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# A Virtual Reality Based Powered Wheelchair Simulator

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A VIRTUAL REALITY BASED POWERED WHEELCHAIR  
SIMULATOR

by

Yuliia Sergeeva

A thesis submitted to the Graduate College  
in partial fulfillment of the requirements  
for the degree of Master of Science in Engineering (Mechanical)  
Mechanical and Aerospace Engineering  
Western Michigan University  
June 2017

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# A VIRTUAL REALITY BASED POWERED WHEELCHAIR SIMULATOR

Yuliia Sergeeva, M.S.E.

Western Michigan University, 2017

Power wheelchairs provide great assistance for people with locomotion disabilities. However, for those who have tremor, operation of the wheelchair can be challenging and result in a chance to get into an accident. The focus of this research project is to create a semi-virtual reality power wheelchair driving simulator that can be used for testing a notch filter for tremors in a safe laboratory environment and obtain data on human operator movements for future mathematical modeling. The simulator incorporates a realistic and immersive virtual environment and power wheelchair movement into it. For the experiment, a physical PWC joystick was connected to the PC through an Arduino programmable controller. The signal from the joystick was converted in the controller into a signal readable by the simulation software to move the virtual power wheelchair in the virtual environment; the simulation software sends a joystick signal back to the physical wheelchair, again through the controller, to produce wheelchair wheel movement and sound consistent with the actions in the virtual environment. A participant experiences the semi-virtual environment sitting in a physical wheelchair located on a stationary drive platform and wearing head-mounted virtual reality headset. Plots of the powered wheelchair joystick inputs, velocity, rotational velocity about the center of mass, rotational angle around the center of mass, rotational velocity of each wheel and trajectory of the wheelchair are compared and discussed in this research work. Results show that the simulator is functioning successfully and outputs the results required for future analysis.

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Yuliia Sergeeva

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# 1. INTRODUCTION

This chapter introduces the applications of virtual reality (VR) in healthcare, power wheelchair (PWC) driving simulators, PWC and assistive robotics, and PWC joystick's tremor filtering as well as nature and types of tremors. It includes a discussion of the research objectives and past work that has been done in this area by other investigators. In conclusion, the chapter describes the steps of creating a semi-virtual power wheelchair driving simulator in this project.

## 1.1. Virtual Reality and Its Practical Application

Virtual Reality is a computer-based technology that uses a VR headset to generate realistic images, sounds and other sensations that replicate a real environment or create an imaginary setting [1]. Within the last 30 years, Virtual Reality (VR) has made a great impact on simulation systems. Thanks to a fast-paced computer hardware evolution, VR has been developing rapidly as an accessible, realistic and at the same time, safe way to test a technology [2].

However, just ten years ago [2] VR was mostly implemented as a room with three connected screens or completely covered with projections of the virtual environment, called a Cave Installation. They were expensive, difficult to transport and didn't show a convincing realistic environment [3]. A new era of VR started in 2012 with the introduction of the first prototype Oculus Rift headset [4]. The idea of a VR headset had been researched since the early 1990's by Sega, Nintendo and Atari but the technology was not yet advanced enough [4]. Rapid smartphone technology development has paved the way to upgrade existing concepts of VR. The technology used for the smartphones' screens has been adopted by the VR headsets developers and made the virtual world more fascinating, realistic and affordable for potential users [5]. Lately, Oculus Rift was followed with Google Cardboard, Samsung Gear, HTC Vive and PlayStation VR from 2012 to 2016. New devices are relatively affordable (\$200-\$800) and provide HD quality for home use [6]. This means that the range of applications can significantly expand.

Oculus Rift [1], used in this project, features per-eye displays running at 90Hz, 360-degree positional tracking, integrated headphones and positional tracking volume. The display provides resolution of 2160x1200. The lenses provide an 110° wide field of view and the distance between them can be adjusted by the user manually on the bottom of device. Oculus Rift has six degrees of freedom rotational and positional tracking within a 1.5 m by 3.35 m area with sub-millimeter accuracy and near-zero latency. The headset uses an accelerometer, gyroscope, magnetometer, and a constellation position tracking system which consists of external infrared sensor. Constellation is a optical-based outside-in positional tracking system developed for Oculus Rift devices. It is also complemented by the Oculus Touch controller, which is a handle-like device that simulates a user's hands in the virtual environment (VE).

Although VR head-mounted displays (HMD) have been evolving drastically over past decades, it's always been followed by motion sickness concerns [7]. From 25% to 40% people experience motion sickness even in modern, advance VR HMD. The number varies and depends on the quality of the virtual environment (VE), previous experience of using VR HMD, as well as sensitivity to motion sickness in the real world. In the early 1990's this concern resulted in a failure of adoption of the technology. However, it has also been frustrating for researchers to characterize VR sickness. It is based on numerous factors, such as adaptation over repeated use, rapidly changing technology, variation among people, and difficulty of measuring symptoms. Side effects have been significantly reduced due to recent, rapid progress in sensing, display and computing technology. However, motion sickness can still be an issue for VR HMD. In most recent cases, if the discomfort is present during the VR HMD usage and the headset is removed immediately, the sickness is gone within 30 min.

### **Virtual Reality Applications Outside of Healthcare**

VR is very engaging (especially for younger generations that have experience with using it in gaming) and user friendly (which could be a big concern for an older generation that experiences a barrier using computer keyboards, mouse, gamepads, etc.). VR has been widely used for communications, marketing, manufacturing, and learning and training.

- *Communication and collaboration:* conferences will not be dictated by physical location anymore [8]. Video calls can take place in a simulated conference room. Additionally, it can provide real-time translation removing language barriers.
- *More engaged learning and training:* VR can provide realistic interactive tutorials without an actual physical equipment. VR simulations can provide training on traditions and customs throughout the world to precise surgeries and machinery assembly without leaving a training room. It also removes a number of safety issues during learning [8].
- *Marketing:* experience with the VR is much richer and can be personalized [8]. An apartment in a building that has a bare basement can be presented in VR including all furniture with an option to personalize it. Luxury tours to the Caribbean islands can be available to explore in the VR before purchasing. A number of companies have already rolled out their VR-centered marketing campaigns.
- *Manufacturing:* VR helps to save time and money on collaboration, digital prototyping, design review and client presentation [8]. Using VR, The Ford Motor Company streamlined its manufacturing process and made it safer. It decreased worker injury rates by 70% and ergonomic issues by 90%.

### **Virtual Reality in Healthcare**

VR has a wide range of opportunities for use in healthcare. For example, The Royal London Hospital broadcasted live a surgery for colon cancer to VR headsets using 360° cameras [8]. Virtual organ models could provide realistic and safe learning environments for practicing. In terms of applying VR for treatment, it could assist with rehabilitation processes transferring patients into a more pleasant environment, simulate movements for exercise in order to recover in more engaging way, and provide safe training for assistive device usage [8]. VR is a powerful tool for mental health and depression treatment at home allowing vulnerable patients to be treated with dignity in their own home where they feel safer and more comfortable but with the quality equal to traditional therapy sessions [9]. It can be used for treating phobias like the fear of heights and anxiety disorders (such as PTSD). VR can take a patient to a remote or artificial location and create controlled stimuli [10]. It can also be used for healthcare teaching purposes to educate patients and their

family members or caregivers about hygiene or conditions like obesity [9]. Using VR in treatment at home also removes limitation of time for appointments and can be used anytime the user requires it [9].

Another side of VR in healthcare is immersing people in “someone else’s shoes” [11]. For example, as elderly populations increase, the need for doctors focusing on geriatric care increases too. To decrease a barrier between medical students and people over 60 years old, a project “We Are Alfred” from Embodied Labs applies VR to bridge the gap and immerse students into patient’s life complete with audio-visual impairments [9]. This simulation allows student to see the live-action story from the perspective of a 74-year old man through the VR headset [12]. The setting also includes headphones and hand-tracking device. The results showed, that an average of 30% more students answered “strongly agree” or “somewhat agree” when questioned if they understand the perspective of an aging patient. Students also revised the words they used for describing elderly people. Control group 1 decreased mentioning stereotypical words (like “old”, “slow”, “grandparent”, “nursing home”, etc.) from 83% to 7%, replacing them with words like “isolated”, “just like us”, “misunderstood”, “frustrating”.

VR also can be used for physical rehabilitation purposes [13]. For example, patients with a history of debilitating strokes could recover faster using immersive gaming technology. A stroke happens when blood supply to a part of the brain stops. If this lasts more than a few seconds, permanent damage to the brain can occur due to a deprivation of blood and oxygen to the brain cells. If the stroke results in paralysis it can be either temporary or permanent. VR immersive games provide the motivation to exercise to speed up recovery after a stroke through the virtual possibility of walking.

## **1.2. Virtual Reality Simulations for Wheelchairs**

Starting from the 1990’s, there were several projects focused on powered wheelchairs simulations. The projects had different motivations: design of powered wheelchairs, drive training for children with disabilities, study the accessibility of public infrastructures for wheelchairs, simulations of the wheelchair’s navigation in domestic environments, development of the intelligence system to assist the driver to control the

powered wheelchair, etc. [14], [15]. The first wheelchair VR simulation [2] was created with the educational purpose to increase awareness of having a motor disability while using a manual wheelchair. Meanwhile, VR has begun to be implemented for rehabilitation purposes [2]. It was used as an evaluation and training tool for persons with disabilities. The most important focus of these simulations is safety which is predominantly important for a user who drives a wheelchair for the first time or receives an upgrade of assistive equipment [2]. Also, as it is stated in [16], a third-party payer (typically, an insurance company) can delay the purchase of a PWC for a person that needs it until he/she demonstrates the ability to operate the PWC independently. A typical way to do this is to loan a PWC to a person with a disability and practice either at home or in the rehabilitation center. However, both of these options have their drawbacks. Practicing at home without prior training is unsafe and practicing in the rehabilitation center means completing a specific task, limited by the equipment, space, and time so they cannot simulate every real-life situation [16], [17].

Schmeller et al. [18] developed a hybrid motorized platform “Turtle trainer” shown in Figure 1, to evaluate the PWC driving abilities of people with physical, cognitive and/or sensory disabilities that already have a manual chair but are unable to use it. This method helps to draw a conclusion concerning whether a PWC will be helpful for them.



Figure 1. Turtle trainer [15]

Swan et al. [19] built a system for driving a motorized wheelchair in a virtual architectural environment to evaluate user’s proficiency with PWC driving, shown in



Figure 2. It also mentioned that it could be used for training new PWC users and as a tool for architects to understand the needs of people with disabilities. The system included a DualScan stereo screen, stereo viewing glasses that gave a more realistic sense of a driving environment, and IR emitter. The IR emitter is used to synchronize the glasses and monitor. It was tested with only one subject, a 16-year-old person with Cerebral Palsy. The results of the experiment showed that it was uncomfortable to drive the wheelchair using the simulator since the subject was used to a customized wheelchair with particular padding. So, the best solution for this would be to connect the simulator to the subject's PWC. Another conclusion shows that VR is a highly engaging game that can enhance the teaching process. This was discovered when the subject realized that there is an option to drive through the walls (because collisions were not set) and became very excited to do that.

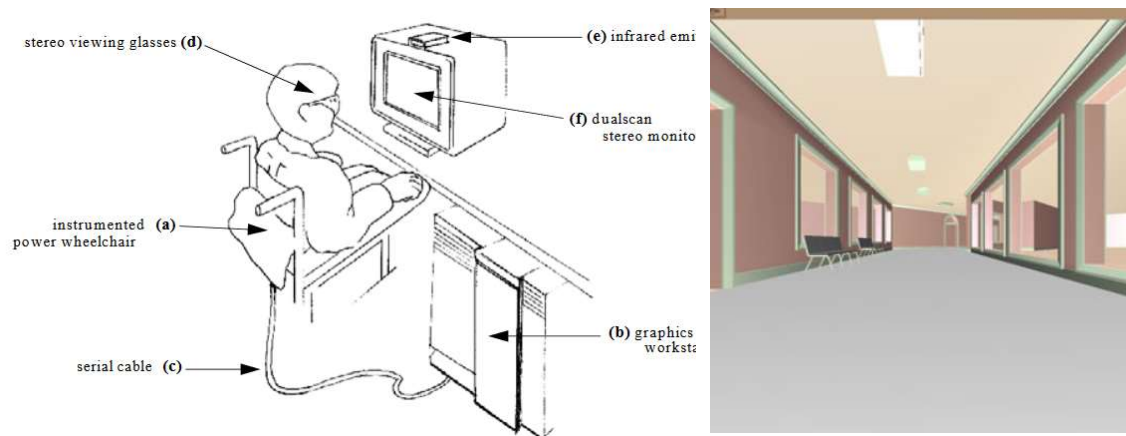


Figure 2. System configuration [15].

Another example is to help people that design buildings and streets consider how accessible they are for wheelchair users [11]. The simulator, built based on the Unreal Engine 3 (UE3) gaming development software, allows users to try to navigate a PWC through the supermarket to understand how challenging it can be and what the most common barriers that needed to be considered. In this project, UE3 integrated physics which was used and balanced with real world PWC driving it. It was discovered that the engine's physics is not capable of implementing indirectly steered wheelchairs with rear

drive wheels as it was conceptualized. This resulted in concerns about a radius double the size of the physical PWC, which means that the simulator needs further improvements.

Hasdai et al. [20] studied the ability of a driving simulator program to evaluate PWC driving skills of children with disabilities and train them. Children of ages 7 to 22 years old, with either muscular dystrophy or cerebral palsy, were evaluated on their skills of controlling an electric wheelchair in a typical route within a school with assorted obstacles (e.g., chairs, other people) modeled in a two-dimensional computer game. The children's performance was evaluated with a functional evaluation rating scale. Then, the group was trained on a similar game for 30-45 minutes twice a week for up to 12 weeks. The game was also constructed out of labyrinths similar to their school environment and was used as a guide with the professionals' instructions and feedback. After the training, the children were reevaluated again and compared to the children that learned the PWC driving skills in a real-life environment. Although their skills of driving in the physical environment were still inferior to those of experienced ones, children recently trained with the computer game made considerable progress and scored similar scores on the simulations to the experienced ones. For example, in the maze simulator, inexperienced children before training scored from 762 to 985 out of 1000 and experienced ones scored from 917 to 990. After the training, the first group scored from 907 to 989. One point was subtracted from 1000 for each collision and each second needed to pass through the maze.

Later, the Royal Hospital for neuro-disability and the University of East London developed two non-immersive virtual environments represented by the wing of the hospital to evaluate and train patients with complex neurologic deficiencies [21]. In this study, an electric wheelchair driving simulator was tested on able bodied adults, experienced and inexperienced PWC users. Their skills were evaluated before and after completing the simulation tasks as well as providing personal feedback about it. The tasks for able bodied participants included: driving the PWC forward in a straight line for 10 meters, reversing the PWC in a straight line for two meters, driving into and reversing back out of an enclosed space, completing a 180° turn around an object, completing a 'slalom' around a series of objects, and stopping suddenly. Tasks for the PWC users were the same but with the

addition of people moving around. The overall feedbacks about color, depth, scale, look of the objects, and level of details were positive. However, participants found maneuverability tasks more difficult than in the physical world, which was proven by the data collected during the simulation. Experienced users mentioned that maneuverability issues were a result of a lack of peripheral vision. The authors concluded that the simulators showed potential in evaluating and training but the visualization has to be enhanced to provide more immersive and engaging experiences.

Niniss et al. [22] developed a more detailed simulator to choose the wheelchair appropriately and to develop a software tool that would help the design of an intelligent PWC to support inexperienced users. The Intelligent PWC is equipped with odometers, a belt of 16 Ultrasonic Sensors, incremental encoders, a computer that generates high-level tasks as avoiding obstacles or global path finding, and a display for the human-chair interaction. The simulator in Figure 3 also includes a physical platform and virtual reality headset. Interesting enough, when the research was conducted in 2000, it aimed to get rid of the headset and replace it with a giant screen. However, headsets are now considered to give a more realistic visualization [23].



Figure 3. Principle of the simulator [22]

The first commercial wheelchair simulator, WheelSim in Figure 4 [24], was released in 1998 by LifeTool Society as a training and diagnostic tool. Additionally, it is still the only commercially available PWC simulator. The simulator was designed to be

more user-friendly than other wheelchair simulators, developed as academic projects, available in the 1990's. WheelSim provides visual feedback about mistakes, guidelines, checkpoints, and had 4 levels of difficulty. As with many game-like simulators, it contained a high score list of top ten results. At the same time, WheelSim has detailed statistics that can be used for diagnosis and progress reports. However, it is unsuitable for training and assessment [23]. It was tested by Alshaer et al. [25] with five evaluators and discovered that it lacks an accurate physical simulation, the size of the wheelchair is unknown, and the driving speed is problematic to identify.



Figure 4 WheelSim interface [24]

According to Spaeth et al. [26], PWC driving simulators, developed before 2008 had under defined protocols and instruments of evaluation, such as evaluating only subjective judgements of the participants or not providing details about data collection. Some of the case studies included subjects with diverse experiences or impairments, so their results are hard to summarize and compare. Spaeth et al. developed a wheelchair virtual driving environment that can provide quantifiable measures of driving ability and measure the performance of alternative controls. During the first day of the experiment, the subjects were familiarized with the VE and performed four driving tasks. On the second day, they completed 40 trials for each of the two joystick types: motion sensing joystick and experimental isometric joystick. In the isometric joystick, the magnitude and direction

of force is applied by a user's hand serves as input rather than just the position of the joystick as in a "normal" motion sensing joystick. The next measurements collected during the study were completion time in milliseconds, number of boundary contacts during the trial, and the joystick's speed and direction input signals, and the wheelchair icon's location coordinates, rotation, speed, and acceleration. The root mean square error (RMSE) was developed as a main outcome measure. RMSE was calculated to evaluate driving performance for left turn, right turn, straight movement, and docking. Despite an advanced level of evaluation, the study has drawbacks. It has been noticed that subjects took advantage of extra clearance space provided in the turn tasks so they drove less precisely. The experiment also had just eight subjects with different levels of traumatic brain injury and didn't consider what hand they were using or their vision problems. Additionally, the wheelchair icon was displayed from a bird's eye viewpoint that is very far from the real life first person view experience.

A study conducted by Archambault et. al [27] compared driving performance in physical PWC and simulated environments. The motivation behind the idea is the safety concerns of PWC driving training and the necessity to perform it in a safe environment as close as possible to the real-life experience. By interviewing 109 PWC users, Archambault et. al determined that all of them had at least one accident within the past five years and 27% of them required going to the hospital afterwards. The simulated environment miWe was developed in Unreal Development Kit as a game and ran on a regular personal computer with a 24-inch monitor operating at 90 Hz. 16 healthy young adults between 20 and 26 years old participated in the experiment with the simulator and 13 healthy adults between 25 and 35 years old drove a physical PWC. Neither of them had previous PWC driving experience. Both groups performed the same set of tasks using joystick-controls. The second group drove a rear drive PWC Oasis 2 Orthofab. Both groups had their maximum speed set at the same level of 1.5 m/s with maximal acceleration at 0.5 m/s. They were asked to navigate the wheelchair through a virtual rehabilitation center environment with a series of corridors and rooms with inclined planes, doorways, and obstacles. The participants were asked to perform each task five times in both directions while operating

the joystick placed on the table in front of the screen. They received guidelines about where to go on the screen from the researcher. Tasks were modeled based on the Wheelchair Skills Test, version 4.1 and included: driving backward 5 meters in a straight line, opening a door, moving through the doorway and closing it (pushing and pulling), turning 180° within the limits of a 1.5 m square (left and right), turning 90° forward and backward (left and right), and moving sideways from one wall to another in a 1.5 square meters.

During the study in [27], smoothness of the joystick control was evaluated together with the time required to complete each task. Results showed that participants from both groups used the same number of joystick movements to perform the tasks. However, it took more time to perform lateral maneuvers and to go through the doorway with the door open in the virtual environment compared to the real one. Also, analysis showed that participants used similar strategies and had similar difficulties performing the tasks. Archambault et. al concluded that miWe is immersive enough to provide an experience close to the real one. However, results showed that participants did not interpret the simulated environment as a real space.

