DEVELOPEMENT AND VALIDATION OF A CASTER DATA LOGGER FOR QUANTITATIVE MEASUREMENT OF ELECTRIC POWERED WHEELCHAIR USAGE

by

Garrett George Grindle

BSE, University of Pittsburgh, 2004

Submitted to the Graduate Faculty of

School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science in Bioengineering

University of Pittsburgh

2007

UNIVERSITY OF PITTSBURGH

SCHOOL OF ENGINEERING

This thesis was presented

by

Garrett George Grindle

It was defended on

March 22, 2007

and approved by

Shirley Fitzgerald, PhD, Associate Professor, Rehabilitation Science and Technology

Michael Boninger, MD, Professor, Physical Medicine and Rehabilitation, and Bioengineering

Thesis Advisor: Rory A. Cooper, PhD, Distinguished Professor and FISA/PVA Chair,

Rehabilitation Science and Technology, and Professor, Bioengineering

DEVELOPEMENT AND VALIDATION OF A CASTER DATA LOGGER FOR QUANTITATIVE MEASUREMENT OF ELECTRIC POWERED WHEELCHAIR USAGE

Garrett George Grindle, M.S.

Electric powered wheelchairs (EPWs) are an important form of mobility for many persons with disabilities. However, little quantitative data exists on how much people use their EPWs in real-world environments. Previous devices have been successful at measuring EPW usage, but they have been limited by the size or the battery life of the device. This study describes the design, development, and validation of caster data logger (CDL) suitable for long-term collection of EPW usage data in real-world environments. Also included in this study is a description of EPW usage data collected during and after the National Veterans' Wheelchair Games (NVWG).

Several device concepts for logging EPW usage were evaluated. A caster data logger concept was chosen and functional prototypes were fabricated. The prototypes were subjected to a variety of bench tests before being deemed suitable for field use. 10 CDLs were constructed of data collection at the NVWG.

At the NVWG, subjects who used an EPW as their primary means of mobility were recruited for this study. In 5 days at the games the participants (n=5) traveled a distance of 7751 ± 3439m per day, while traveling 3397±1300 m (n = 4) per day during 5 days the following week. The results were limited due to small sample size; however, they could provide useful pilot data for future studies.

Overall, the CDL showed potential as a useful tool for measuring EPW usage. Future development should focus making the device easier for researchers and clinicians to use.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to thank all those who contributed in some way to the success of this study. I would like to express my appreciation to Dr. Boninger and Dr. Fitzgerald for serving on my committee and for always being willing to sit down and talk with me. I would like to thank Dr. Guo for all the electronics wisdom he has passed along to me. And a special thanks goes to Dr. Cooper who has unwaveringly supported me in countless ways over the past five years, for which I will always be grateful.

I wish to extend sincere thanks to the staff at HERL for all they have done for me over the years. I would especially like to thank Michele Tolerico, Mark McCartney, and Jeremy Puhlman for their efforts; I could not have finished this study without them. I would also like to express my gratitude to Paula Stankovic, who has made sure I never got lost in the shuffle at HERL.

Lastly, I would like to thank my friends and family for their support during my graduate career, with special thanks going to my Mom and Dad for always being there.

1.0 INTRODUCTIION

1.1 RESEARCH OBJECTIVES

The broad goal of this study is create a device suitable for the collection of electric powered wheelchair (EPW) usage data that can be utilized for a broad range of research and clinical applications. The long term objective is to use this device in conjunction with other data collection devices and reported information in order to better quantify the driving characteristics of populations of EPW users. The knowledge gained from these studies may be used to improve EPW design, elucidate barriers to participation, validate standards, and influence public policy. The narrow goal of this manuscript is to chronicle the rational of the design, bench testing, and pilot use of this device.

1.2 SIGNIFICANCE

In the United States over 200,000 people rely on EPWs as their primary means of mobility [1]. EPWs are typically used by persons who are unable to functionally ambulate and do not have the ability to propel a manual wheelchair. The diagnosis of EPW users varies greatly and can include spinal cord injury, cerebral palsy, multiple sclerosis, traumatic brain injury, cerebral vascular accident, and numerous others. In 2003 Medicare spent over 1 billion dollars on powered mobility [2]. Despite the prevalence and economic impact of EPW use, little is known about the driving habits of their users. Hence, Cooper et al [1] cites determination of wheelchair usage patterns as a research priority.

Electric powered wheelchairs also serve as an important facilitator for community participation. In a study of older EPW users, Brandt et al [4] concluded that EPW are a relevant intervention that makes participation possible. In an investigation by Meyers et al [4] of barriers and facilitators facing wheelchair users, assistive technology and equipment was often cited as a facilitator. Despite the opportunities wheeled mobility provides, barriers to participation still exist [4,5,6,7,8]. Better methods for measuring environmental barriers are needed in order to address the problems [6]. In a study of activity, Tudor-Locke et al [9] claims that self report tools can be inaccurate and the quantitative and self report technique should be used in combination.

1.3 BACKGROUND

1.3.1 Portable research data loggers

Small, battery powered data loggers have been valuable tool for collecting data in a variety of biomedical research applications. Recent advances and reduced costs of micro processor, solid state memory, and battery technology, have allow the development and use of data loggers that can be worn by humans or animals in their environment, without altering their activities. Some recent examples include, Vyssotski et al [10] who utilized a data logger for collecting electroencephalography (EEG) and global positioning system (GPS) data in airborne homing pigeons. Witte el al [11] collected limb accelerations and GPS data of thorough bred horses, while running, using radio telemetry data logger. While, Yao et al [12] developed a wearable, plug and play, microcontroller based system for recording physiological parameters home health monitoring in humans.

