development of intelligent and autonomous systems that can work with people in natural ways. The applications of this research range from helping individuals with autism and other developmental disabilities in learning skills, aiding stroke patients to regain through robot-assisted rehabilitation, and providing autonomy in robots for a variety of tasks. He strives to develop a new generation of robots and intelligence such as systems that can sense human emotion from implicit signals and cues like physiology, gestures, and facial expressions. His current research involves both theoretical analysis and experimental investigation of electromechanical systems, sensor fusion and machine learning, human-robot interaction, and the necessary kinematics, dynamics, and control theory leading to smart systems.

William Emfinger

William Emfinger is CTO of Max Mobility, LLC. In Nashville, TN and holds an appointment as an Adjunct Assistant Professor of Mechanical Engineering at Vanderbilt University. He manages the research and development at Max Mobility, with a primary focus on novel methods of propulsion, environmental sensing, autonomous systems, and alternative control interfaces. At Vanderbilt he advises the Vanderbilt Aerospace Design Laboratory which designs, builds, and flies scientific payloads on sub-orbital rockets. As part of his continuing research, he develops novel integrated modeling tool suites (ROSMOD) for software and systems, specifically for real-time distributed systems. He received his B.E. in Electrical Engineering and Biomedical Engineering from Vanderbilt University in 2011 and his Ph.D. in Electrical Engineering and Computer Science from Vanderbilt University in 2015 – where his focus was on modeling and predicting the performance of networked distributed systems.

Ben Hemkens

Ben Hemkens earned his bachelor’s degree from Vanderbilt University, then in 2010 started working with Max Mobility, LLC in Nashville, TN as part of earning his masters in Mechanical Engineering from Southern Illinois University - Edwardsville. His thesis research focused on the development of what is now the SmartDrive - a revolutionary power assist device for manual wheelchairs. Now the Director of Operations at Max Mobility, Ben oversees the growth of the company as more and more users experience the life-changing benefits of the SmartDrive, while continuing to help drive innovation through creative solutions to user's mobility needs. With exceptional experience in regulatory requirements / clearance to go along with extensive knowledge of the commercial landscape of mobility products worldwide, he provides valuable insight into all aspects of the product throughout its entire lifecycle.