An important limitation of the study in [27] is that the research used healthy adults and not current PWC users. The subjects didn't have any motor, sensory or cognitive impairment that could affect the results. Further research on the same project [17] has proven that experienced PWC users show much better driving performance than healthy adults without any previous experience. Archambault et. al [27] proves, that virtual driving simulators for PWC can potentially replace physical training in rehabilitation centers. Rehabilitation centers have a major limitation, such as being oversimplified and highly protective in terms of the safety environment which is far from the real-life experience, especially in busy cities and areas not adjusted for the PWC drivers. Virtual simulators can model any level of difficulty with unique and customized tasks and also provide safe experiences while saving a lot of resources. It can be used by the patient at home anytime they want to practice.

Further research based on the miWe simulator by Tao et al. [17] implemented a 3D hand motion controller that showed approximately 40% higher involvement and moderate

to excellent agreement between the virtual and physical environments but a greater risk of collisions and reaching errors in VE. The VR simulator task also took more time to complete. Unlike in the previous study, they compare results for the same group of people and all of them had at least two years of PWC driving which means an experienced behavior on how best to perform tasks. They were asked to complete three tasks: working at the desk, using an elevator, and opening the door, as showed in Figure 5, a. In this experiment, the simulator joystick was placed in the position of the PWC joystick. Participants were also wearing Hydra motion controllers that are capable of one-to-one position and orientation tracking in 3D space (Figure 5, b).

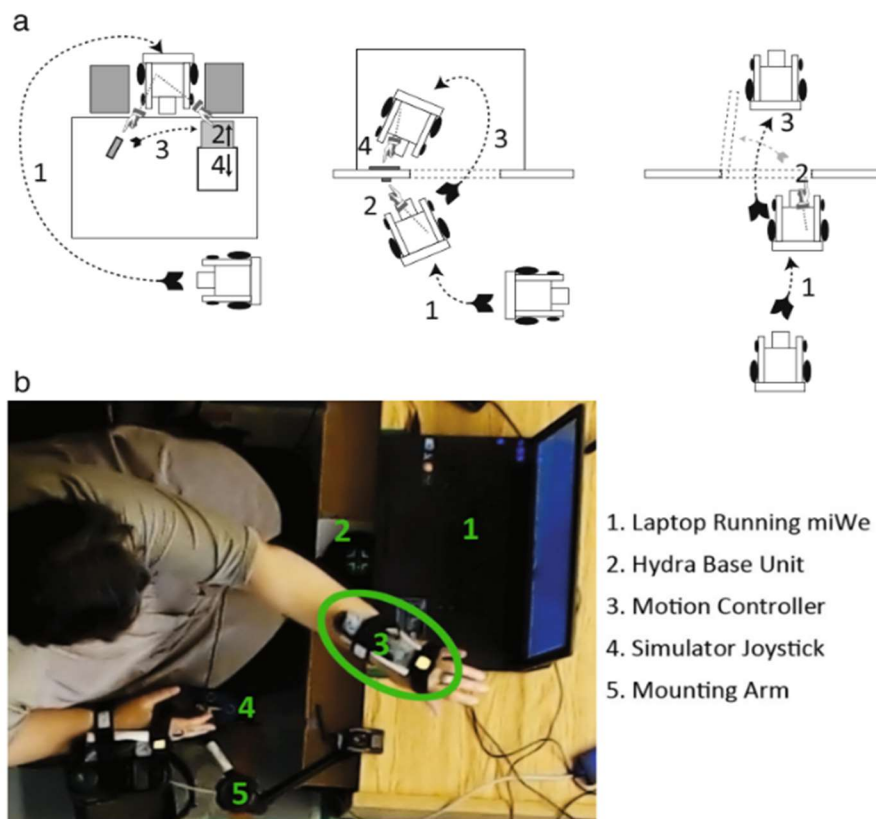


Figure 5. miWe task diagrams (a), the simulator overview (b) [17].

Although results of miWi simulator with 3D hand motion controllers in [17] showed greater immersion when comparing it to the simulator with joystick controls only, the controllers also brought some confusions to the participants. Subjects saw movement of the virtual hand, synchronized with their own one but didn't experience the touch or

couldn't adequately judge the distance to the desk/elevator/door to reach it with a hand. It was concluded that the greater complexity and variety of features that are available in the PWC simulator, the more opportunities users have to experience unrealism like the one that lack of haptic feedback caused in this experiment. It was recommended [17], that the upcoming electromagnetic-field-based Sixense wireless motion tracking system, which provides additional haptic feedback, should be implemented in future research. Also, head-mounted displays, like Oculus Rift, were suggested as a possible solution to the issue of depth perception.

Alshaer et al. [23] investigated factors affecting size and distance perception and behavior in a virtual power wheelchair simulator based on Oculus Rift Development Kit 2 (

Figure 6). They focused on correctness of estimation of the scale of the space in the virtual environment (VE) and how it can be improved. The three factors that were compared during the experiment included using a HMD versus a 21-inch monitor, the ability to freely change the Field of View (FOV), and presentation of a self-avatar (a visual representation of the subject's own body or body parts) in VE. Behavior was measured through embedded actions (e.g. implicit measure of gap pass-ability); sense of presence (questionnaire); and perception were measured through self-reporting of the perceived size/distance in the VE (explicit judgment). The VE was a low-distraction hallway meaning the hallway had no furniture or objects that may give indications about the size and distance. Recorded data included participant's name, tested factor's name and order, attempted gap width (minimum that PWC could pass through is 72 cm), number of correct attempts, collisions and time required to complete the task. Results of the 72 participants were evaluated quantitatively and qualitatively and showed significant influence of HMD and FOV on the performance. Using HMD resulted in up to 30% improvement in performance and FOV helped to improve on up to 44%. At the same time, presence of self-avatar in the simulation didn't affect the results much.





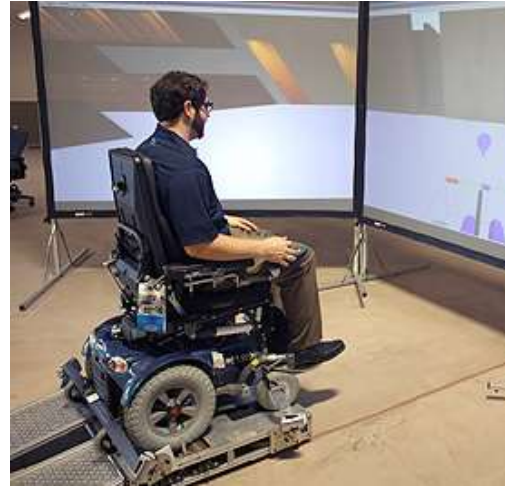
Figure 6. Experiment components including monitor, joystick, HMD, laptop, and HMD tracker placed at the top of the screen [23].

### **1.3 Real Motion Experience in Power Wheelchair Simulators**

Locomotion experience contributes to the decision-making process in PWC driving simulators when it is related to the judgment of the distance or spatial qualities [28]. Motion can be simulated using belted treadmills (Figure 7, a), dynamometers (Figure 7, b) and wheelchair ergometers (Figure 7, c) [29]. According to Klaesner et al. [29], each system has strengths and weaknesses related to cost, adjustability, size, and usability. There is no unified answer as to which system is the best and each of them can be applied for different purposes. For example, belted treadmills and dynamometers are used for kinetic and kinematic aspects of the wheelchair propulsion [29]. Treadmills provide movement angle to experience driving up on the hill or along the angled surface. However, treadmills are difficult to apply in the investigation of surface rolling resistance. Roller systems [29], also called dynamometers, are simple to use but do not simulate over the ground propulsion. Ergometers [29] are used for psychological aspects and usually use a standard laboratory manual wheelchair. However, they can also collect propulsion variables.



(a)



(b)



(c)

Figure 7. (a) University of Pittsburgh Wheelchair Simulation Platform based on the treadmill [30]; (b) dynamometer [31]; (c) manual wheelchair ergometer [32].

Alternatively, Sonar et al. [16] used a modified form of the Stewart platform, shown in Figure 8. The Stewart platform, that was originally designed for flight simulations. The platform is a parallel manipulator that is built of a rigid body top plate, connected to a bottom plate via adjustable legs. The position and orientation of the top platform depend on the length of each leg.

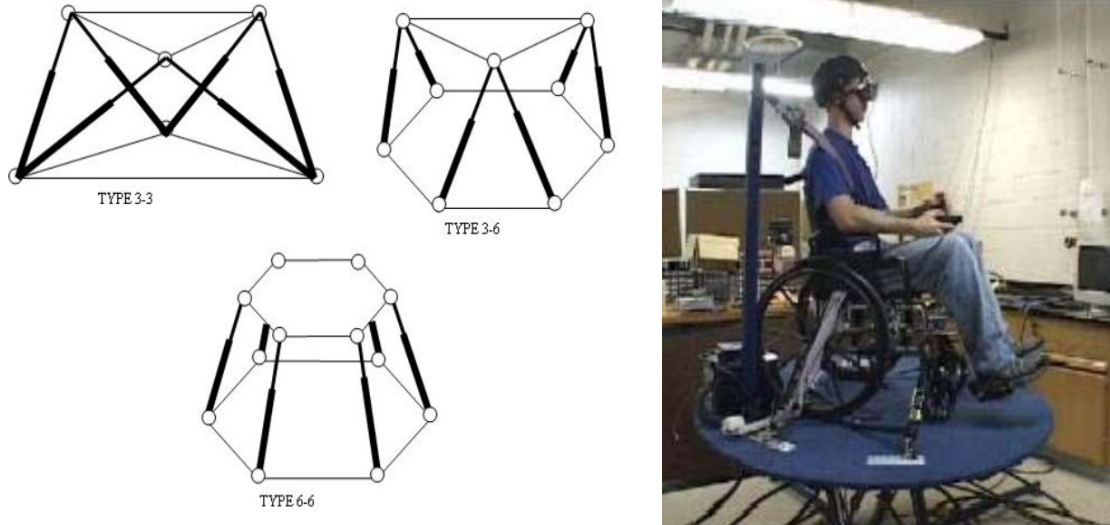


Figure 8. The Stewart platform [16].

vMocion's 3v™ Platform [33], a device based on Galvanic Vestibular Stimulation (GVS), can also potentially be used for motion feedback translation to the user. The system stimulates the body's vestibular system (located in the inner ear) and produces a real-time sense of motion based on what a user is seeing (Figure 9). It includes all three dimensions of movement and synchronizes the visual and vestibular fields within 0.1 sec, which helps to eliminate VR sickness. Samsung has also developed headphones based on the GVS approach as a potential solution of VR motion sickness problem [34]. However, the technology is still in the development process and is not yet available for PWC simulation implementation.



Figure 9. vMocion's 3v™ Platform [33].

#### **1.4. Power Wheelchair and Robotics**

Technologies to assist people with severe motor impairments to drive a PWC wheelchair have been actively researched in the last decades. Even if most of the people with disabilities may be completely satisfied with a traditional manual or powered wheelchair, some users may find it difficult or impossible to operate a PWC. Such difficulties can occur because of low vision, visual field reduction, spasticity, tremors, or cognitive deficit [35]. To assist people with such problems, various devices have been developed. Starting from minor devices like sip-puff control or chin control instead of joystick and sound feedback during collision to smart PWC that avoid obstacles, go through doors, etc. [15], [36]. Smart wheelchairs may use control based upon voice, ultrasonic and infrared sensors, wheel odometers, barcode scanners, planar laser, machine vision, identify facial gestures, and read brain signals [35], [37].

The Intelligent Wheelchair Project of MIT [38] improved a standard electric wheelchair with sensors to analyze the wheelchair surroundings, a speech interface to interpret commands, and a wireless device to identify a specific location, e.g., a room, to assist in navigation. It learns surroundings through the prior guided tour provided by the user or caregiver and later can move to a previously titled location like “bus stop”, “coffee shop”, “kitchen” under voice command (e.g. ‘Take me to the bus stop’).

CALL’S smart powered wheelchair [39] can be equipped with sensing systems: remote detection, line following and collision detection to ease navigation. Further, Intelligent Wheelchair System (IWS) [37] is an add-on to a commercial PWC that features navigation assistance. It detects collisions and gently stops the wheelchair and helps to maneuver around the objects through the audio commands. Technology used in the system includes infrared sensor, stereovision camera and a mechanical contact skirt.

#### **1.5. Tremor behavior and parameters**

A human tremor is a common movement disorder that is associated with neurological disorders (pathological tremor) or physiological phenomena, such as aging (physiological tremor). Tremors are characterized by an involuntary, rhythmic, oscillatory movement of a body part. Common examples of pathological tremors [40] are Parkinson’s,

cerebellar, and essential. Cerebellar or intention tremor is a dyskinetic disorder characterized by broad low frequency, under 5 Hz tremor, and is usually perpendicular to the direction of movement. Essential tremor may affect not only someone's arms but also head, vocal cords or other body parts. It is distinct from Parkinson's disease tremor but can be misdiagnosed as such. Rarer tremor types are psychogenic, orthostatic and neuropathic. Severe tremor disorders indicate diseases related to the central nervous system (CNS). Circumstances in which tremors occur can be divided in two groups: resting and acting. The resting tremor manifests when the muscles in the body part are not contracted and it is not affected by gravity. The most common example of resting tremors is that from Parkinson's disease. The action tremor is observed during a voluntary muscle contraction and can be classified as postural, kinetic, intentional, task-specific, and isometric tremors [40].

Different diseases can produce tremor with different frequency and severity. Usually, a tremor is evaluated via drawing and handwriting tests [41]. Electrophysiological analysis of a human tremor is applied to analyze the tremor in greater detail to get parameters for its modeling. Electromyography (EMG) and spectral analysis were applied to measure amplitude and frequency of the tremors with an analog computer device. Later on, with the development of digital computers, tremors have been recorded and analyzed off-line with spectral and cross-spectral analysis of stochastic processes and measured with piezoresistive accelerometers (ACC). Currently, more recording techniques are implemented such as lasers or systems based on ACC along with the developed mathematical methods (e.g. the theory of linear stochastic process or linear time series analysis) to measure and model tremors. The main issue that remains is the accurate interpretation of the results in terms of physics and physiology.

According to Rocon et al. [41] Parkinson's disease tremors range from 3 to 6 Hz and are often asymmetric. It is distal and progresses to more proximal body parts as the illness develops. The frequency band for cerebellar tremors are from 2 to 4 Hz and all measured signals (EMG, acceleration and torque) are stationary. The cerebellar tremor

frequency band is independent of external loading. The estimated frequency range for Multiple Sclerosis (MS) tremors is 3 to 5 Hz [42].

### **1.6. Semi-virtual reality PWC driving simulator concept**

This research is a Phase 2 of the project devoted to the development of the notch filter for tremors while driving a PWC. Phase 1 [43] started the project by developing a notch filter to remove the main Parkinson's tremor followed by a model predictive control strategy to track velocity, orientation, and distance to a wall commands from the PWC joystick. The result of Phase 1 showed that the filter helps to keep a suitable wall distance and respecting velocity and acceleration limits that were considered as a significant improvement of safety for driving PWC by people with tremors. However, the notch filter in Phase 1 was tested on the simulated input with tremor and for further development and investigations it has to be tested with human operators in a physical wheelchair.

To test the notch filter with human operators in a physical wheelchair, safe conditions are required. The main objective of the Phase 2 is to create a semi-virtual reality (SVR) PWC driving simulator to obtain operator performance data and eventually test the filter developed in [43]. The simulator has to provide a maximum realistic and immersive virtual environment in the lab setting. For the experiment, a physical PWC joystick was connected to the PC through a programmable controller. The signal from the joystick is processed through the conversion in the controller and simulation software to move the virtual PWC in the VE. A participant would see the VE in the VR headset from the first-person view and navigate it with a physical joystick, mentioned before. To provide the motion feedback from the PWC it was placed on the stationary drive frame with rollers.

The following Phase 3 will test a the notch filter and other operator assistive technologies in the human operator controlled, semi-virtual reality PWC driving simulator.

## 2. SEMI-VIRTUAL REALITY WHEELCHAIR SIMULATOR

The semi-virtual reality (SVR) wheelchair simulator block diagram is shown in Figure 10. By way of explanation, the Operator sits in a PWC, which is located on a “Stationary Drive Frame” that allows the wheels to turn while the PWC remains in place. Normally, the joystick sends input commands directly to a control board in the PWC that interprets them and commands the drive motors. However, in the simulator the wheelchair joystick connection to the PWC circuit board is routed through a PC, processed, and then sent back to the PWC circuit board. The commands from the joystick are first normalized using an Arduino controller, which acts as the interface between the PWC and PC, and then they are sent to the PC through the serial port. In the PC, the normalized values are read by a VR application (VRA) developed using Unreal Engine 4. The VRA takes the joystick values and converts them into movement commands within the VR. These movements within the VE are experienced in the first person by the operator wearing the Oculus Rift HMD. Use of the Stationary Drive Frame allows the user to experience the physical sound and vibration from the wheelchair while driving in the VE. Finally, joystick commands, which may have been modified by the PC, are returned to the Arduino for conversion to the signal format expected by the PWC circuit board.

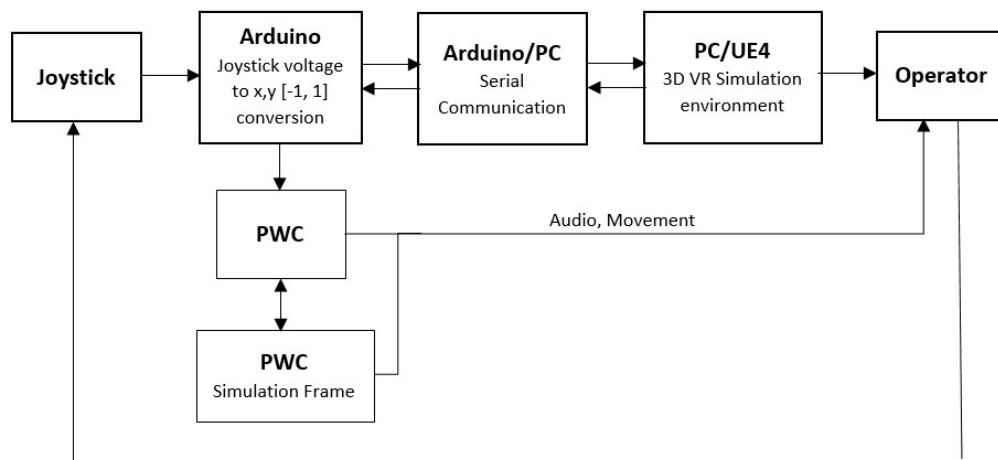


Figure 10. Flow diagram of the experiment setting.



## 2.1 Power Wheelchair

An Image EC Power Chair [44], shown in Figure 11, is used in this research. It is a mid-wheel drive power wheelchair with adjustable suspension on the front wheels, mid wheels with coil spring tension suspension, and a joystick that can be mounted on either side. Detailed specifications of the Image EC Power Chair are presented in Table 1.

Table 1. Image EC Power Chair specification [44].

Property	Value
Dimension (L×W×H)	1060x625x1100 mm
Weight, with batteries	87 kg
Battery	12V 36h×2
Wheel Drive Motor	200W
Front wheels	150 × 50 mm
Drive wheels	260 × 85 mm
Anti-tip wheels	150 × 50 mm
Brake system	Electromagnetic
Top speed (approximate)	2.2 m/sec
Climbing angle	8°
Cruising range	20~30 km
Turning radius	700 mm
Maximum weight	136 kg
Controller	PG VR2 50A
Total moment of inertia about the center of mass	10.768 kg·m <sup>2</sup>
Wheel moment of inertia about its axle	1.587 · 10 <sup>-1</sup> kg·m <sup>2</sup>
Half-length of the robot body	0.30 m
Half-width of the robot body	0.2675 m



Figure 11. Image EC Power Chair [44]: (1) controller, (2) armrest, (3) headrest, (4) seatback, (5) seat, (6) seatback release lever, (7) drive wheel, (8) caster wheel, (9) footrest, (10) seat belt, (11) drive engage levers, (12) joystick adjustment knob, (13) rear casters.

### 2.1.1 Power Wheelchair Dynamics

A Wheeled Mobile Robot (WMR) is used for modeling a physical PWC like in [45]. The WMR, and by association the PWC, is considered as a rectangular parallelepiped body with two right circular cylinders as wheels as shown in Figure 12. The dynamics of the developed WMR model includes either rolling or sliding depending on the magnitude of the constraint forces and friction coefficients. It considers conditions for lateral sliding and wheel slip as they are determined to be unsafe operation states. Figure 12 demonstrates the orientation of WMR velocities relatively to the global coordinates ( $X, Y$ ).