Many data logger studies have been aimed specifically at capturing human activity. A light-weight, low power, thigh worn data logger and algorithms were created by Miyazaki [13] to measure thigh accelerations, and calculate stride length and walking velocity. Herren et al [14] showed that running speed and terrain incline could be detected and logged on real running courses using a tri-axial accelerometer data logger worn on the lower back. Similarly, Culhane et al [15] demonstrated that activities, such as sitting, standing, and dynamic movements of older adults could be logged and identified using an accelerometer data logger. A wearable data logger for recording electromyographical (EMG) signals was developed by Hansson et al for estimating physical workload. In regards to wheelchair activity, Postma et al [16] were able to use a six accelerometer data logger system to identify periods of manual wheelchair propulsion.

A subset of activity monitors commonly used in research is pedometers, which count steps during ambulation. The accuracy of various pedometers has been verified in several studies [17, 18, 19, 20). Schneider [17], in a study of 10 commercially available pedometer models, concluded that all tested pedometers were accurate; however, some were very accurate. Melanson [19] found that the accuracy of the pedometer decreased with increasing age, weight, and Body Mass Index. Pedometers have been successfully used in a variety of research studies to quantify activity [21-27]. The study topics ranged validating self reported activity data [23] to determining the effects of weather on walking [24]. One limitation of pedometers cited by Knapik et al [26] was the participants sometimes forgot to wear their pedometer, resulting in incomplete data sets. The use of pedometers as an intervention has also been studied [22,27]. De Blok et al [22] follow two groups of chronic obstructive pulmonary disease patients through rehabilitation with one group receiving activity level feedback from a pedometer and the other group did not receive feedback. They concluded that the pedometer aided in rehabilitation. Mermon et al [27] compared two groups of sedentary individuals who wished to become more active with one grouping pedometer feedback and the other without. They found that the group using the pedometers was more active.

1.3.2 HERL data logging

In attempt to better quantify daily driving habits of wheelchair users, the Human Engineering Research Laboratories (HERL) developed a first generation data logger for the collection speed and distance traveled by wheelchair users [28]. This data logger utilized a commercial data logger board and was encased in a water tight aluminum chassis. The chassis was mounted to the frame and was wired to reed switch sensor placed behind the wheel. A magnet was placed on the wheel to activate the reed switch, allowing the data logger board to count revolutions. This device was used on both power and manual wheelchairs in a study by Cooper et al [29]. However, this data logger was bulky and was greatly limited due to high power consumption, so Spaeth et al [30] developed low power, miniature data logger (MDL) for manual wheelchairs. Electrically, the MDL circuit board consisted of MSP430 microcontroller (Texas Instruments), a 32 MB flash chip, and three reed switch sensors. For this concept, the entire data logger was placed on the wheel and a stationary pendulum activated the reed switches. The device was light, compact, and had battery life on the order of months, instead of days with previous generation.

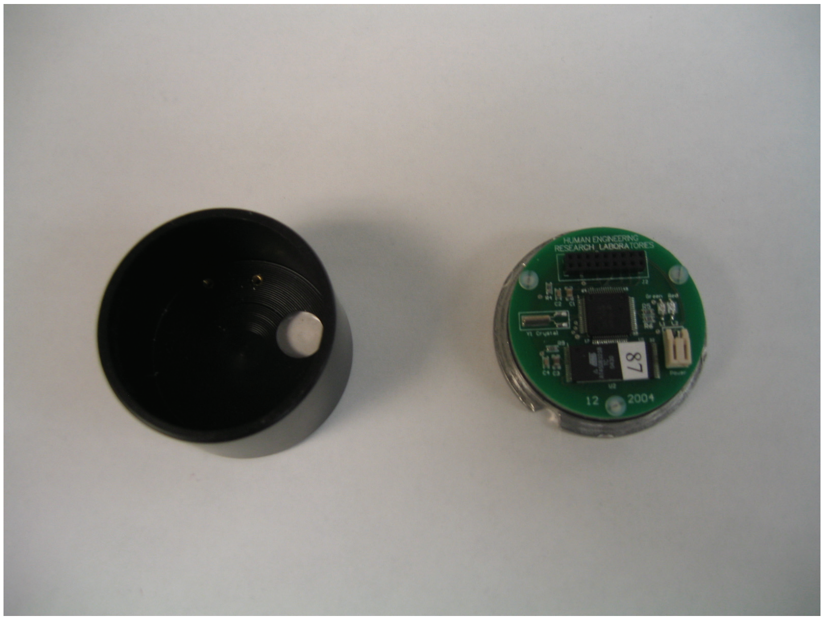

Figure 1.1 Photograph of the insides of manual wheelchair data logger described in Spaeth el al [30]