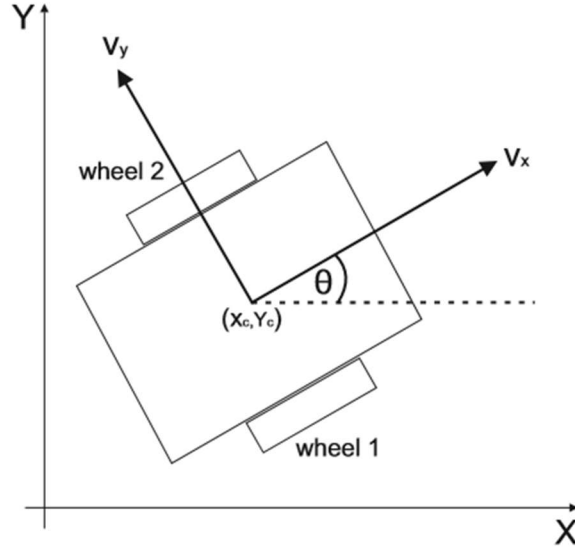


Figure 12: Relationship of the WMR velocities orientation and global coordinates

WMR dynamics and constraints developed in [43] are used in the driving simulator.

$$\dot{x}_c(t) = v_x(t) \cos(\theta(t)), \quad (1)$$

$$\dot{y}_c(t) = v_y(t) \sin(\theta(t)), \quad (2)$$

$$\dot{v}_x(t) = \frac{F_{x,1}(t) + F_{x,2}(t)}{m_t}, \quad (3)$$

$$\dot{\theta}(t) = \omega(t), \quad (4)$$

$$\dot{\omega}(t) = \frac{L(F_{x,1}(t) - F_{x,2}(t))}{I_t}, \quad (5)$$

$$\dot{\omega}_1(t) = \frac{u_{m,1}(t) - rF_{x,1}(t)}{I_w}, \quad (6)$$

$$\dot{\omega}_2(t) = \frac{u_{m,2}(t) - rF_{x,2}(t)}{I_w}, \quad (7)$$

where  $(x_c, y_c)$  is the position of the center of mass in the  $(X, Y)$  global coordinate system,  $v_x$  is the forward velocity,  $\theta$  is the orientation angle of  $v_x$  with respect to the  $X$ -axis,  $\omega$  is the rotational velocity about the center of mass,  $\omega_i$  is the rotational velocity of wheel  $i$ ,  $u_{m,i}$  is the applied torque on wheel  $i$ , and  $F_{x,i}$  and  $F_{y,i}$  are the wheel  $i$  forward and lateral ground reaction forces, respectively,  $m_t$  is the total mass that includes the occupant,  $I_t$  is

the total moment of inertia about the center of mass,  $I_w$  is the wheel moment of inertia about its axle,  $L$  is the half-width of the robot body, and  $r$  is the wheel radius. Further, the constraint forces of wheel  $i$  when it is rolling are

$$F_{x,1}(t) = \frac{I_t r \left[ m_t r^2 u_{m,1}(t) + I_\omega (u_{m,1}(t) - u_{m,2}(t)) \right]}{(2I_\omega L^2 + I_t r^2)(2I_\omega + m_t r^2)} + \frac{I_\omega L^2 m_t r (u_{m,1}(t) + u_{m,2}(t))}{(2I_w L^2 + I_t r^2)(2I_\omega + m_t r^2)}, \quad (8)$$

$$F_{x,2}(t) = \frac{I_t r \left[ m_t r^2 u_{m,2}(t) + I_\omega (u_{m,1}(t) - u_{m,2}(t)) \right]}{(2I_\omega L^2 + I_t r^2)(2I_\omega + m_t r^2)} + \frac{I_\omega L^2 m_t r (u_{m,1}(t) + u_{m,2}(t))}{(2I_w L^2 + I_t r^2)(2I_\omega + m_t r^2)}, \quad (9)$$

$$F_{y,1} = F_{y,2} = \frac{\omega v_x m_t}{2}. \quad (10)$$

Equation 10 ensures that there is no lateral sliding, i.e., ( $v_y \approx 0$ ). Rolling without sliding is enforced by

$$\| [F_{x,i}, F_{y,i}]^T \|_2 \leq \frac{\mu_s m_t g}{2}, \quad (11)$$

where  $\mu_s = 0.7$  is the coefficient of static friction.

For safety purposes, the WMR velocity and acceleration in the  $v_x$  direction and its rotational velocity in [43] are limited:

$$|v_x(t)| \leq 2.2 \text{ m/s}, \quad (12)$$

$$|\dot{v}_x(t)| \leq 1.1 \text{ m/s}^2, \quad (13)$$

$$|w(t)| \leq 1.5 \text{ rad/s} \quad (14)$$

### 2.1.2 Power Wheelchair Joystick

The PWC is operated by a controller that includes a P&G VR2 joystick [46] as displayed in Figure 13. Informal research indicates that the VR2 is a common joystick used in PWCs. The controller on/off button activates power to the control system electronics for driving and operation. A lit battery gauge indicates if the PWC is switched on. The maximum speed/profile indicator displays the maximum speed setting, i.e., if the speed of the wheelchair is being limited, or if the PWC controller is locked and not

accepting any commands. The maximum speed is controlled by the speed/profile decrease/increase buttons. The controller is also equipped with a horn button.

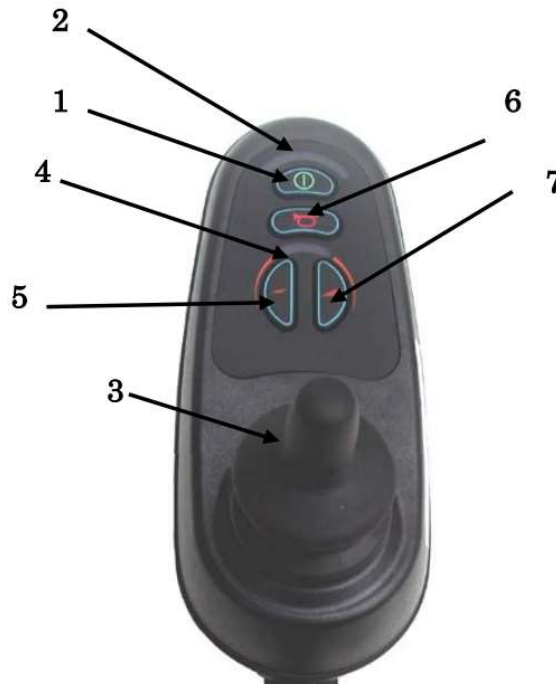


Figure 13. Image EC joystick and controller [44]: (1) ON/OFF button, (2) battery gauge, (3) joystick, (4) maximum speed/profile indicator, (5) speed/profile decrease button, (6) horn button, (7) speed/profile increase button.

The main function of the PWC joystick is to control the speed and direction of the PWC within the context of the maximum speed setting. The further an operator pushes the joystick forward the higher the final speed will be. The joystick position along the  $x$  and  $y$  axis corresponds to the range of voltage from 1.1V to 3.9V that is sent to the controller circuit board which uses these values to regulate the voltages sent to the electric motors. Also, an electromagnetic brake applies automatically when the joystick is returned to its default center position.

The PWC direction of movement corresponds to the joystick commands. The joystick full right makes the PWC rotate in the clockwise direction, full left rotates in the counterclockwise direction, full forward/backwards commands moves the PWC

forward/backward, respectively. Joystick Forward Left/Right positioning guides the PWC towards left and right directions, respectively. However, during the backwards movement, the PWC rotates in the opposite direction. For example, pushing the joystick backwards and left results in PWC moving backwards and right.

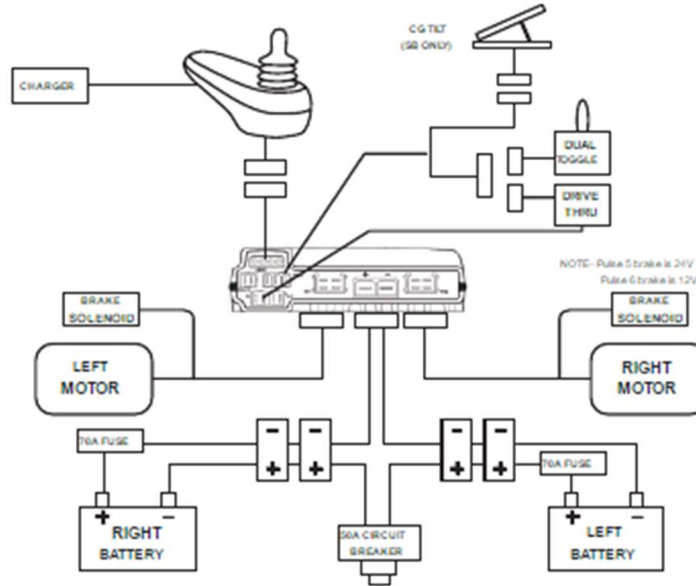


Figure 14. Joystick circuit operation [44]

The joystick circuit operation is presented in Figure 14. In this research, the joystick is connected to an Arduino controller instead of the PWC circuit board as shown. The joystick pin out is displayed in

Figure 15. Note that there are redundant Left/Right and Forward/Reverse pins. The voltage signals from pins 2 and 4 were chosen for use. Any combination of Left/Right and Forward/Reverse output pins could have been used without modification to the setup.

	Pin Number	Description
	XY Joystick	XYZ Joystick
	1 Positive voltage supply	Positive voltage supply
	2 Left/Right output 1	Left/Right output
	3 Zero voltage supply	Zero voltage supply
	4 Forward/Reverse output 1	Forward/Reverse output
	5 Forward/Reverse output 2	NC
	6 Center tap	Center tap
	7 Left/Right output 2	Z Axis output
8 Switch output (NC if no switch)	Switch output (NC if no switch)	
Switch is connected between pin 1 and 8		

Figure 15. Joystick pin out identification

The joystick outputs voltage for X (Forward/Reverse) and Y (Left/Right) axis through 4,5 and 2,7 pins respectfully. It supplies 5VDC, 1.1 VDC is minimum at corresponds full backward for X axis and full left for Y axis. Maximum is 3.9 VDC that is a result of the joystick's full forward and full right position. The center position, when the joystick is released supplies 2.5 VDC.

## 2.2 Arduino Development

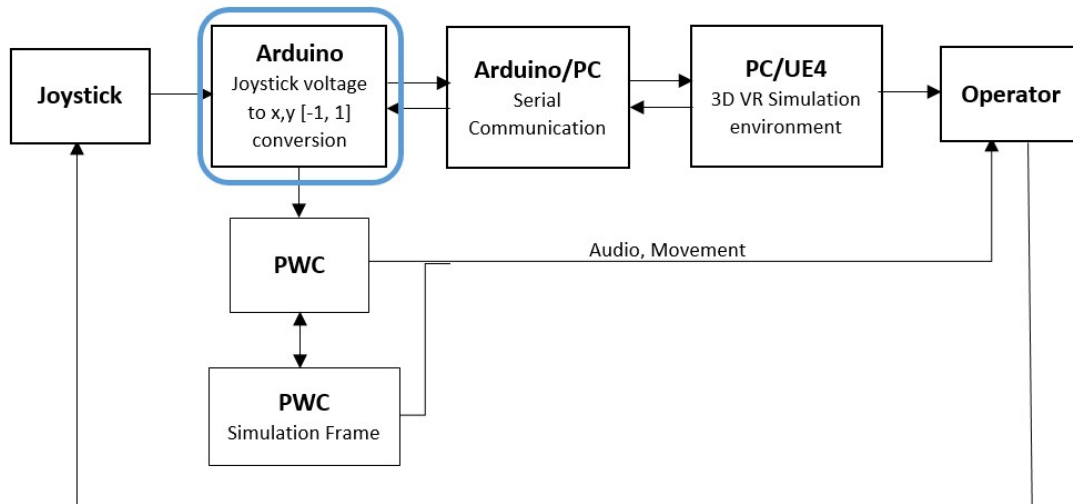


Figure 16. Flow diagram of the semi-virtual reality simulator

First, joystick voltage is processed through the Arduino, as shown in Figure 16. Figure 17 shows details of the processing. The voltage from the Joystick has a maximum value of 3.9 Volts and the Arduino has a maximum input of 3.3 Volts; thus, a voltage divider is used to scale the Joystick output by 0.8. Arduino communicates with UE4 through the serial port based on a master/slave protocol. UE4 has unidirectional control over Arduino. After it is triggered by UE4, Arduino converts and sends signals from the PWC joystick to the UE4 and from UE4 to the PWC circuit board. A noninverting voltage amplifier is used between Arduino and PWC circuit board to raise the output voltage of the Arduino by a factor of 1.5 to achieve the needed voltages into the PWC circuit board. Both, voltage divider and amplifier will be described in more details in the next section. Figure 18 shows the Arduino connections.



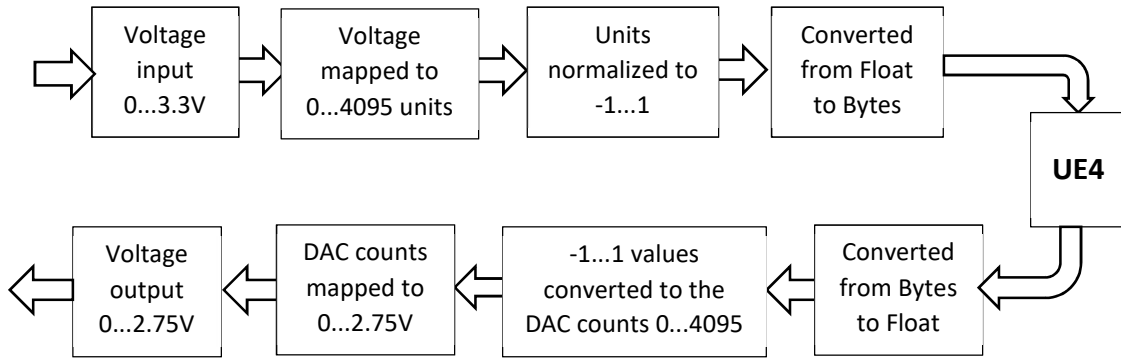


Figure 17. Arduino conversion

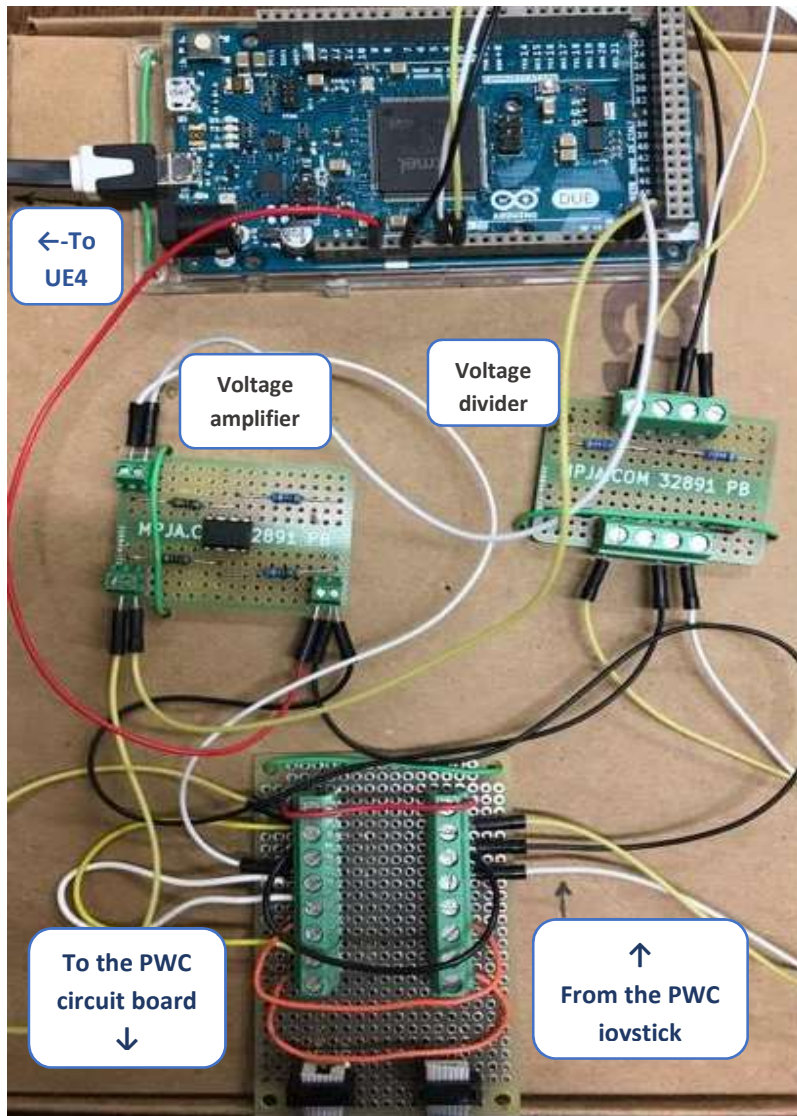


Figure 18. PWC-PC connection

Arduino Due [47] in Figure 19 is used in this project to connect the PWC joystick and PC running the virtual reality generator. This microcontroller was selected because it has two analog output pins that send Left/Right and Forward/Backward voltages back to the PWC circuit board. Arduino Due operates at 3.3V and has 512Kbytes of Flash memory for code.

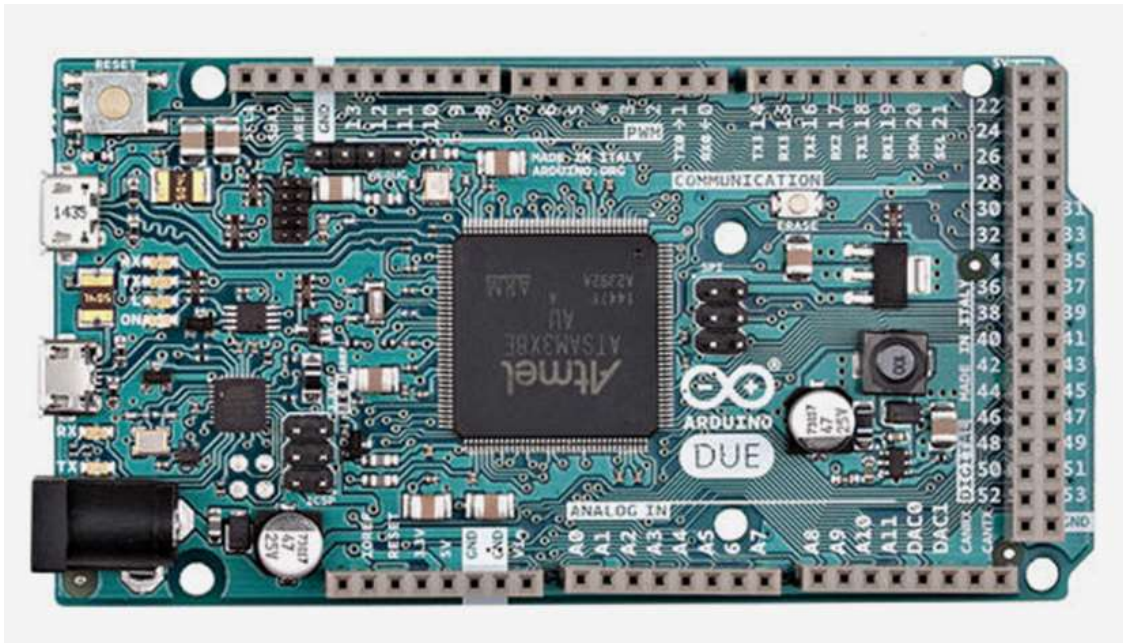


Figure 19. Arduino Due [47]

### 2.2.1 Analog Input

The Image EC powered wheelchair generates joystick signals with voltages up to approximately 3.9 V. Since Arduino Due analog inputs have a 3.3 V upper limit, there is a need for a voltage divider to rescale the joystick input for the Arduino input. Voltage division is accomplished with two resistors in series as shown in Figure 20.

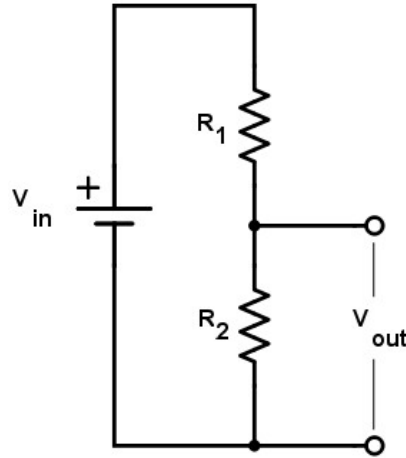


Figure 20. Voltage divider circuit [48]

The input voltage is from the joystick and the output voltage, measured across the second resistor, is the input to the Arduino analog input. The specific expression for the voltage scaling is

$$V_{Arduino} = \frac{R_2}{R_1 + R_2} V_{joystick} \quad (15)$$

Here, the values are chosen as  $R_1 = 1000 \Omega$  and  $R_2 = 4000 \Omega$ . These values result in the voltage from the joystick to scaled by a factor of 0.8.

The pin out of the voltage divider board is shown in Figure 21. The ground is connected between the Arduino ground and wheelchair ground.

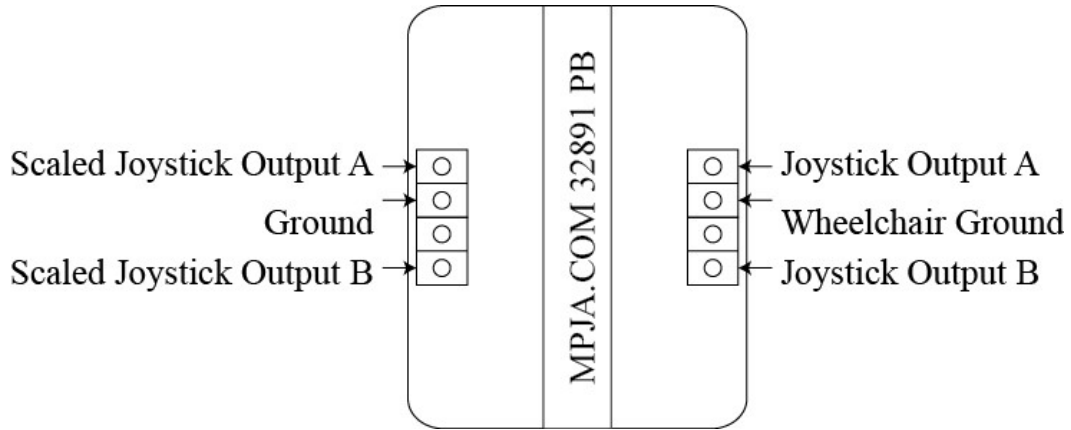


Figure 21. Voltage divider board pin out.

The output of the board is the scaled joystick voltage values which are the inputs to the Arduino analog inputs. The `analogReadResolution` command is set to 12 bits for the best possible input resolution. The number of bits determines the resolution (in bits) of the value returned by `analogRead` function. Setting read resolution equal to 12 means that input voltage will be mapped from 0 to 4095. As stated above, the current project voltage range from 1.1 to 3.9 V is used. It is divided through the voltage divider, described before and Arduino receives voltage range from 0.88V to 2.12V. Table 2 shows the mapping of the relationship between voltage, counts, and normalized values.

Table 2. Voltage to counts mapping

	Joystick voltage, V	Joystick voltage after the divider, V	Arduino counts	Normalized values
<b>Min</b>	1.1	0.88	$C_{fb,min}=C_{tr,min}=1042$	-1
<b>Center</b>	2.5	2	2102	0
<b>Max</b>	3.9	3.12	$C_{fb,max}=C_{tr,max}=3822$	1

Arduino is programmed to normalize the joystick input values from 1042 to 3822 into values between -1 and 1 for torque calculations in UE4. Joystick input Forward/Backward movement is set along  $x$  axis and Left/Right coordinates belong to the  $y$  axis.

$$j_x = -1 + 2 \frac{(C_{fb} - C_{fb,min})}{(C_{fb,max} - C_{fb,min})} \in [-1,1] \quad (16)$$

$$j_y = -1 + 2 \frac{(C_{lr} - C_{lr,min})}{(C_{lr,max} - C_{lr,min})} \in [-1,1] \quad (17)$$

where  $C_{fb}$  is the measured Forward/Backward joystick counts,  $C_{fb,min}$  is the predefined minimum Forward/Backward counts,  $C_{fb,max}$  is the maximum Forward/Backward counts,  $C_{lr}$  is the measured Left/Right counts,  $C_{lr,min}$  is the predefined minimum Left/Right counts,  $C_{lr,max}$  is the predefined maximum Left/Right counts. The normalized values are sent to UE4 for torque calculations via the serial communication to be described shortly. Arduino counts and corresponding normalized values are mentioned in Table 2.

### 2.2.2 Analog Output

UE4 returns joystick values, potentially modified, with values on [-1,1] via the serial communication to be described shortly. First, the normalized values [-1,1] are converted to a voltage, and then the voltage is converted to the counts with a range from 0 to 4095. The equations to convert normalized values to voltage and voltage to the analogWrite counts, which are used to set the actual Arduino output voltage, are

$$V = N \times 1.4 + 2.5 \quad (18)$$

$$C = \frac{V - 0.54217}{5.3490 \times 10^{-4}} \quad (19)$$

where  $N$  is a normalized joystick value,  $V$  is the desired voltage output of the Arduino and  $C$  is the number of counts.

The Arduino sends commands to the Arduino Due analog output pins DAC0 and DAC1. Then, the output voltage is amplified by multiplying the voltage by 1.5. The pin out of the amplifier board is shown in Figure 22.

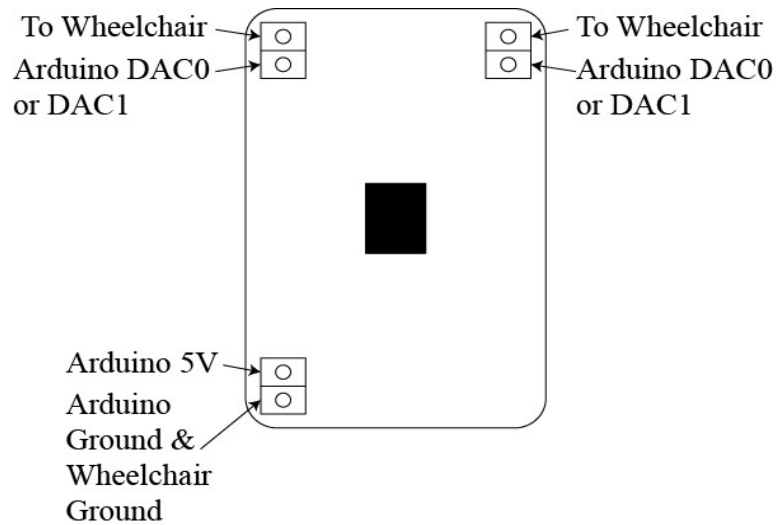


Figure 22. Amplifier board pin out

By way of explanation, the DAC0 and DAC1 voltage signals enter into the amplifier board and then are increased by a factor of 1.5. These amplified voltages are available to send to the wheelchair circuit board via the terminals labeled “To Wheelchair.” Left/Right 1 and 2 joystick signal lines are connected to the same amplifier board output terminal and similarly, Forward/Backward 1 and 2 are connected to the same amplifier board output terminal.

### 2.3 Serial Communication Development

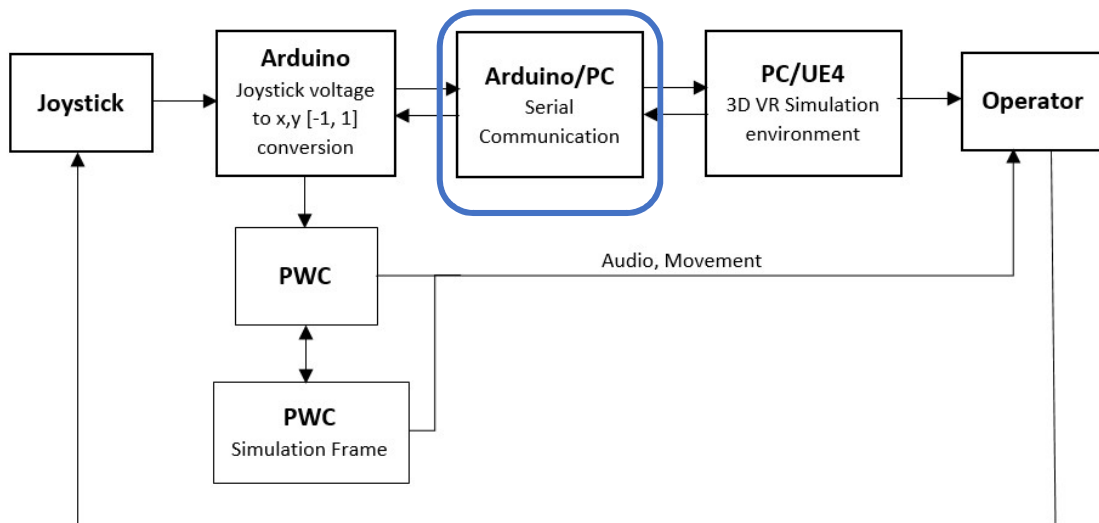


Figure 23. Flow diagram of the experiment setting

In this step, shown in *Figure 23*, UE4 and Arduino are communicating via serial port. UE4 and Arduino have master/slave communication relationship where UE4 has control over the serial port operation of the Arduino. That is, UE4 controls when the Arduino sends and receives messages. Arduino takes no action on the serial port unless it receives either the SERIAL\_TX\_START (0x0F) or SERIAL\_MESSAGE\_START (0x0B) value.

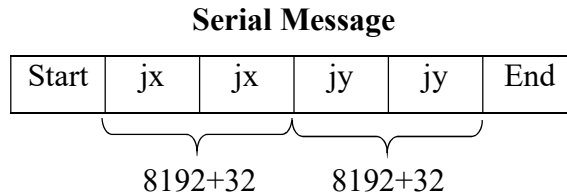


Figure 24. Serial Message composition

UE4 commands Arduino to send joystick data consisting of 6 bytes as shown in Figure 24. UE4 sends SERIAL\_TX\_START. This triggers the Arduino to compose a message of 6 bytes. The first byte is the SERIAL\_MESSAGE\_START value, which is followed by 2 bytes of x axis joystick data that corresponds to a value between 32 and 8224 (8192+32) that can be converted to a value on [-1,1]. This value informs Arduino that data receiving has been started. The offset of 32 is used to reserve 0 to 31 as command values. The joystick x axis data is sent as two bytes because one byte can only be between 0 and 255. Two bytes has the potential for 0 to 65535. The Y axis joystick data is the next two bytes which has a similar conversion to the X-axis data. The last byte is the SERIAL\_MESSAGE\_END (0x0E) which tells UE4 the message is over after it receives it. Arduino receives joystick data from UE4 it in the same 6 byte format as was sent to UE4 as just described.

## 2.4 Virtual Reality Simulation Environment Development

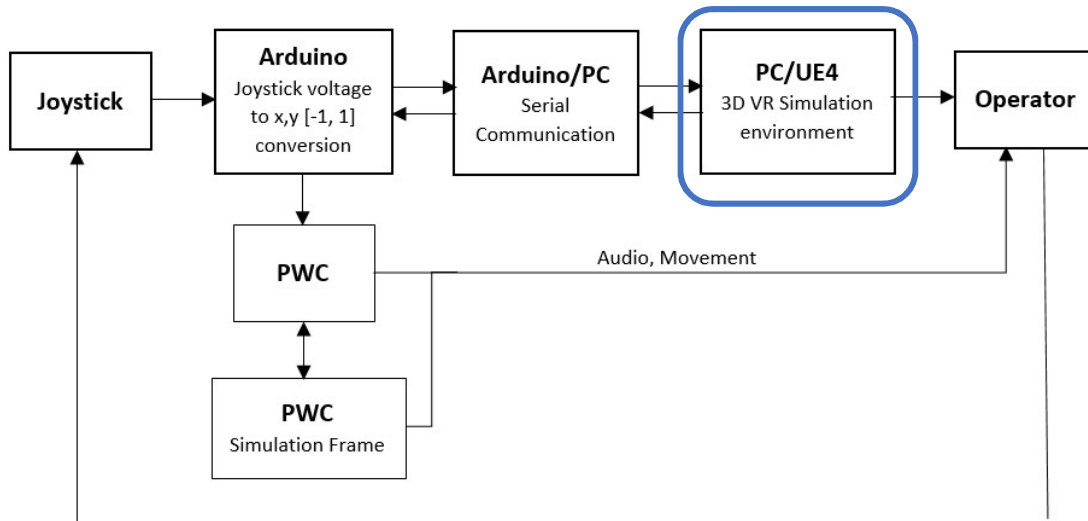


Figure 25. Flow diagram of the experiment setting

Unreal Engine 4 is a VR development environment and is commonly used for game design [49] employed in this project as shown in *Figure 25*. UE4 has a wide variety of tools for creating a 3D visualization/animations. Further, it automatically applies stereoscopic rendering, orientation, and positional tracking - which is needed when using an VE headset such as the Oculus Rift used herein. It has a graphical-user-interface-based builder (GUI builder) that allows the designer to arrange graphical control elements without traditional coding. The GUI builder in UE4 is used to create ‘blueprints’ and within the blueprints graphical control elements usually are called ‘nodes’. A connected sequence of sequentially executing nodes in a blueprint is called an event graph [50]. If the native nodes are insufficient to the needs, UE4 allows the development of 3D environment components in Visual Studio from using C++ as well. In this project, a combination of C++ code and blueprints were used together to create the interactive VE.



## 2.4.2. Blueprint Event Graph development

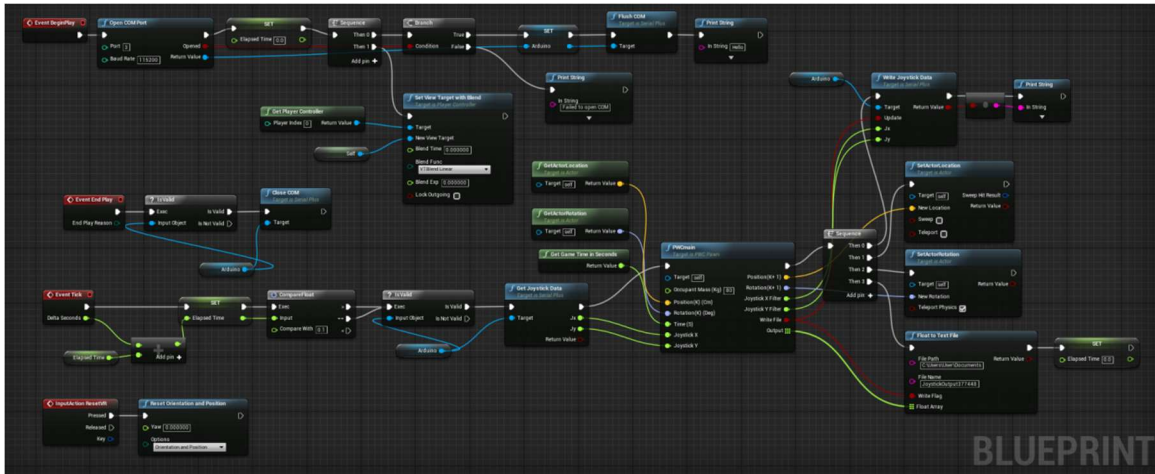


Figure 26. Blueprint event graph outlook

Figure 26 shows a UE4 blueprint event graph that will be discussed in this section. Once the simulator is launched, the blueprint node Event Begin Play from Figure 27 is executed and runs the event graph that opens the COM port #3 at 115200 baud rate (the same as was previously set in Arduino). The baud rate is chosen empirically after the initial one in 9600 didn't control the virtual wheelchair correctly. After that, about every 0.1 s UE4 receives and outputs joystick commands as well as saves the joystick and virtual PWC movement data in a .txt file for data collection.

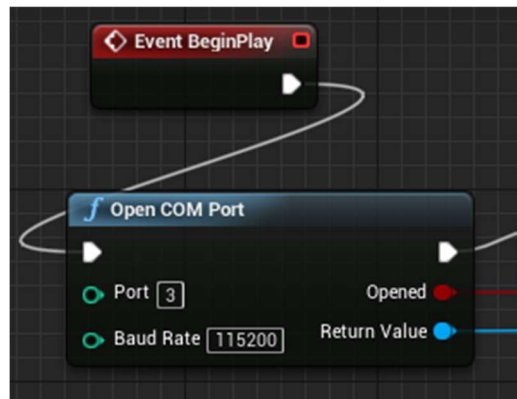


Figure 27. Event Begin Play node executing Open COM Port node

The next steps after opening the COM port, shown in Figure 28, are to set an elapsed time equal to 0.0 (it will be used later), attach the camera view to the virtual avatar head,

locate at 1.2 m above the ground, check whether the COM port has been successfully opened or not and depending on that either flushes it or prints out “Failed to open COM” on the screen.

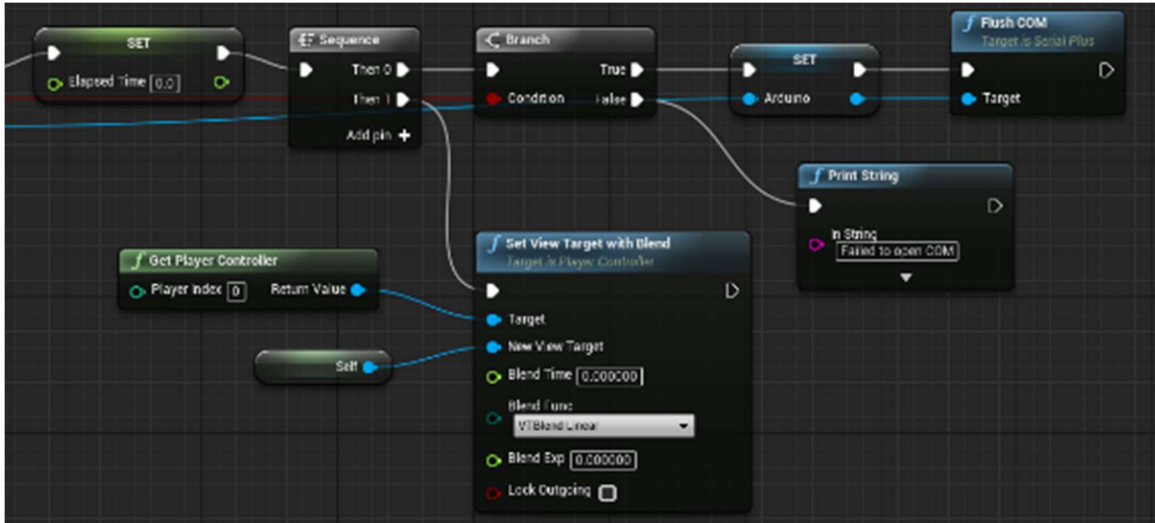


Figure 28. Continuing Figure 27, setting elapsed time, camera view, checking whether serial port open or not.

Unreal Engine 4 doesn't have native components to support serial port reading so to read Arduino output, a modified UE4Duino 2.0 plugin was installed [51]. The plugin was modified to be able to communicate according to the serial communication protocol described in Section 2.3.

Next, the Event Tick node is called in the blueprint every frame of gameplay. Figure 29 shows the beginning of the node sequence after Event Tick. To set the frequency of events executed after it is triggered, an Elapsed Time variable is incremented.

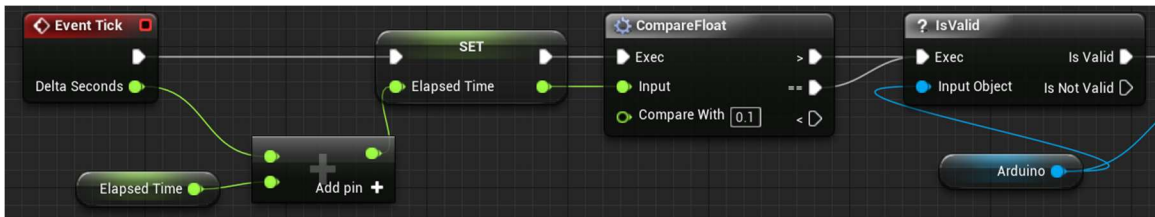


Figure 29. Event Tick graph, part 1.

As soon as it reaches a value greater than or equal to 0.1, a sequence of nodes is executed starting with Get Joystick Data. This node reads values from the serial port and sends them to the PWC main node.