These data loggers have been successfully used in several research studies. Cooper et al [29] used the first generation data logger to study two groups of EPW users: one from Pittsburgh and the other from the National Veterans Wheelchair Games (NVWG), both over a 5 day period. They conclude that all users were more active in the afternoon and evening and that the NVWG group was more active than the Pittsburgh group. The MDL has demonstrated its usefulness in several research studies. Fitzgerald et al [31] utilized this data logger while comparing pushrim-activated, power-assisted wheelchairs to standard manual wheelchairs. Kaminski [32] used the first generation data logger to track EPW usage and the MDL to track manual wheelchair usage in children. The study showed that children manual wheelchair users traveled 1,583.6±880.2 m and that EPW users traveled 1,524.5±1,057.0 m on an average day. Tolerico [33] used the MDL to track 39 manual wheelchair users at the NVWG and for two weeks in their home setting following the games. In addition to the use data collect with the MDL, demographic data was obtain through a questionnaire. The study resulted in the participants traveling an average of

6,566.84±3,203.09 m at the NVWG and 1,994.09±1,851.2 m in their home setting. The study concluded that participants who had used a wheelchair longer traveled farther, and that employment influenced wheelchair usage in the home setting.

1.3.3 Wheelchair caster testing

Various research studies have examined the loads placed on wheelchair caster assemblies in different scenarios. During an investigation of the accelerations during wheelchair caster impacts with a curb, Cooper et al [34] found that the maximum resultant accelerations were 7.4±2.09g. Base on this information, a pendulum impact test was proposed, as a more convenient, equivalent, alternative test to driving wheelchair casters into a curb. Bertocci et al [35] used a computer model to simulate a 50th percentile male occupying an 85 kg wheelchair in a 20g / 48kph fontal vehicle crash. The simulation determined that in worst case, the front wheel loading was 8,002 N. In 1999, Bertocci et al [36] test several caster assemblies from commercial wheelchair using a dynamic drop test. The inquiry determined that all the assemblies failed at less than 8000 N and had a range of loading rates from 89 – 218 N/msec. They concluded that caster assembly designs may not provide adequate performance during a frontal vehicle crash. In order to validate the earlier computer simulation Bertocci and van Roosmalen [37] used a dynamic sled impact test to measure caster loads. Using the same parameters as the simulation, the maximum normal load on the caster was 7,209 N. In conclusion, they recommended that manufactures design caster for a normal load of 8000 N, assuming an 85kg wheelchair and a 75kg occupant.

1.4 CONCLUSION

The previously described data loggers have shown that these devices can be leverage to accomplish a wide range of research and can be used as an intervention tool. The cited studies suggest that many barrier exist that hinder community participation by EPW users. It stands to reason that data logging applied to EPW usage could result help elucidate specific factors that limit mobility, which has been successfully done with both pedometers and manual wheelchair data loggers.

2.0 CONCEPTS

2.1 SECTION INTRODUCTION & DESIGN CRITERIA

The purpose of this section is to describe the formulation and evaluation of different device concepts aimed a recording EPW use. This work was completed prior to the 2005 NVWG. Each of the concepts is described and the benefits and problems of each device are discussed. The various concepts were developed using following design criteria:

-The device must capture and store driving patterns traveled by the EPW users
-The device should have a battery life of at least 90 days
-The device should easily be attached and removed from the EPW
-The device must not damage the EPW
-The device must not compromise the safety of the EPW user
-The device should attach to a wide variety of EPWs
-The device must not interfere with the user's activities in any matter

Theses design criteria are based previous information gained in the development and usage of the Manual Wheelchair Data Logger and to ensure the safety and dignity of the participant is maintained.

In order to further characterize the situation, the drive wheels of several popular makes and models of EPWs were investigated. Observations of these EPWs were taken at the Center for Assistive Technology and included the diameter of the drive wheel, distance, the type of hub, and a digital photograph was taken of each wheel. A wheel was considered a hub with spokes if it had openings from the front to the back of the hub and if no opening existed it was considered solid. A table of EWP models and wheel dimensions are given in Table 2.1.

Table 2.1 gives the evaluated makes and Models, along with the diameter of the wheel in inches and the type of hub.

Model(s)	Brand	Wheel Size	Hub Type
Alante	Golden	10 inch	Solid
Technique	Hoveround	10 inch	Spokes
Arrow	Invacare	13 inch	Spokes
ProntoM50	Invacare	10 inch	Solid
ProntoM91	Invacare	13 inch	Spokes
TDX	Invacare	13 inch	Solid
1113, 1103	Jazzy	10 inch	Solid
1120	Jazzy	13 inch	Spokes
1121, 1122, 1170	Jazzy	13 inch	Spokes
1420, 1470	Jazzy	13 inch	Spokes
Entra, C2K, C2KS, HD3	Permobil	13 inch	Spokes
Jet	Pride	13 inch	Solid
Vibe, Blast	Pride	13 inch	Spokes
320	Quickie	10 inch	Solid
Aspire	Quickie	10 inch	Solid
626	Quickie	13 inch	Spokes
Rascal	Electric Mobility	10 inch	Solid

2.2 MODIFIED REED SWITCH ARRAY

2.2.1 Concept description

The modified reed switch array concept is based on a previous attempt to repackage the MDL to fit EPWs. The original design included an array of three closely spaced reed switches in a custom thin plastic package, which was to mount behind the drive wheel using Velcro. A wire connected the reed switch package to a box containing the MDL circuit board and a battery. The box could be attached with wire ties or Velcro to convenient location on the frame. A pictorial description of the system is given in figure 2.1

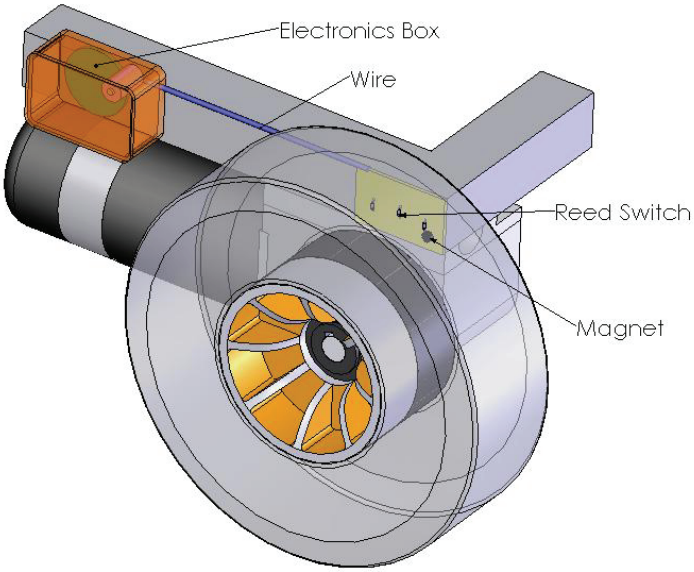

Figure 2.1 is conceptual model of the previous generation of the reed switch array

A magnet is glued to tire of EPW, which activates the reed switches. The original concept was unsuccessful for couple of reasons: the reed switches all activated at once, the magnet was difficult to align with the array, and it took an extended time to glue the magnet. In order to improve this design, the reed switches could be placed further apart in an arc as shown in figure 2.2.

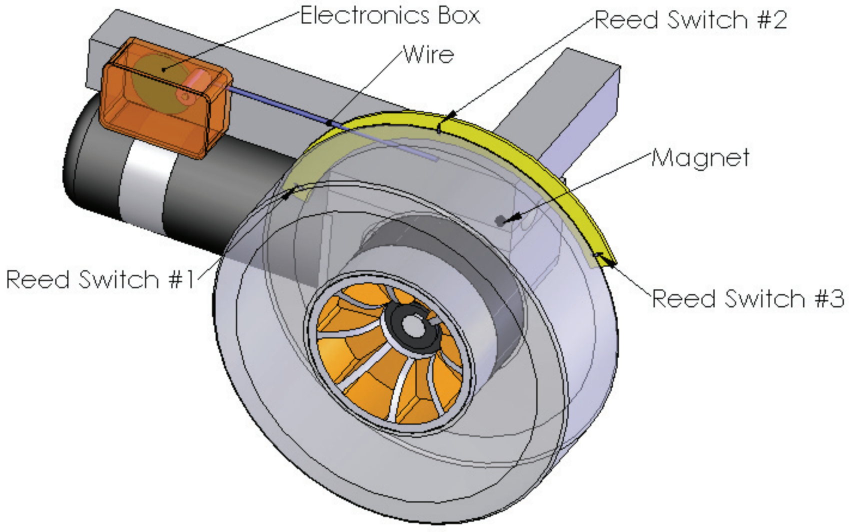

Figure 2.2 is a conceptual model of the modified reed switch array.

Several arcs of various radii could be constructed and could be plugged in to the electronics box in a modular manner.

2.2.2 Concept advantages

One of the potential advantages of this concept was that the electronics box could be mounted securely and discretely on nearly any EPW frame. The modular arc design also allowed some flexibility to accommodate wheels of various diameters. The package of the arc shaped array gave it more surface area to attach Velcro to, giving it greater potential to interface with a variety of EPW frames. By distancing the three reed sensors, they would be activated at different times, creating the ability to calculate the wheel direction.

2.2.3 Concept disadvantages

The modified array would have solved the problem of all three sensors activating at once; however, the issue with mounting alignment and the use of adhesive to attach the magnet are still present in this concept. The larger size of the array package would add to the attachments robustness, but could have caused additional problems in the tight space behind the drive wheel. This device would also be difficult to mount on an EPW with a shroud blocking access to the area behind the wheel.

2.3 REPACKAGED PENDULUM CONCEPT

2.3.1 Concept description

The repackaged pendulum concept was closely based on the MDL; however, the housing was designed to be thinner, as to fit in the tight space inside the drive wheel hub. As shown in figure 2.3, a pendulum with a magnet mounted into it was encircled by three reed switches. The reed switches were connected to a circuit board resting next to the pendulum, instead of on top of it, as in the case of MDL. When mounted on the backside of the drive wheel, the pendulum and magnet would hang in place, while the reed switches and circuit board revolved around them. These components were housed in a thin plastic housing that would have eyelets for attachment using wire ties to the spokes of the drive wheel. In the cases where the drive wheel did not have spokes a clamp could be made.