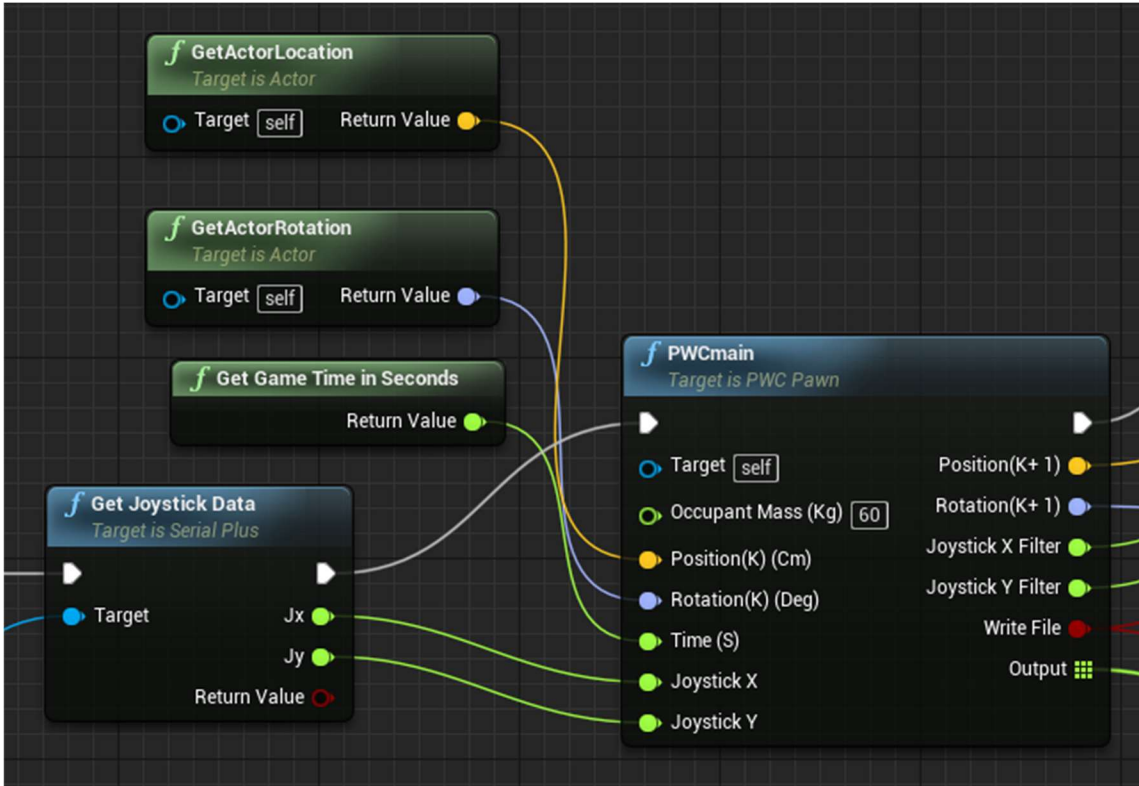


Figure 30. Event Tick graph, part 2. Reading inputs for the dynamic's calculations.

The PWC main node shown in Figure 30 performs the key function of the blueprint, collecting all the required inputs such as the virtual avatar position location, avatar rotation heading angle, game time, PWC occupant mass and joystick inputs, calculates the virtual avatar position after the applied command, and the outputs calculated value as shown in Figure 31.

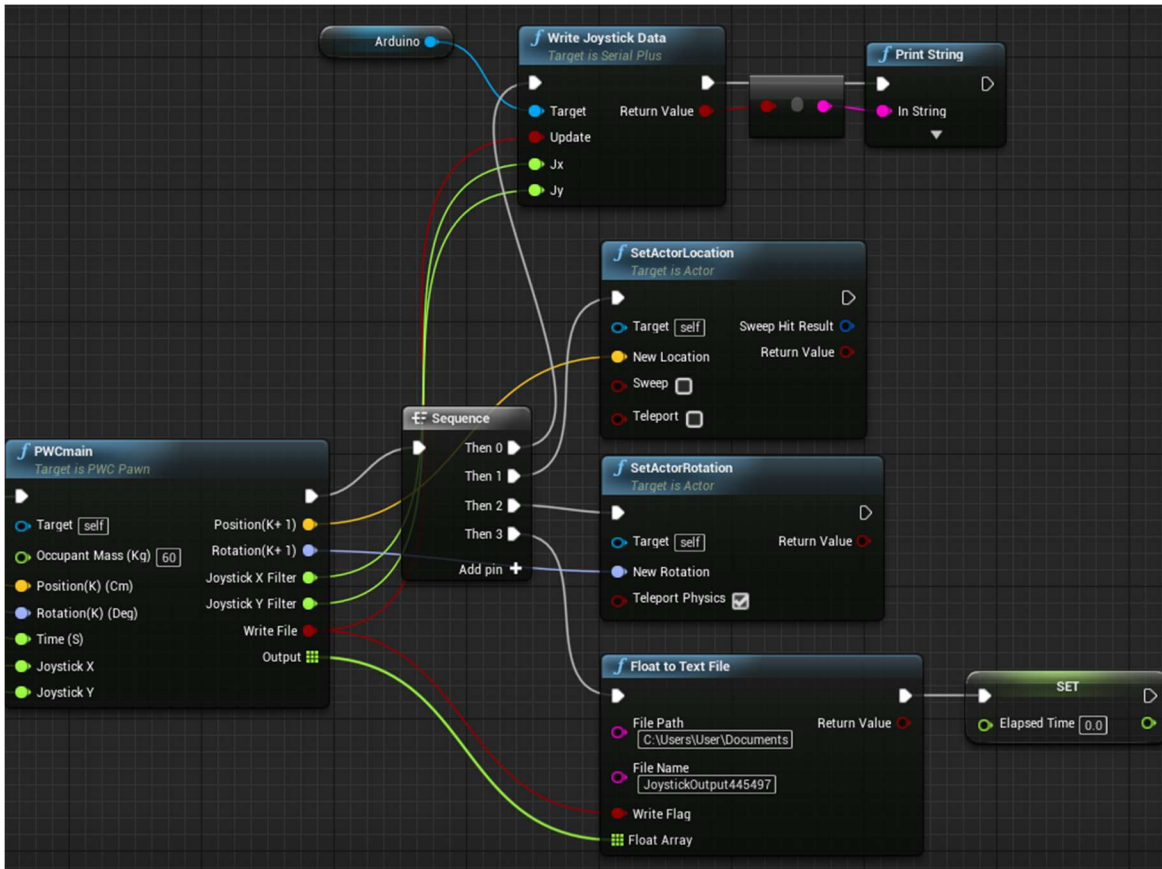


Figure 31. Event Tick graph, part 3. PWC main outputs.

The calculations in PWC main are based on the PWC dynamic calculations from the Chapter 2 implemented in C++. The following steps are performed in the PWC main code:

- 1) Reading inputs: position, rotation, time,  $j_x$  and  $j_y$  joystick coordinates; conversion to the MSK metric system (UE4 inputs are in centimeters and degrees rather than meters and radians);
- 2) Filter  $j_x$  and  $j_y$ . In this projects, the notch filter is not applied yet, so filtered  $j_{x_f}$  and  $j_{y_f}$  values are equal to the original  $j_x$  and  $j_y$ ;
- 3) Torque calculation (see Appendix A for more details).  $u_{m1}$  and  $u_{m2}$  are calculated based on the filtered joystick inputs;
- 4) Calculate time difference  $t_s$
- 5) The Runge-Kutta solver is called to get new states at the end of  $t_s$ .

- 6) Converting  $X$ ,  $Y$  coordinates of the PWC location and  $\theta$  into UE4 units. Creating updated position and rotation structures;
- 7) Output filtered  $j_{x_f}$  and  $j_{y_f}$ , updated position and rotation structures.

The outline of the PWC main node outputs is shown in Figure 31. The PWC main node sends new joystick commands as normalized  $j_x$  and  $j_y$  values through the serial port to Arduino using Write Joystick Data node. These values potentially will be filtered joystick commands to the PWC. The PWC main node also sends new location and rotation values to the nodes that update virtual avatar location and rotation. While the physical and virtual PWCs' control is performed, a separate node adjusts and resets orientation and position for the view in Oculus Rift. Further, the PWC main node outputs data that is printed into .txt file by the Float to Text file node. The data written in the file contains the current time, joystick input for the joystick  $x$  and  $y$  axes, filtered joystick commands for the joystick  $x$  and  $y$  axes,  $X$  and  $Y$  coordinates for the virtual wheelchair in the VE, velocities  $v_x$  and  $v_y$ , orientation angle of  $v_x$  with respect to the  $X$ -axis, rotational velocity about the center of mass, and rotational velocities of the each wheel. The last node resets Elapse Time to 0.0 s.

The last event, happening in the simulation is shown in Figure 32. Event End Play is executed in the end of simulation and closes the COM port.

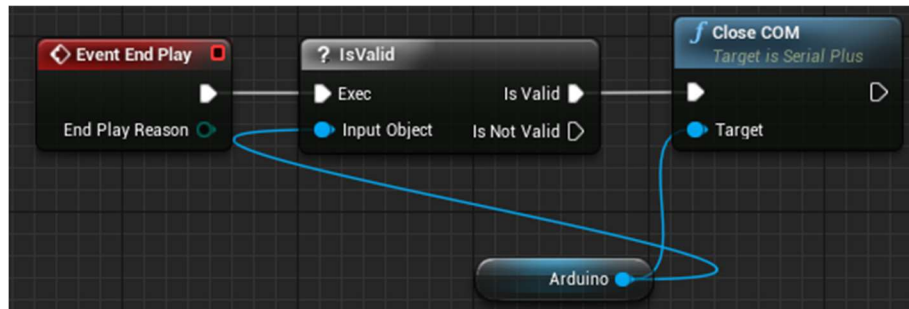


Figure 32. Event End Play graph.



### 3. VIRTUAL REALITY TEST ENVIRONMENT

The VR test environment herein consists of the hallway scene shown in Figure 33. The hallway scene was developed directly in the Unreal Engine 4 using the basic geometry and blueprints. This hallway was designed following the dimensions of the one in [43]. It is a 4 m wide and 20 m long hallway without obstacles that turns at 90° to the right and continues for another 20 m.

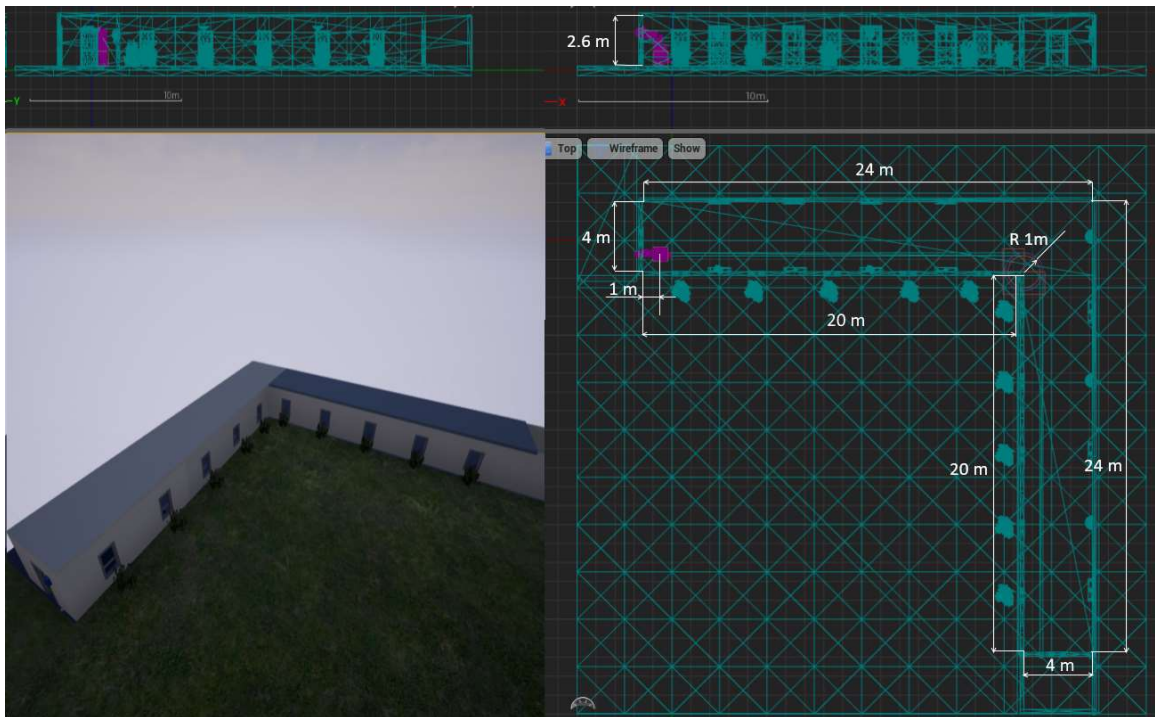


Figure 33. The hallway.

Unreal Engine 4 contains a library of basic objects like walls, floor, door frames, chairs, lights, etc. to build an environment from. The library shown in Figure 34 provides an opportunity to build simple architecture with a possibility to import custom created objects from 3Ds Max or the UE4 online store.

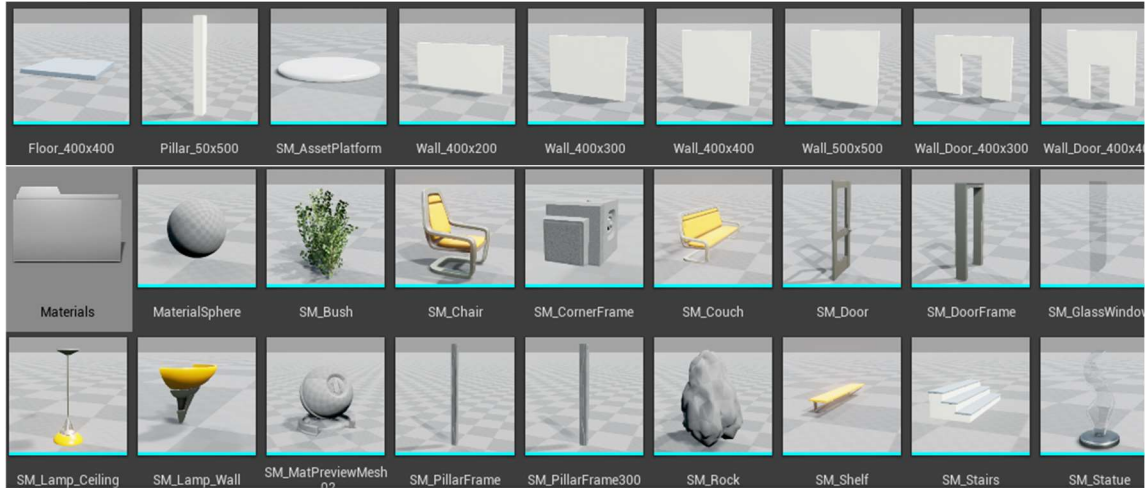


Figure 34. Unreal Engine 4 architecture and furniture library

The hallway has a 15cm wide line on the floor that the PWC has to follow all the way to the end of the corridor and it is located 1m away from the inner wall, which lies on the right-hand side of the PWC when it is initially placed in the VE. At the start of the experiment, the PWC is positioned on the line, 1 m away from the beginning of the hallway, facing looking down the hallway. The middle point of the wheelchair base is matched with the middle line of the line on the floor. Figure 35 and *Figure 36* show the hallway from the first-person and third person view respectively.



Figure 35. Virtual hallway, a first-person view

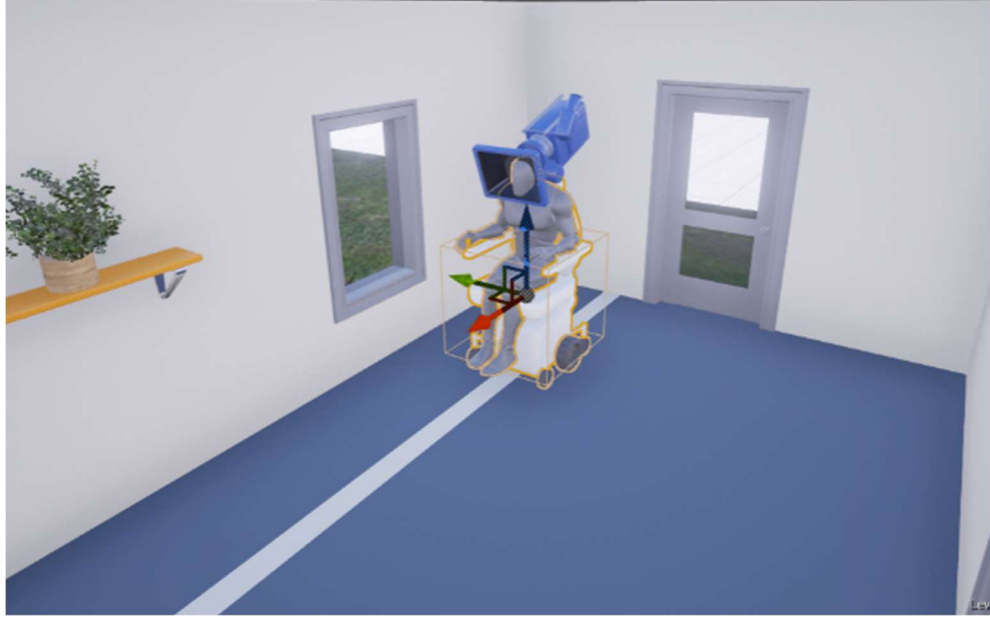


Figure 36. Virtual hallway, a third-person view

Unfortunately, UE4 doesn't have many native graphics tools and materials and textures so 3Ds Max is an alternative for creating more advanced environments. The PWC requires a more detailed figure, therefore it was built in 3Ds Max software and imported to the UE4. Figure 37 compares the physical and virtual PWCs. It was built at a simplified detail level but retains all the important features and dimensions of the physical PWC. Since all the dynamics were implemented in C++ there is no need to follow the exact sizing of the PWC for the simulation except for the aesthetic. PWC main node from the previous section has the mass and sizing of the PWC built in and it calculates and outputs the PWC location based on that. An approximate picture is needed so the user can see a virtual avatar in VE similar to the real-world one, not just an empty spot underneath them, and experience collisions with the objects in the VE. Collision box has been added from UE4 built in settings to prevent the PWC from running through the walls. The limitation of the collision box versus a custom collision mesh is that it is a roughly marked area around an object versus a mesh that considers much more detail. However, since the wheelchair base has a shape close to the cube, a collision box was used. A virtual robot body from the UE4 library has been placed in the simulator PWC for the aesthetics purposes.





Figure 37. Physical and virtual PWC comparison

## 4. RESULTS

This chapter describes the test procedure and subject performance during the experiment. Human Subject Institutional Review Board (HSIRB) approval has been received prior to conducting the test as required by WMU policies. HSIRB approval and subject consent form are attached in the Appendices B and C.

### 4.1 Test procedure

The test setup includes the physical PWC Image EC Power Chair connected to the PC through the Arduino controller. The PWC is placed on the stationary drive frame, detailed in Appendix D, and fastened with securing belts. The stationary drive frame allows the wheelchair wheels to turn without actual movement, providing tactile and audio feedback similar to actual motion. The Oculus Rift positional tracking sensor is located at 1.3m off the floor with approximately 20cm offset to the right from the center of the PWC and in front of the subject to provide a sufficiently accurate VE display during the test. Oculus Rift is connected to the PC in a way that its wire will be long enough to reach the PWC and move comfortably in the wheelchair.



Figure 38. Experiment setup

The experiment subjects are WMU students that volunteered without compensation. They were tested separately and each received detailed guidelines about the experiment setting, safety issues, and what is expected from them during the experiment. Participants have also been reminded that they may experience motion sickness from the VR headset but they are free to remove it as soon as they feel uncomfortable. The subjects signed the informed consent prior the test. After that, personal adjustment of the VR headset lenses distance was done before the test started.

Subjects were also requested to provide their name, age, sex and weight for the experiment. They were informed that age, sex and weight data may be made available to the public without their names. Subjects names are stored separately from the remaining data. The remaining data will be associated with a random number code. The name associated with each code is kept in a secure location and will not be stored electronically, according to the HSIRB policies.

#### 4.2 Human Subject Performance

All three adults that participated in the experiment completed the simulation successfully. Information about participants is provided in Table 3. Subject data. Table 3.