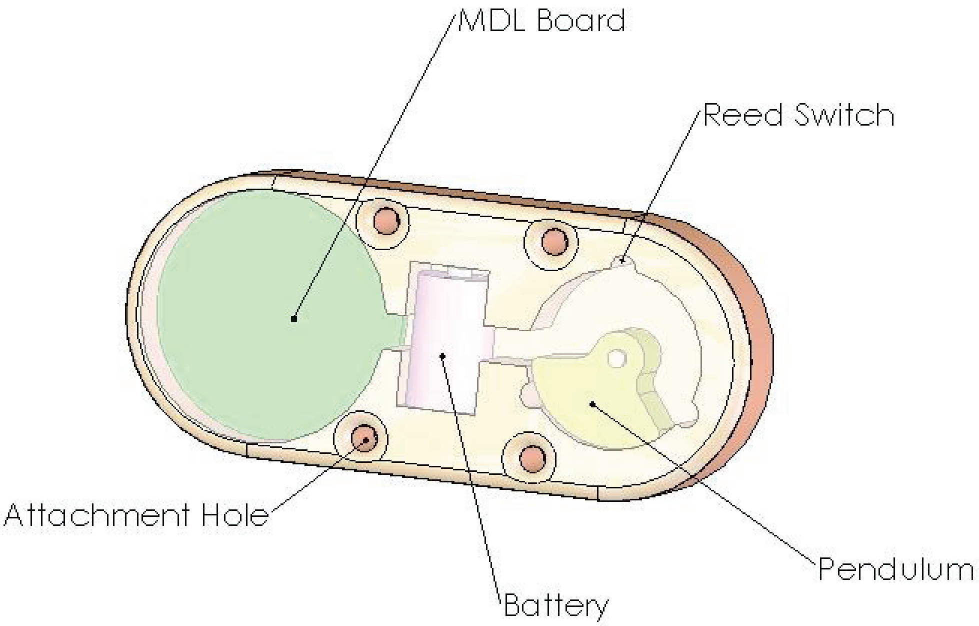

Figure 2.3 shows the conceptual model of the repacked pendulum concept with the circuit board and pendulum side-by-side.

2.3.2 Concept advantages

The primary advantage of this concept was that is self contained in one small package. With the sensors, circuit board and battery in a single housing, the need to carefully route wires, glue magnets, and align the sensor is eliminated. The concept would be virtually unnoticeable behind the wheel. Since this concept very closely followed the MDL design, parts such as the pendulum which had previously gone through extensive development could be used to expedite the development process.

2.3.3 Concept disadvantages

Despite having a clean and compact package the issue of attaching the modified pendulum concept to a wide variety of EPWs remained. Plastic zip ties would work for wheels with open spokes; however, if the wheels were solid, a bracket would need to be made, which would be specific to that EPW wheel. As demonstrated by the study of EPW drive wheels, considerable variation exists among wheels and making individual brackets for all wheel styles would be impractical. The limited and sometimes difficult to access space behind the wheel could make it very difficult or impossible to mount on some models.

2.4 ACCELEROMETER CONCEPT

2.4.1 Concept description

The accelerometer concept utilized a biaxial MEMS-based accelerometer as the sensor for capturing the motion of the drive wheel. A PCB board would be created with a micro-controller that would interface with the accelerometer. If the accelerometer is fixed with the both axis normal to the axle, a sine would be expected with the frequency proportional to wheel velocity. The PCB and battery would be placed in a small protective package that could be attached to the drive wheel with zip ties or Velcro.

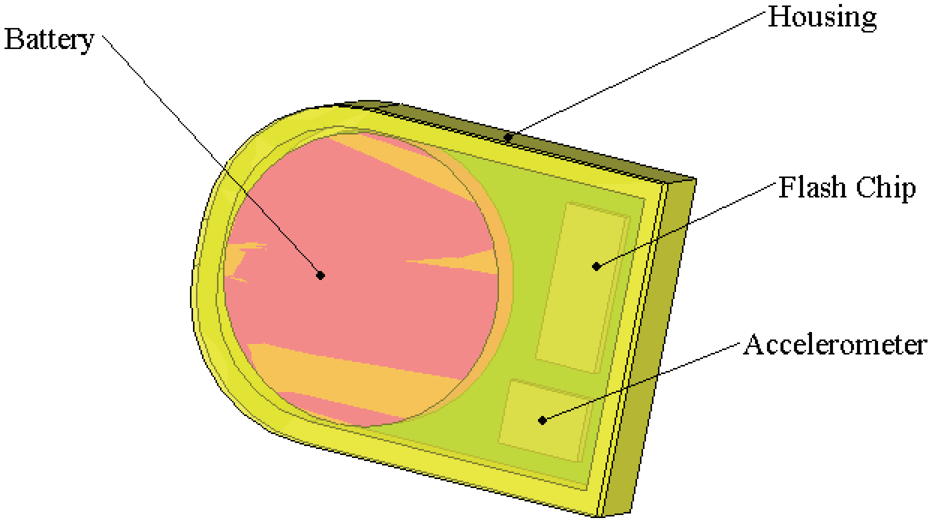

Figure 2.4 was a conceptual model of he compact packaging of the accelerometer concept.

2.4.2 Concept advantages

The distinct advantage on this concept is that it contains no mechanical parts. One result of having an entirely mechanical design was that size of this data logger concept could be extremely compact and lightweight. The small size would allow this device to mount in tighter spaces than the modified pendulum concept and with a lighter weight could be attached to solid wheels using Velcro. Having no mechanical parts would greatly reduce the time required for manufacturing. Since none of the parts are custom machined, it would be easier to maintain quality from board to board.