Table 3. Subject data.

Number #	Gender	Age	Mass, kg	Test completion time, sec	Previous experience
Subject 1	Male	35	80	35.1	Driving physical PWC few times
Subject 2	Female	31	40	69.7	15 years of manual wheelchair driving experience
Subject 3	Female	25	60	47.1	4 month working on the PWC simulator development

Figure 39 shows the trajectories performed by the subjects.

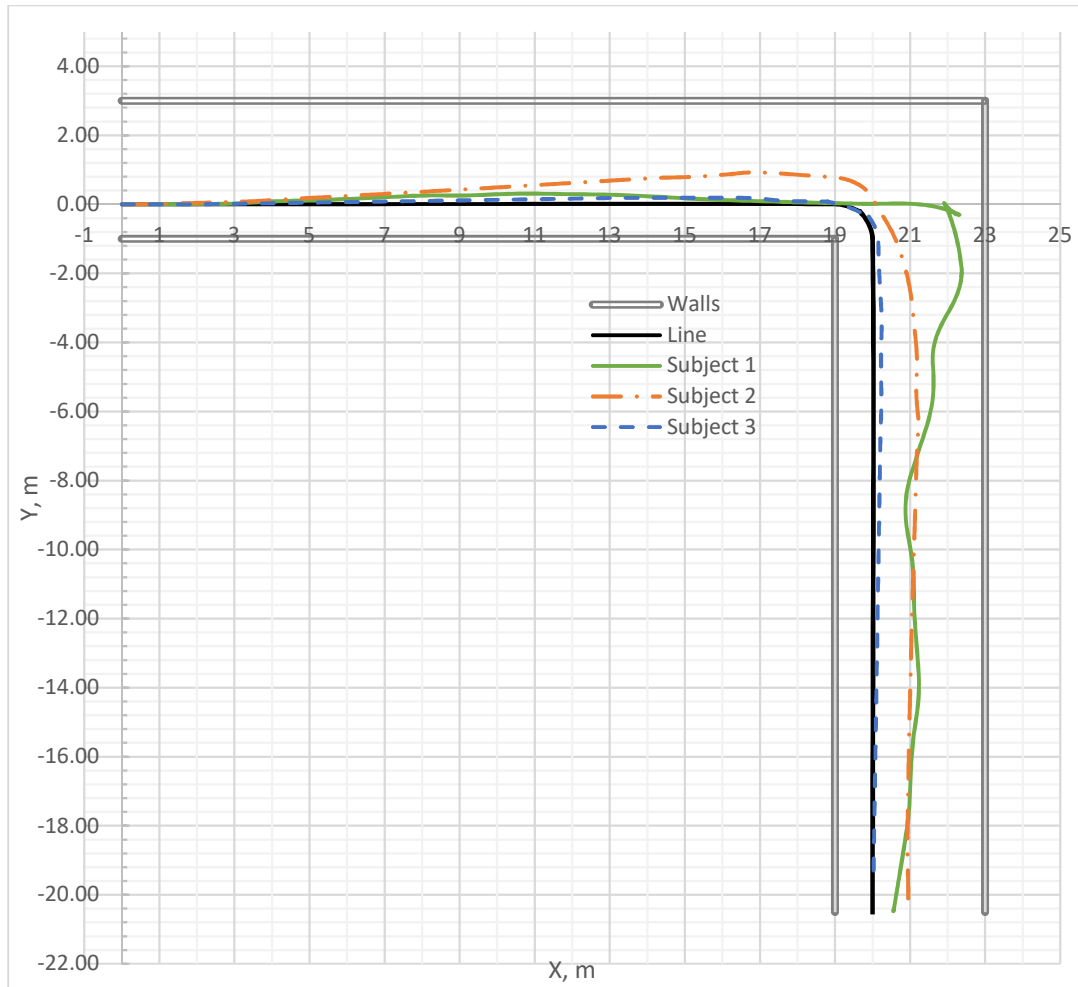


Figure 39. Trajectory of three subjects during the test

Figure 39 together with a record of time performance from Table 3 shows very diverse behaviors of the subjects. Subject 1 has the shortest completion time but at the same time, their trajectory at the corner is about 2.5 m off the marked line. Subject 2 took twice the time to complete the test but showed relatively smooth path. However, both of them were about 1 m off the marked line after the turn. Both, subject 1 and subject 2 attempted to get closer to the line but both of them stayed closer to the center of the hallway than to the line. Subject 3 took medium time to complete the test and produced the most accurate path compared to the other subjects. The reason for such smoother performance could be due to previous experience in testing the simulator during the development.

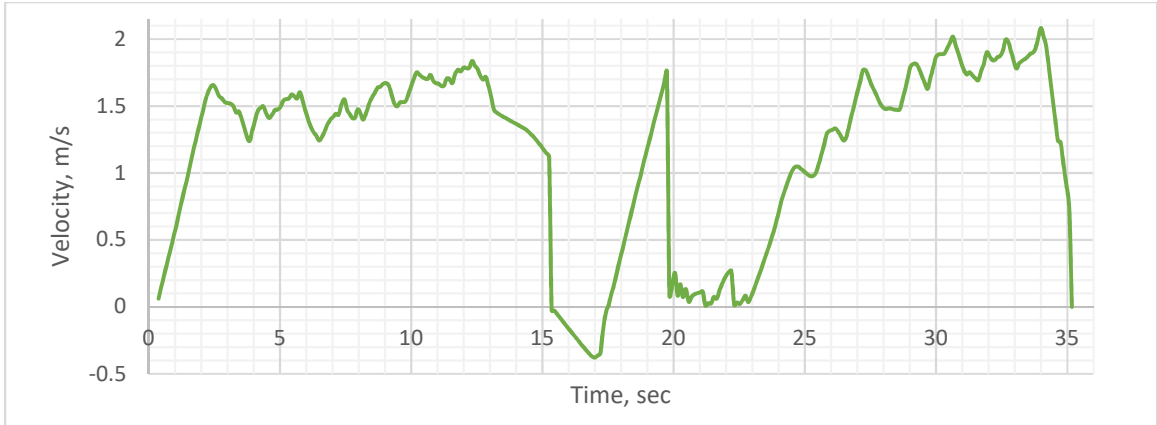


Figure 40. Forward velocity, Subject 1

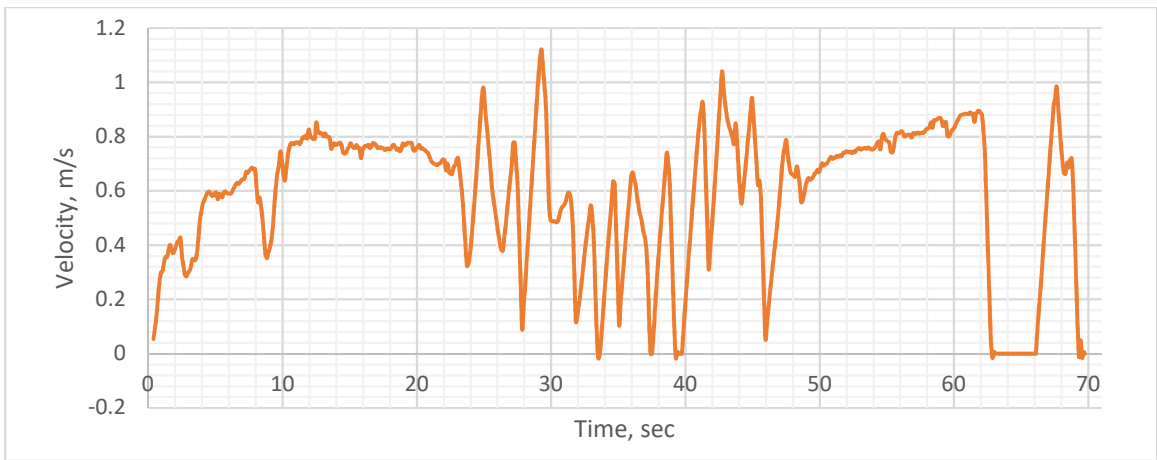


Figure 41. Forward velocity, Subject 2

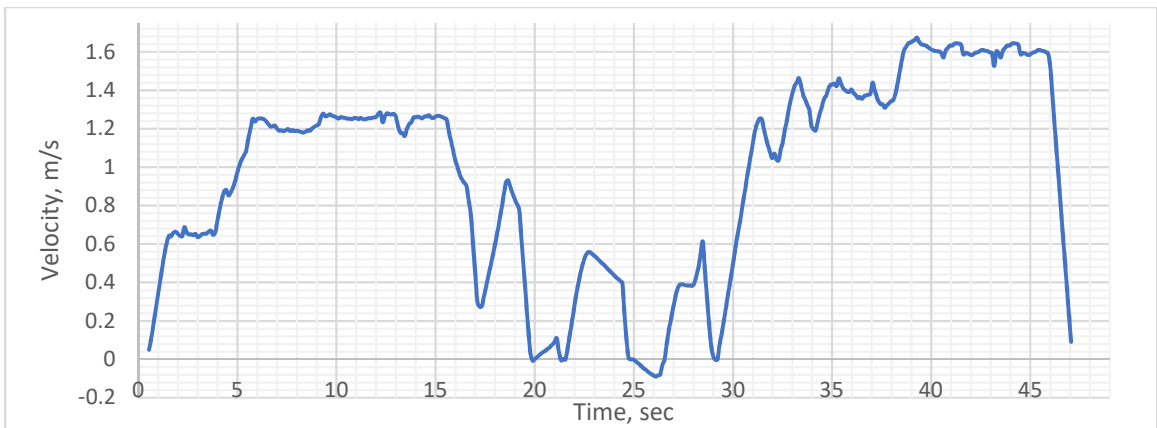


Figure 42. Forward velocity, Subject 3

Forward velocity in Figure 40-42 displays subject 1 moving back and forth during the cornering in the middle of the simulation. Subject 2 in Figure 41 has much more peaks comparing to subject 1 in the middle of the simulation that are results of trying to turn around the corner precisely and smoothly. Subject 2 had to stop several times to perform cornering, however the subjects hasn't moved backward to correct the position. Subject 3 moved almost without stops and maintained more constant speed while following a straight line as shown in Figure 45.

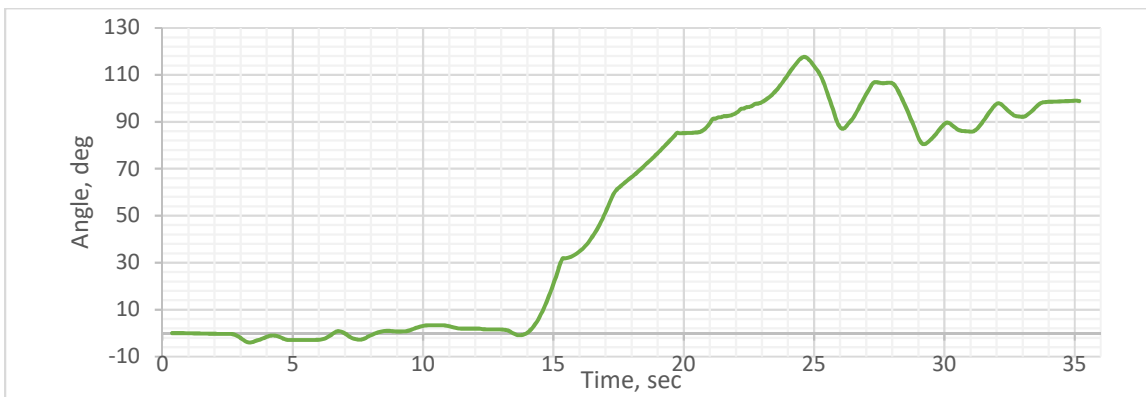


Figure 43. Orientation angle, Subject 1

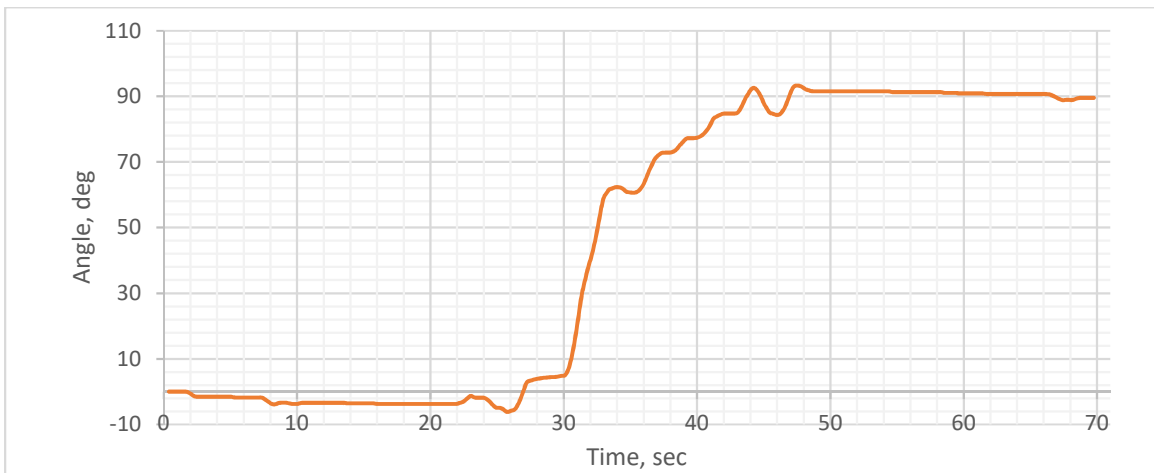


Figure 44. Orientation angle, Subject 2

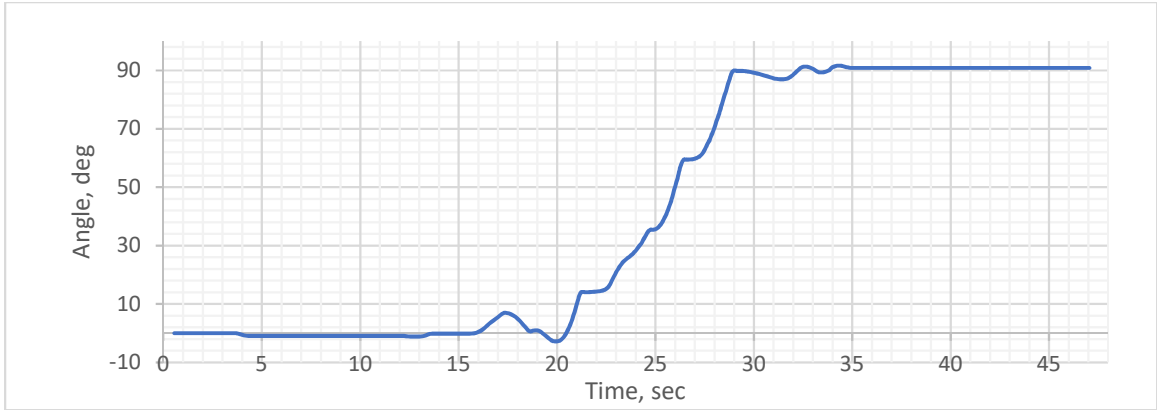


Figure 45. Orientation angle, Subject 3

Results of all three subjects displayed in Figure 43-45 show fairly constant orientation angle during the following of the first straight line, gradually changing during the cornering and subjects 2 and 3 continued moving straight with an angle  $90^\circ$  to the original position until the end of the hallway. Subject 1 passed by the corner and had to go back, turning to almost  $120^\circ$ , as it shown in Figure 43, to get back to the marked line

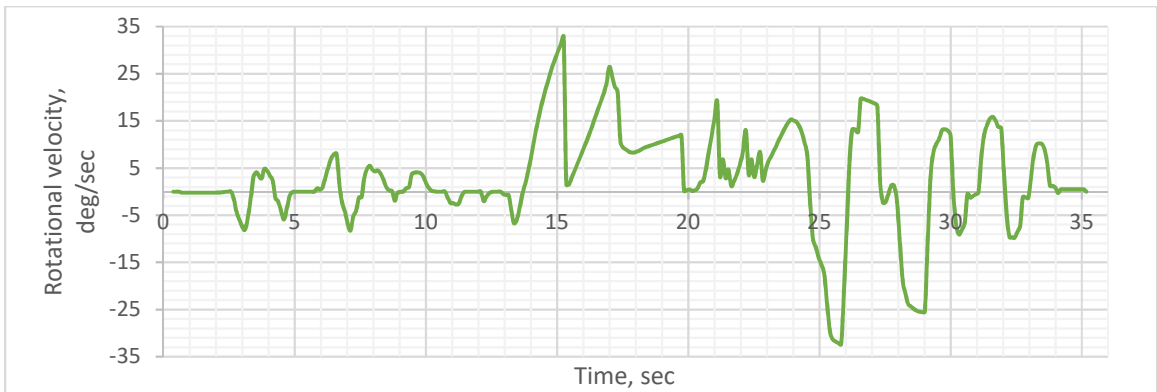


Figure 46. Rotational velocity about the center of mass, Subject 1

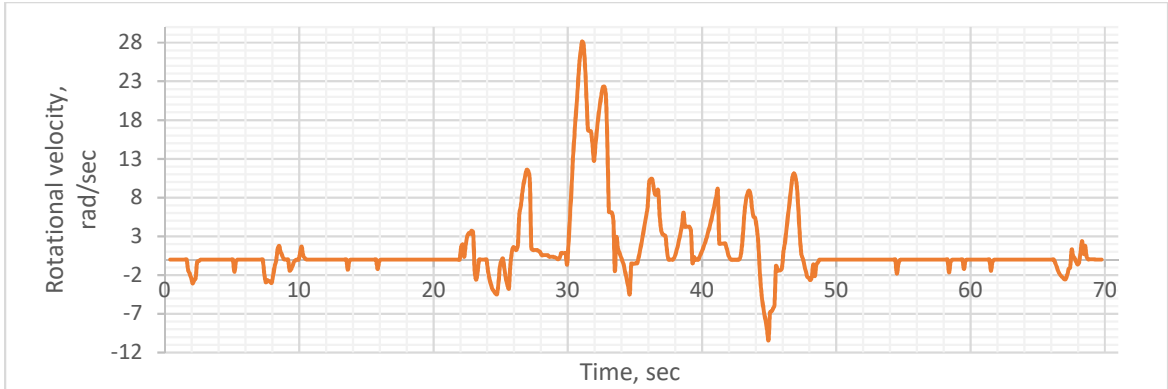


Figure 47. Rotational velocity about the center of mass, Subject 2

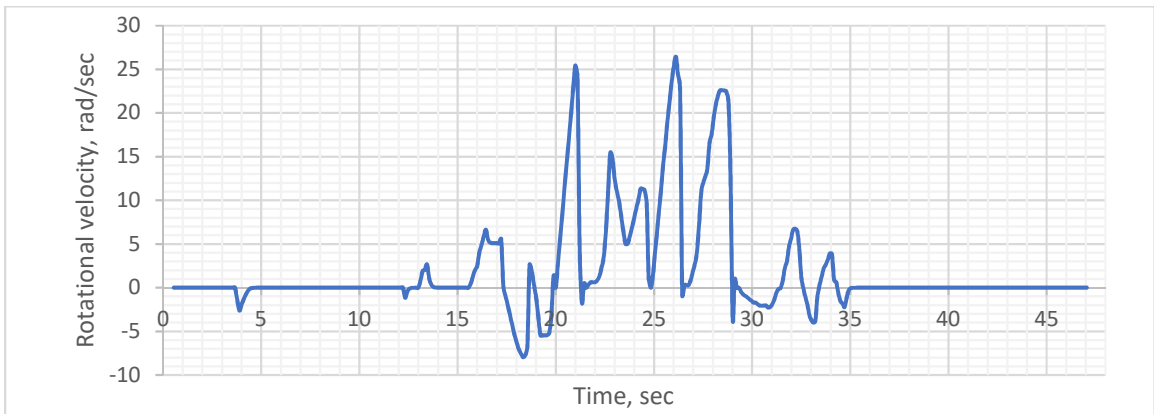


Figure 48. Rotational velocity about the center of mass, Subject 3

Subjects 2 and 3 rotational velocities, shown in Figure 46-48, have peaks during cornering only. This is in contrast to subject 1's rotational velocity in Figure 44, which shows peaks from the corner and until the end of the test. An explanation for this discrepancy is that have relatively accurate performance compared to subject 1; subject 1 bypassed the line on the floor during the cornering and was trying to get back on track all the way until the end of the test so his rotational velocity has more peaks in the end of the test.



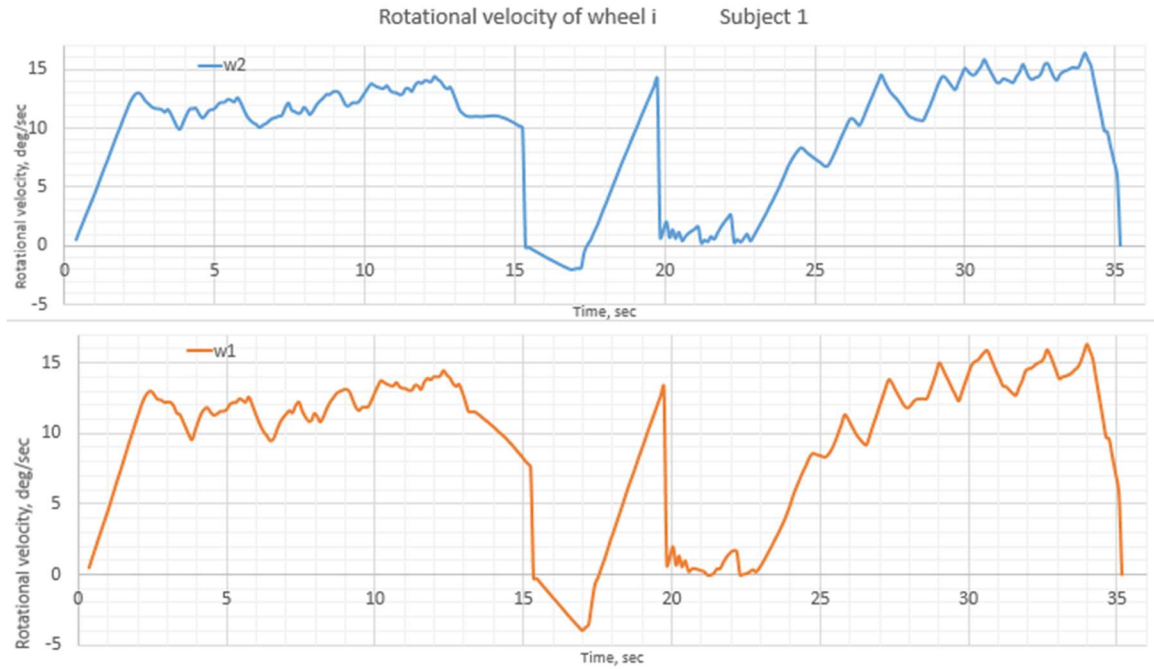


Figure 49. Rotational velocity of wheel  $i$ , Subject 1

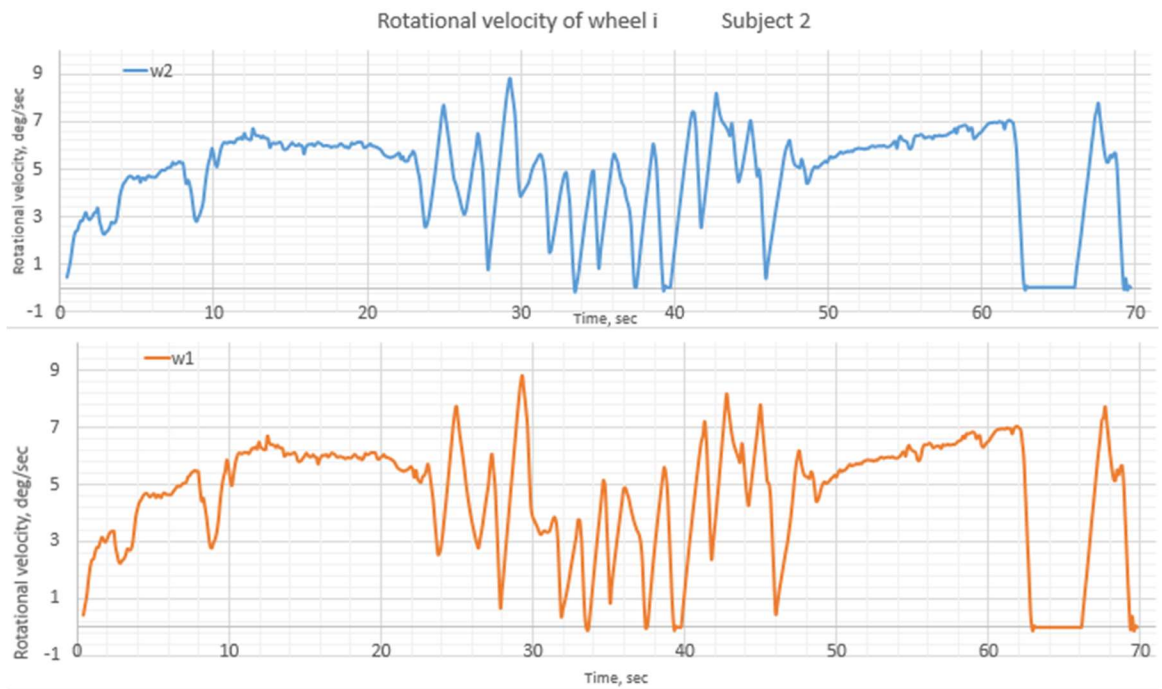


Figure 50. Rotational velocity of wheel  $i$ , Subject 2

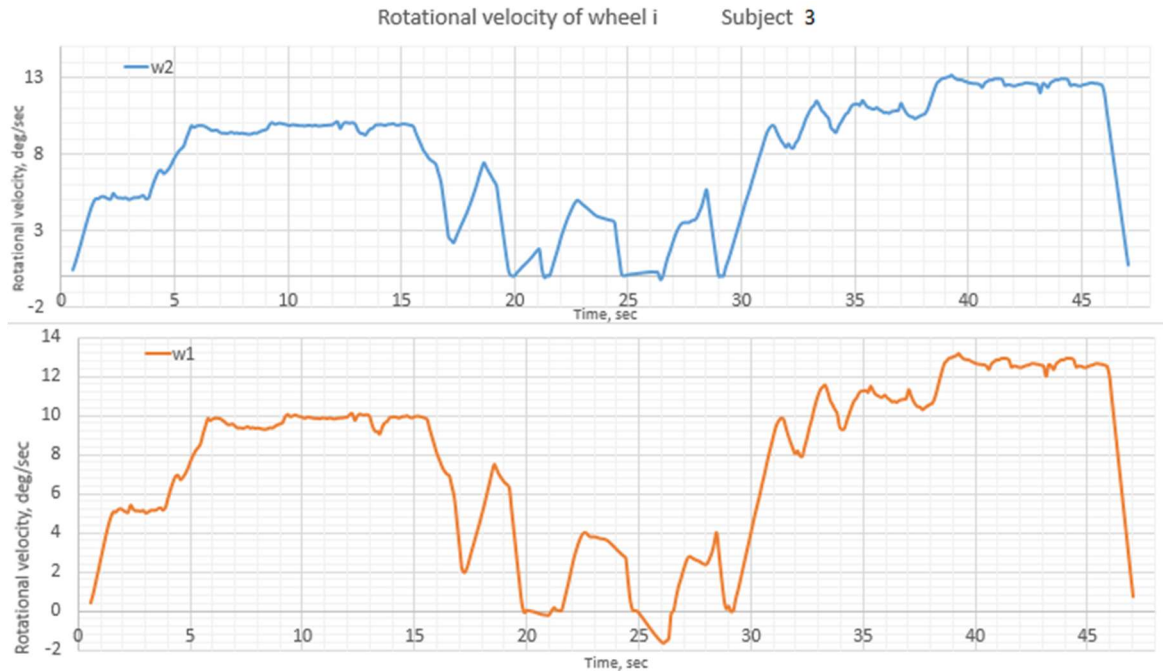


Figure 51. Rotational velocity of wheel  $i$ , Subject 3

Rotational velocity of the right ( $w_1$ ) and left ( $w_2$ ) wheels are displayed in Figure 49-51. While following a straight line, the subjects are almost or completely matching except during the cornering, when the left wheel is rotating faster. This is predictable since the physical PWC is operated by two separate electrical motors that rotate the wheels individually to turn left or right.

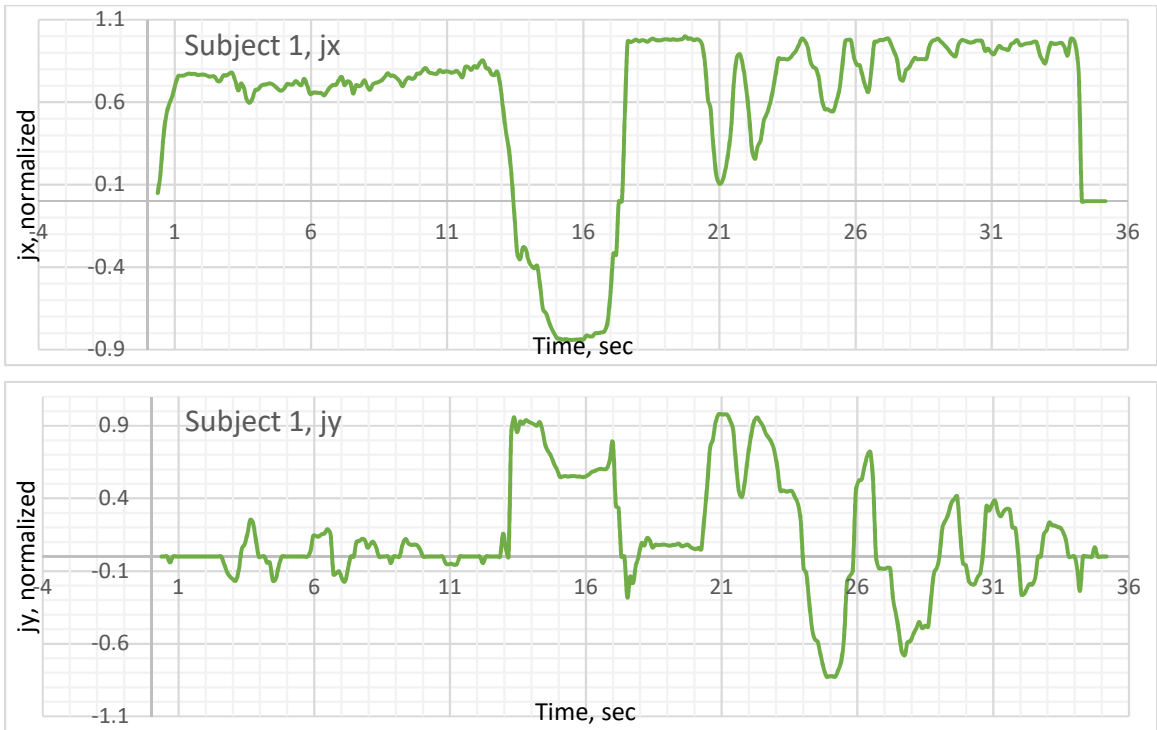


Figure 52. Joystick inputs along x and y axis, Subject 1

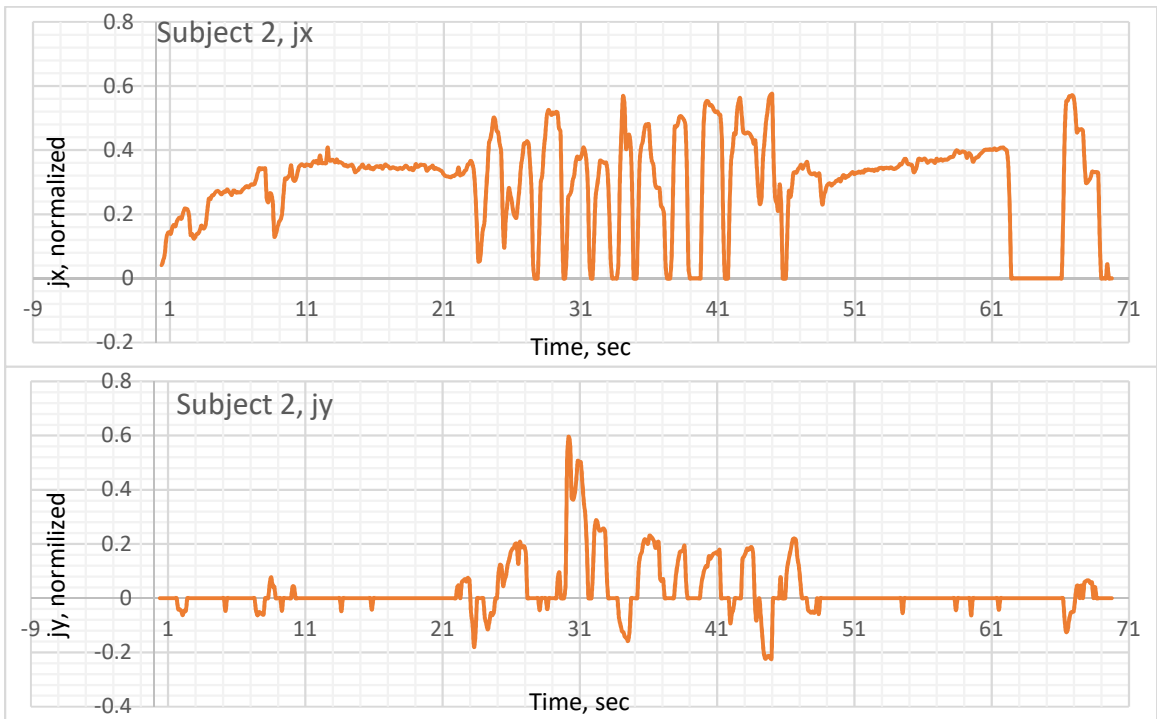


Figure 53. Joystick inputs along x and y axis, Subject 2

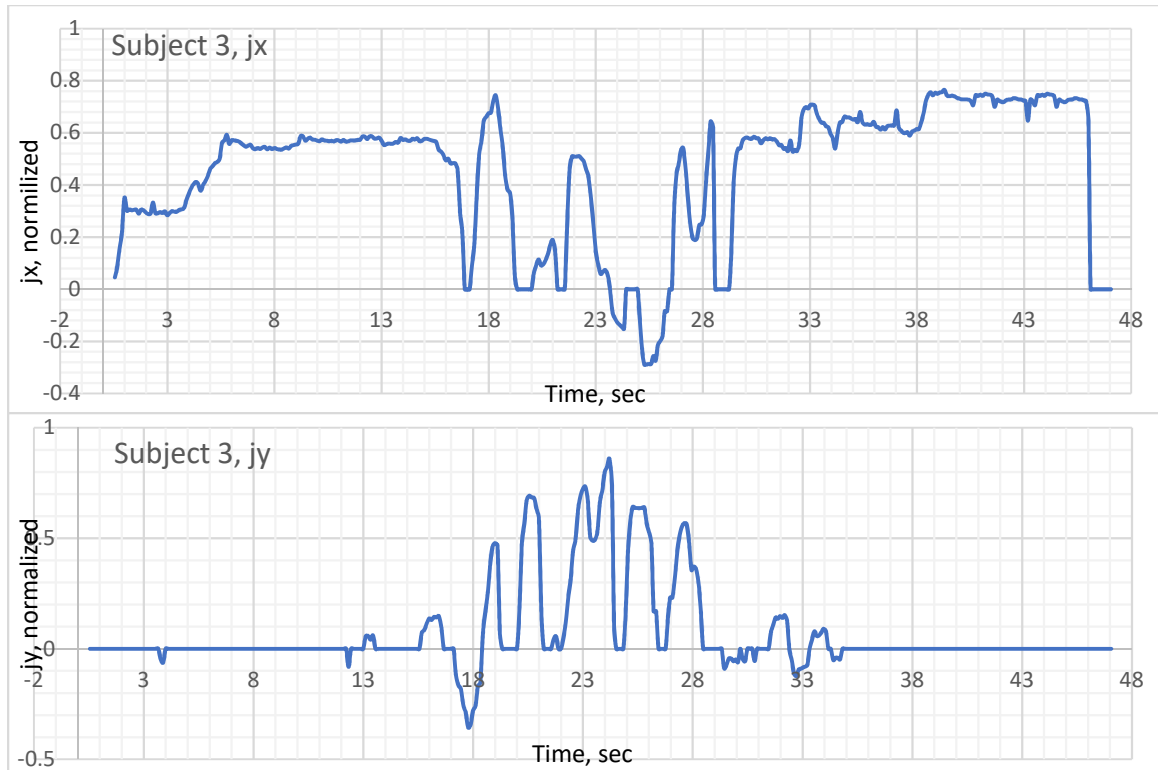


Figure 54. Joystick inputs along x and y axis, Subject 3

As a means to further explain the PWC movements, Figure 52 show joystick movements along it's  $x$  and  $y$  axis for each of the subjects. As expected,  $j_y$  input values are higher during the cornering, it is especially noticeable for subjects 2 and 3 since they had relatively accurate turns. Besides that, they were mostly following the straight line while pushing the joystick forward. Subject 2 indicated they didn't feel very confident while turning as verbally expressed during the turn and frequent stops with looking around. Another feature that distinguish subject 2 from the others is that the subject hasn't practiced any backwards movements. Subject 1 went forward much faster and ended up bypassing the line. It took a while and a number of movements back and forth to get back on the line. Subject 3 felt confident after positioning himself on the line, which can be concluded from moving with little deviation and was supported by the individual's verbal feedback.

## V. CONCLUSIONS AND FUTURE WORK

A semi-virtual driving simulator for a power wheelchair, developed in this project, has passed initial testing with human subjects. All of the subjects completed the test. The criteria for passing was that the subjects were able to drive the wheelchair in the virtual reality environment, appropriate tactile and audio feedback was delivered, and data was collected for each.

The simulator has been built on the base of 3D game environment controlled a physical PWC joystick interfaced with the programmed controller Arduino. The connection via serial communication has been established successfully and allowed to test an actual physical wheelchair on the stationary drive frame in the lab. Human subjects provided positive feedback regarding the semi-virtual reality experience and one of the test subjects showed accurate performance, although they had previous experience with the simulator. The feedback was expressed verbally and included excitement about the concept, quality of the VE visualization, and virtual and physical motion feedbacks. The most challenging part of the experiment for all of the subjects was turning; additionally, subjects without previous PWC experiences indicated some difficulties with deceleration.

The semi-virtual PWC simulator is ready for the upgrade in Phase 3 by adding the notch filter for tremors and testing with it. Future work in terms of VE can be conducted on improvement of the Unreal Engine 4 environment and blueprints; developing a survey to evaluate subjects perceived realism of the semi-virtual reality to help guide the improvements. In this simulation, a basic collision box around the PWC avatar was used, however it can be improved by using custom collision mesh to provide more accuracy. Virtual reality headset implementation in the simulator can be advanced to provide more realistic experiences. VR technology has been growing drastically and it is expected that with every update of Unreal Engine it may open new opportunities. Also, for further testing, the current hallway environment can be replaced with different architectures, scenery, rendering, lightning, etc.

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## APPENDICES

### A. Torque calculations

The conversion of the normalized joystick values to motor torque is based upon experimental testing of the PWC. Accelerometer and gyroscopic sensors were used to obtain measurements to estimate the maximum forward and backward speeds, maximum acceleration and deceleration, maximum rotational velocity, maximum rotational acceleration, and forward propelling torque. These estimates, along with observational data, results in the presented conversion. Before setting forth the conversion, the distance of the joystick from its center position and its angle from the PWC's forward direction are needed:

Joystick radial position:

$$r_j = \sqrt{j_{x,f}^2 + j_{y,f}^2} \quad (20)$$

Joystick angle from heading angle:

$$\theta_j = \tan^{-1} \left( \frac{j_{y,f}}{j_{x,f}} \right) \quad (21)$$

The conversion starts with identifying braking. In this case braking occurs when the joystick is at its approximate center position, specifically,  $r_j < 0.01$ . The wheel torque is equal to

$$u_{m,i} = \begin{cases} 0, & |w_i| < 0.1 \\ -2T_{max} \tanh(\omega_i), & \text{otherwise} \end{cases} \quad (22)$$

where  $i = 1,2$  denotes either wheel 1 or wheel 2, respectively, and  $T_{max}$  is the estimated maximum propelling torque equal to 6.5 Nm. Next, normal, non-braking operation is considered. Torque during normal operation is based upon the difference between the current wheel speeds and a constant, reference velocity speed. Thus, if the wheel speed is already at the reference wheel speed, torque will be zero. The use of zero torque at a constant speed is necessary for the WMR model used because it contains no dissipative elements. Specifically, the torques are

$$u_{mi} = -\text{sgn}(w_{i,ref}) \tanh(w_i - w_{i,ref}) T_{max} \bar{w}_{i,ref,max} \quad (23)$$

where

$$w_{i,ref} = r_j w_{i,ref,max} \bar{w}_{i,max} \quad (24)$$

$w_{i,max}=17.323$  rad/sec is the maximum angular velocity of a wheel,  $\bar{w}_{i,ref,max}$  is a normalized maximum reference value based upon the joystick angle  $\theta_j$ , There are four possible outcomes for  $\bar{w}_{i,ref,max}$  given the angular position of the joystick.