2.4.3 Analytical model & simulation

The accelerometer concept is highly dependent on recovering the acceleration due to the wheel rotating, so an analytical model was created and realistic parameters were used to simulate what the biaxial accelerometer output would look like while driving over a real surface. In figure 2.5 a free body diagram (FBD) of a rotating and translating wheel with an accelerometer on it is given. The FBD has two coordinate systems: a global coordinate system, which represented with capital letters, and local coordinate system coincident with axis of the accelerometer, which is represented with lower case letters. In the global system A_g represents the acceleration due to gravity, A_t represents the acceleration due to translation, and A_{vib} represents vibration acceleration. In the local system a_x represents the acceleration at the x axis of the accelerometer, a_y represents the acceleration at the y axis of the accelerometer, a_t represents the local translational acceleration, and α represent the angular acceleration of the wheel. The constants R and r symbolize the radius of the wheel, and the radius of the accelerometer respectively. The model assumes that system is planar.

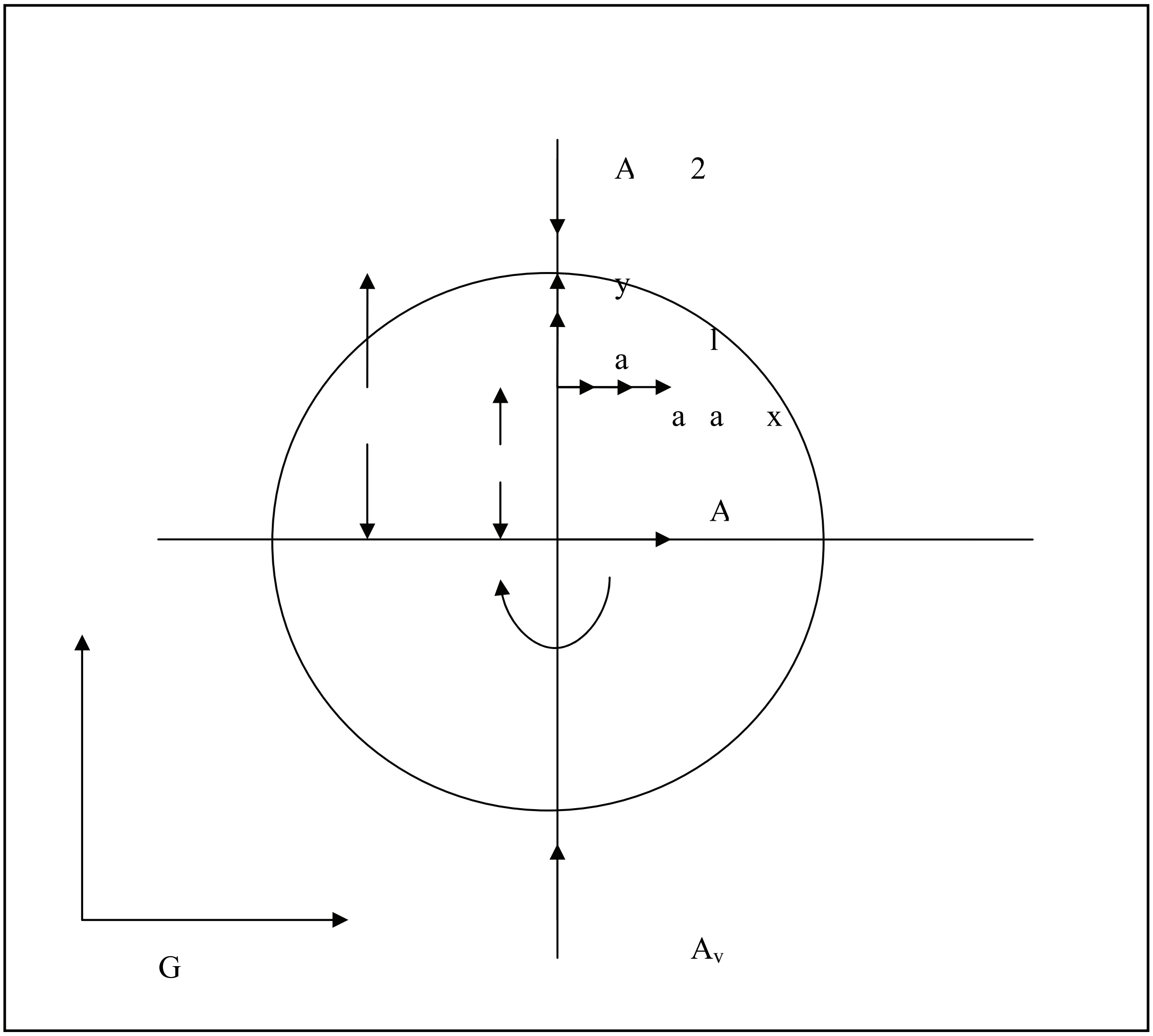

Figure 2.5 gives the free body diagram of the accelerations acting on the wheel and accelerometer. The Global coordinate system is given in capitals and the local coordinate system is given in lower case.