1. If  $0 \leq \theta_j < \pi/2$ ,

$$\bar{w}_{1,ref,max} = \left(-\frac{5}{6}\right) \frac{\theta_j}{\pi/2} + 1 \quad (25)$$

$$\bar{w}_{2,ref,max} = \left(-\frac{7}{6}\right) \frac{\theta_j}{\pi/2} + 1 \quad (26)$$

2. If  $\pi/2 \leq \theta_j \leq \pi$ ,

$$\bar{w}_{1,ref,max} = \left(-\frac{2}{3}\right) \frac{(\theta_j - \pi/2)}{\pi/2} + \frac{1}{6} \quad (27)$$

$$\bar{w}_{2,ref,max} = \left(-\frac{1}{3}\right) \frac{(\theta_j - \pi/2)}{\pi/2} - \frac{1}{6} \quad (28)$$

3. If  $-\pi/2 \leq \theta_j < 0$ ,

$$\bar{w}_{1,ref,max} = \left(-\frac{7}{6}\right) \frac{|\theta_j|}{\pi/2} + 1 \quad (29)$$

$$\bar{w}_{2,ref,max} = \left(-\frac{5}{6}\right) \frac{|\theta_j|}{\pi/2} + 1 \quad (30)$$

4. If  $-\pi < \theta_j < -\pi/2$ ,

$$\bar{w}_{1,ref,max} = \left(-\frac{1}{3}\right) \frac{(|\theta_j| - \pi/2)}{\pi/2} - \frac{1}{6} \quad (31)$$

$$\bar{w}_{2,ref,max} = \left(-\frac{2}{3}\right) \frac{(|\theta_j| - \pi/2)}{\pi/2} + \frac{1}{6} \quad (32)$$

## B. Human Subjects Institutional Review Board Letter of Approval

WESTERN MICHIGAN UNIVERSITY



Human Subjects Institutional Review Board

Date: July 25, 2016

To: Richard (Rick) Meyer, Principal Investigator  
Yuliia Sergeeva, Student Investigator for thesis

From: Amy Naugle, Ph.D., Chair

Re: HSIRB Project Number 16-06-02

This letter will serve as confirmation that your research project titled “Powered Wheelchair Human Operator Modeling and Tremor Filtering” has been **approved** under the **expedited** category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note: This research may **only** be conducted exactly in the form it was approved. You must seek specific board approval for any changes in this project (e.g., ***you must request a post approval change to enroll subjects beyond the number stated in your application under “Number of subjects you want to complete the study.”*** Failure to obtain approval for changes will result in a protocol deviation. In addition, if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

**Reapproval of the project is required if it extends beyond the termination date stated below.**

The Board wishes you success in the pursuit of your research goals.

**Approval Termination: July 24, 2017**

1903 W. Michigan Ave., Kalamazoo, MI 49008-5456

PHONE: (269) 387-8293 FAX: (269) 387-8276

CAMPUS SITE: 251 W. Walwood Hall

## **C. Informed Consent Western Michigan University**

### **Department of Mechanical and Aerospace Engineering**

**Principal Investigator:** Richard (Rick) Meyer, Ph.D., P.E.  
**Student Investigator:** Yuliia Sergeeva  
**Title of Study:** Powered Wheelchair Human Operator Modeling and Tremor Filtering

You have been invited to participate in a research project titled “Powered Wheelchair Human Operator Modeling and Tremor Filtering”. This project will serve as Yuliia Sergeeva’s thesis for the requirements of Master of Science.

This consent document will explain the purpose of this research project and will go over all of the time commitments, the procedures used in the study, and the risks and benefits of participating in this research project. Please read this consent form carefully and completely and please ask any questions if you need more clarification.

#### **What are we trying to find out in this study?**

The purpose of this study is to obtain (i) the inputs to a joystick while being held at rest and (ii) the joystick inputs of a powered wheelchair driver while they drive the wheelchair in a virtual reality world. These measurements will be first used to determine the frequency at which a person’s tremor (if any) is most severe. Also, the measurements will be used to see whether or not a simulation of the person driving the wheelchair can be made. Driving the wheelchair in the virtual world will let us test the effects of a tremor filter and electronic driving assistance on driver actions.

#### **Who can participate in this study?**

Participants are to be male or female, between 18 and 60 years of age, may or may not have a neurological disorder that causes hand tremor, can operate a powered wheelchair, and are not prone to motion sickness, are not anyone the principal investigator has grade giving power over at the time of your application to the study, are not a child (under 18), and are not cognitively impaired. You will be asked (i) if you are aware of any reason that you

cannot operate a powered wheelchair, (ii) if you are prone to motion sickness, (iii) if you are current student of the principal investigator, (iv) if you are a child, and (v) if you are cognitively impaired.

**Where will this study take place?**

The study will take place in Floyd Hall at Western Michigan University Parkview Campus. The possible rooms are F-209 and F-107.

**What is the time commitment for participating in the study?**

The study will require one visit to Floyd Hall. The study should take approximately 40 minutes from beginning to end.

**What will you be asked to do if you choose to participate in the study?**

You will be seated in the powered wheelchair for all of the tests below.

*Test 1.* You will be asked to hold the joystick in the center position with your “normal” grip while keeping your hand at rest. Your joystick inputs will be recorded over two minutes.

*Test 2.* You will put on the 3-D headset after the powered wheelchair simulator is started. Then you will be asked to drive along the course seen in the headset. During your drive, you will see both the ideal path to take as well as the ideal velocity to follow. To help you follow the ideal velocity, your velocity will be shown to you too. You will not have a time limit for the test, but it is not expected to take more than five minutes. To help you better understand the driving test, Figure 1 shows the 3-D world of the driving scenario looking down the first corridor and Figure 2 shows the overall driving task. No tremor notch filter or electronic driving assistance is on during Test 2 to help you.

*Test 3.* If you have tremor, Test 2 will be repeated now with the tremor filter active. This test should typically take no more than five minutes after the filter frequency is determined.

*Test 4.* You will perform Test 2 again now with the tremor filter inactive and electronic driving assistance active. This test should typically take no more than five minutes.



*Test 5.* If you have tremor, Test 2 will be repeated now with both the tremor filter and electronic driving assistance active. This test should typically take no more than five minutes.



Figure 55. Virtual corner turning scenario-looking down the first corridor.

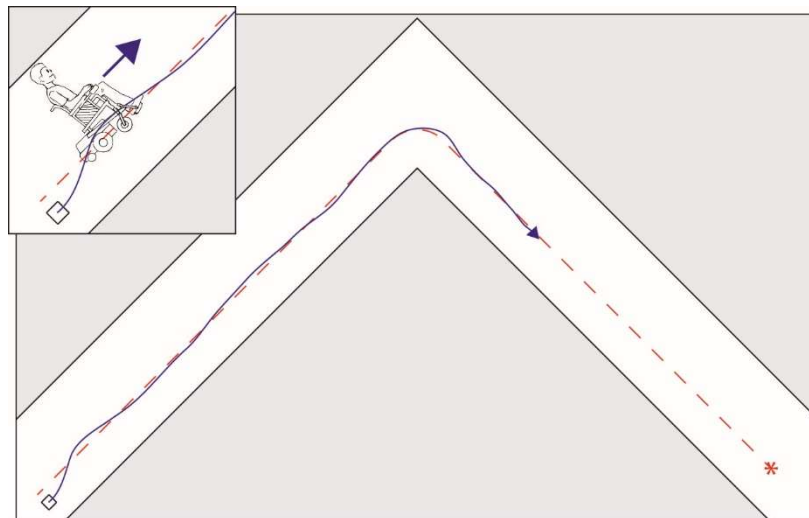


Figure 56. Powered wheelchair operation corner turning scenario.

**What information is being measured during the study?**

During all tests performed, your joystick inputs are measured. In addition, the virtual powered wheelchair movements are recorded. In addition, the following will be collected:

your name, age, sex, neurological disorder (if any), and self-evaluated powered wheelchair driving experience level.

**What are the risks of participating in this study and how will these risks be minimized?**

The risk of participating in this study is experiencing motion sickness from use of the 3-D headset. The risk is minimized by removing your 3-D headset at the first feeling of discomfort.

**What are the benefits of participating in this study?**

There will be no direct benefits to you in this research.

**Are there any costs associated with participating in this study?**

There is no cost for participating in this study.

**Is there any compensation for participating in this study?**

There is no compensation for participating in this study.

**Who will have access to the information collected during this study?**

The public will have access to age, sex, neurological disorder condition, and joystick measurements using physionet.org, a data repository supported by the National Institute of Health. Your name will be stored separately from the remaining data. The remaining data will be associated with a random number code. The name associated with each code will not be stored electronically and kept in a secure location.

**What if you want to stop participating in the study?**

You can choose to stop participating in the study at any time for any reason. You will not suffer any prejudice or penalty by your decision to stop your participation. You will experience NO consequences either academically or personally if you choose to withdraw from this study.

The investigator can also decide to stop your participation in the study without your consent. A potential reason to stop your participation is an inability to operate a powered wheelchair simulator.

Should you have any questions prior to or during the study, you can contact the primary investigator, Rick Meyer at 269-276-3427 or richard.meyer@wmich.edu. You may also contact the Chair, Human Subjects Institutional Review Board at 269-387-8293 or the Vice President for Research at 269-387-8298 if questions arise during the course of the study.

This consent document has been approved for use for one year by the Human Subjects Institutional Review Board (HSIRB) as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is older than one year.

-----  
I have read this informed consent document. The risks and benefits have been explained to me. I agree to take part in this study

---

Please Print Your Name

---

Participant's signature

Date

#### **D. Stationary Drive Frame**

The stationary drive frame showed in Figure 57-61 was designed by a Senior Design group at Western Michigan University [52]. The intent of the design was to keep the frame as small as possible and easy to transport. A folding test frame was designed with rollers for both drive wheels, ramps that can slide in and out of the frame as needed, a retractable handle and two swivel wheels for transportation. Testing of the frame showed it satisfied the design objectives.

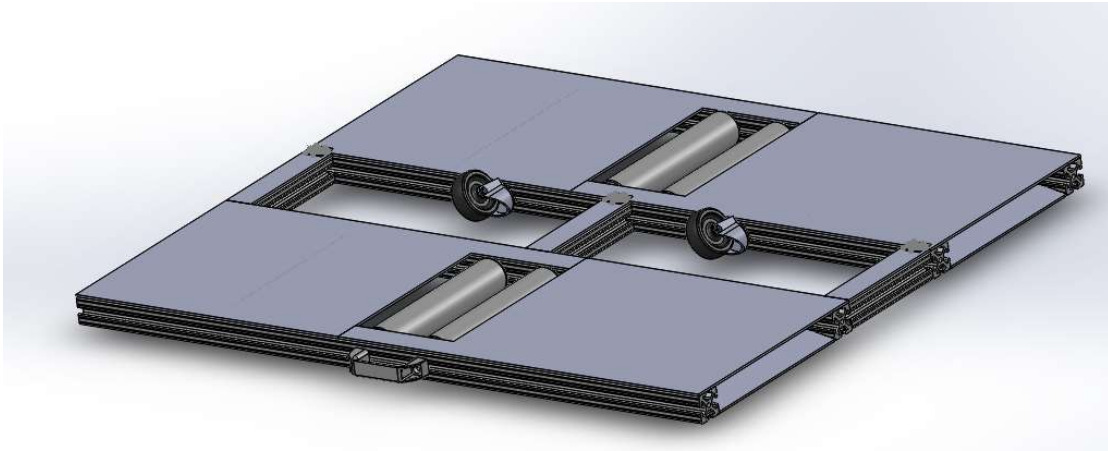


Figure 57. Frame showing ramp inserted [52]

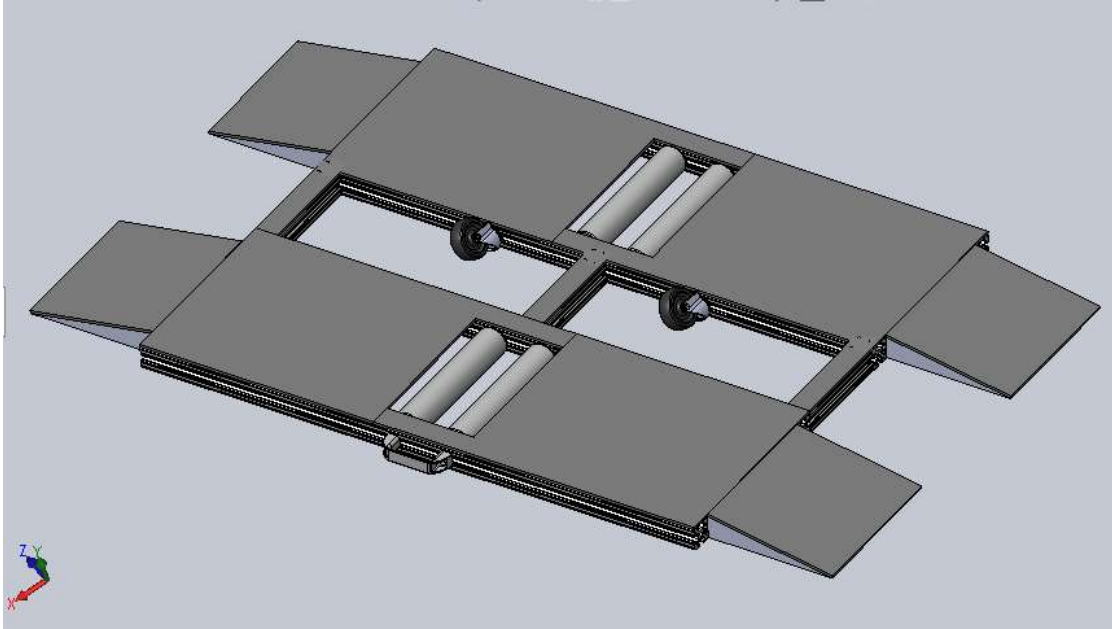


Figure 58. Frame showing ramps extended [52]

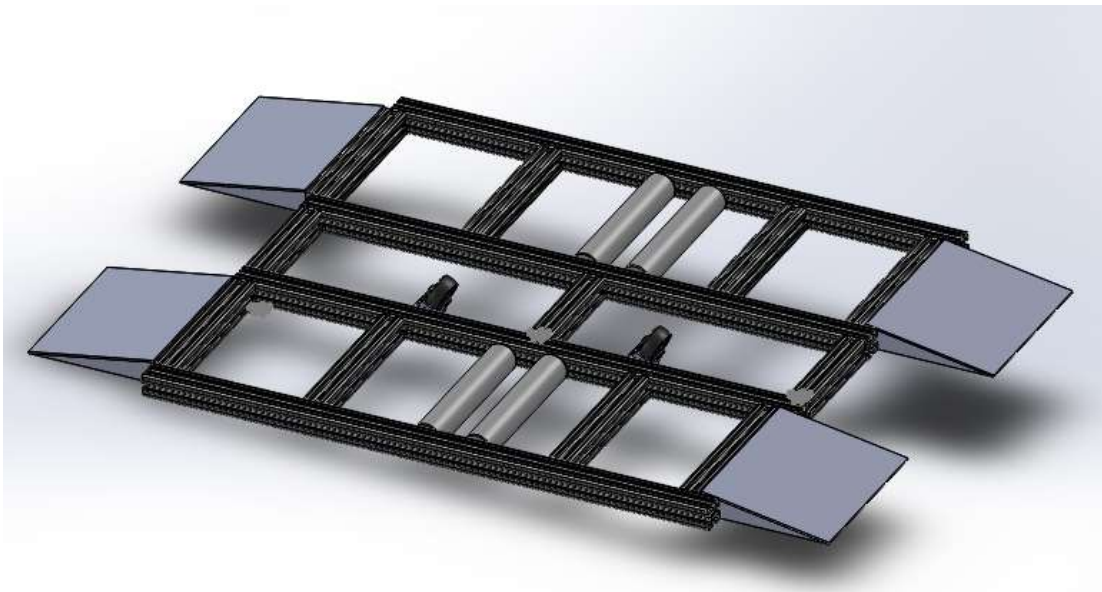


Figure 59. Frame showing internal structure [52]



Figure 60. Folded frame [52]

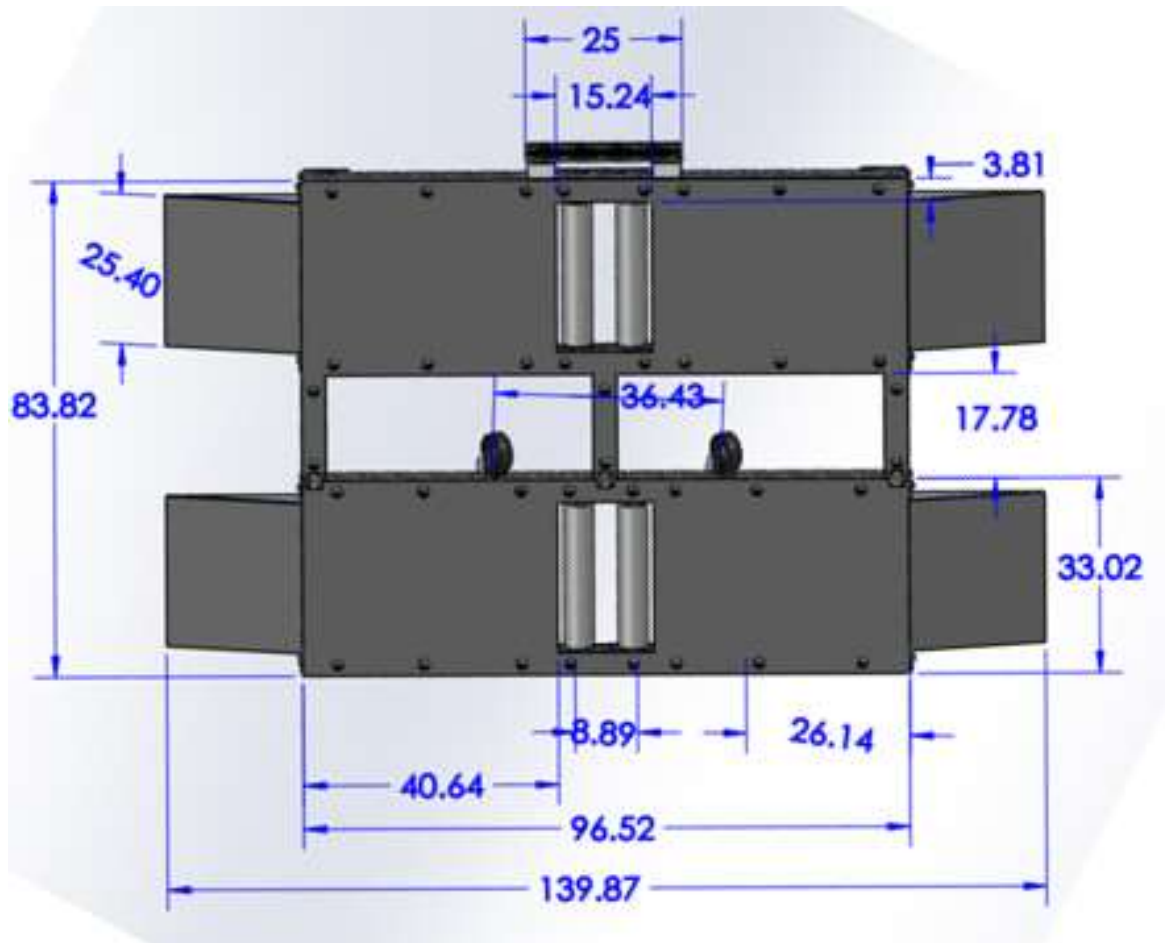


Figure 61. Frame dimensions [52]