Using the free body diagram, the general accelerations were summed to find the acceleration at the accelerometer as given in equation 2.1.

$$a_{Local} = A_{Vibration} - A_{Gravity} + a_{Translational} + a_{Rotational} \qquad \text{Equation 2.1}$$

The acceleration can be written specifically for each axis of the accelerometer as given in equations 2.2 and 2.3.

$$a_x = A_{vib}\sin(\theta) - A_g \sin(\theta) + A_t \left[\frac{r}{R}\right]\cos(\theta) + \alpha * r\cos(\theta) \qquad \text{Equation 2.2}$$

$$a_y = A_{vib}\cos(\theta) - A_g\cos(\theta) + A_t\left[\frac{r}{R}\right]\sin(\theta) + \alpha * r\sin(\theta) \quad \text{Equation 2.3}$$

Once the equations for the acceleration experienced by the accelerometer were obtained, realistic parameters were selected to create simulation. A 10 inch wheel was selected for R and 4" was selected for the position of the accelerometer. A translational acceleration of 2.75 m/s^2 was chosen, which is a high rate but achievable by many EPWs. The angular acceleration, α, is related to the translation acceleration, A_t, by equation 2.4.

$$\alpha = A_t\left[\frac{1}{R}\right] \quad \text{Equation 2.4}$$

The vibration noise term, Avib, was included to simulate driving over a surface. A random number function in Excel was used to create vibration noise, with the range of the random number taken from the values collected by Wolf et al in a study of vibration caused by driving an EPW over various interlocking paving surfaces. Figure 2.6 shows the simulated accelerations at the x and y axis of the accelerometer, and 2.7 compares the entire a_x signal to the x axis gravity component. The gravity components result in the most prominent sine wave and serve as the idea signal for recovering wheel position and velocity.

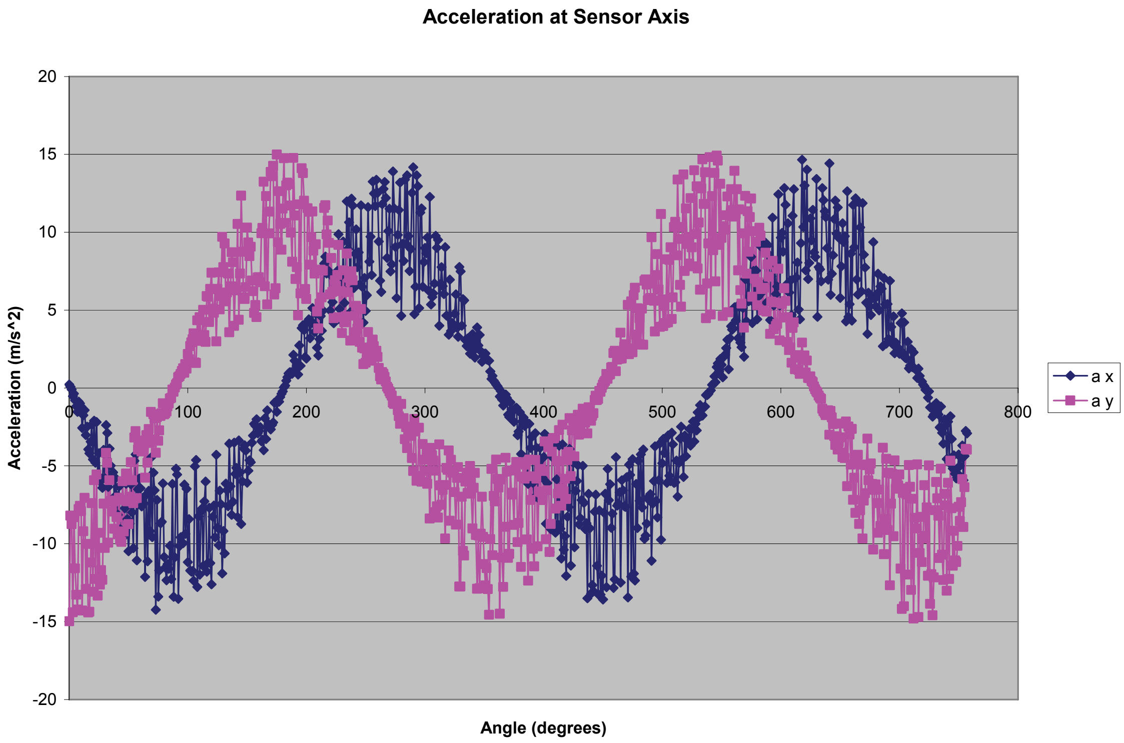

Figure 2.6 is acceleration vs. angle plot for the simulated total acceleration experienced by the x and y axis of the accelerometer.

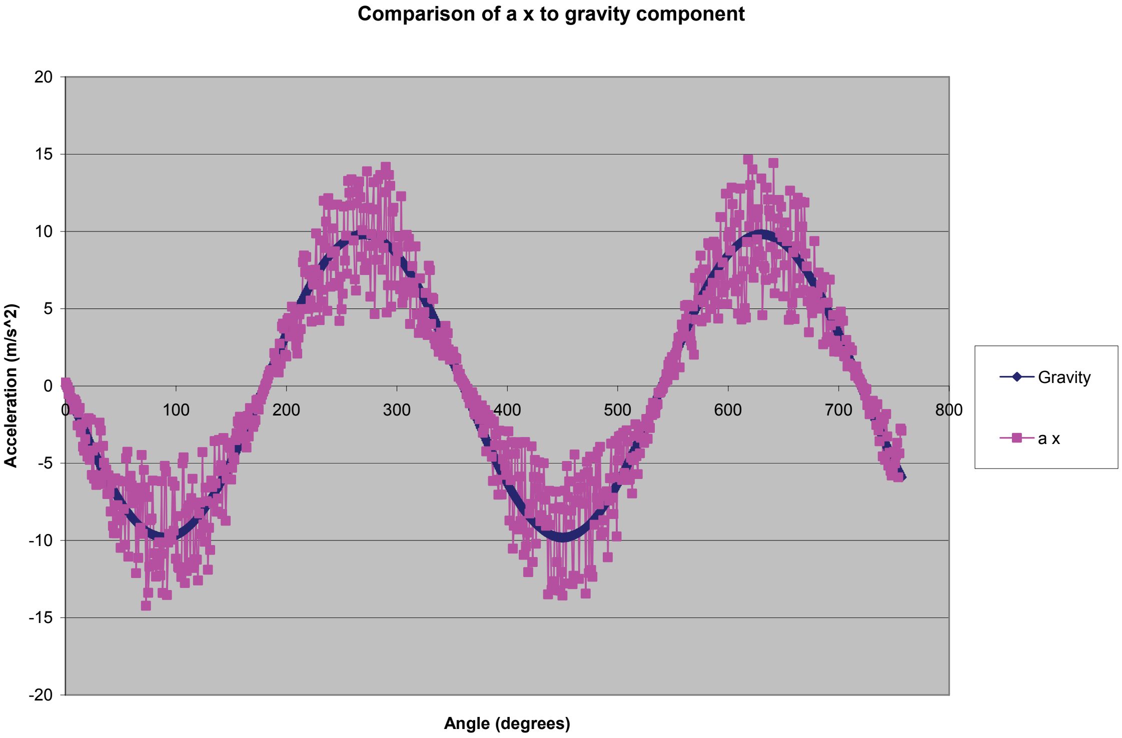

Figure 2.7 is the plot of acceleration vs. wheel angle for the gravity component, which is the ideal signal and the entire signal of the x axis of the accelerometer.

2.4.4 Concept disadvantages

The simulation shows that signal could be utilized to recover the desired components of the signal; however, real-time signal analysis would be necessary to identify and efficiently store the wheel rotation data. This may require a more powerful processor than the msp430 currently utilized by the MDL, which would require significant development.

Another drawback of the accelerometer concept is the relatively high power consumption of the accelerometer. In MDL circuit the reed switches draw no power and are connected to the interrupt lines of the msp430 microcontroller. The microcontroller can shut its processing unit down and enter a hibernation mode to save power when it is not in use. A signal on the interrupt lines can be used to wake the processor from this low power mode. The accelerometer; however, is not wired into the interrupt port of the microcontroller, but rather into one of the timers or the serial port, depending on the accelerometer. The implication of this is that the processor must be on at all times to read the accelerometer output, even if the output is no acceleration. The following calculations are based on the power consumption of the ADXL320 accelerometer, which draws 350μA, and the msp430 microcontroller, which draws 280μA, and the AT45DB321B flash memory chip which draws 15000μA while writing. The calculations assume that the memory chip is writing 1/16 of the time and a 1.2Ahr battery

$$T*[0.00028+0.0007+1/16\ (0.015)]\ A = 1.2Ahr \qquad \text{Equation 2.5}$$

When solved, the time, T, in equation 2.5 is equal to 32 days, which is well short of the desired 90 days without a battery change.

Lastly, difficulties may exist in attaching the accelerometer concept to the wheel. Although attachment of the accelerometer concept would be more feasible than the modified pendulum concept, the issues of tight spaces and irregular shaped hubs is still a factor and would limit the number of EPW models the data logger would be compatible with.

2.5 TRAILING CASTER DATA LOGGER

2.5.1 Concept description

The trailing caster data logger (TCDL) concept features as small instrumented caster that attached to the EPW base and is pulled around while recording data. The caster was kept intentionally small as to fit under an EPW without interfering with driving. Electronically it was similar to the MDL; however, it utilized only two switches. One switch recorded the revolutions of the caster wheel, while the other was used to determine the forward or backward orientation of the caster. The caster was attached to a spring loaded arm that in turn was connected to a bracket that was secured to the EPW. The system could be customized to fit different models of EPWs, in three different ways. First, the type of bracket was selected to fit the particular model. Examples of bracket geometry include one that utilized hose clamps to attach to a motor and one that clamped to rectangular tubing. Next, the length of the arm was chosen. Three different lengths were manufactured to allow the caster to properly contact the ground. Lastly, a bolt could be used to adjust the caster angle. Ideally the stem bolt would be angled as close to vertical as possible, as to keep the orbit of the caster flat. A solid model of the TCDL is given figure 2.8.

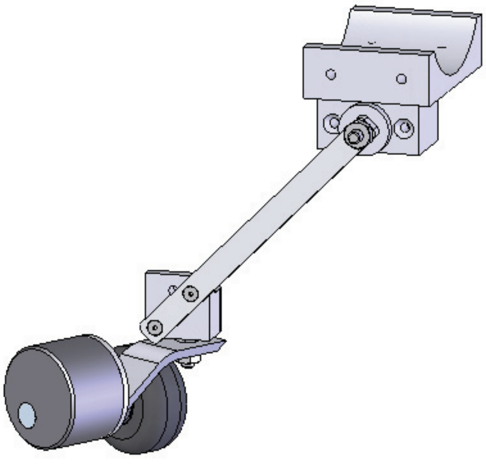

Figure 2.8 gives the solid model of the TCDL.

2.5.2 Functional prototypes

Twenty-five functional TCDL prototypes were produced using the machining facilities at HERL. The prototypes were used to test the concept in real-world environments. A photograph of a TCDL prototype is given in Figure 2.9.

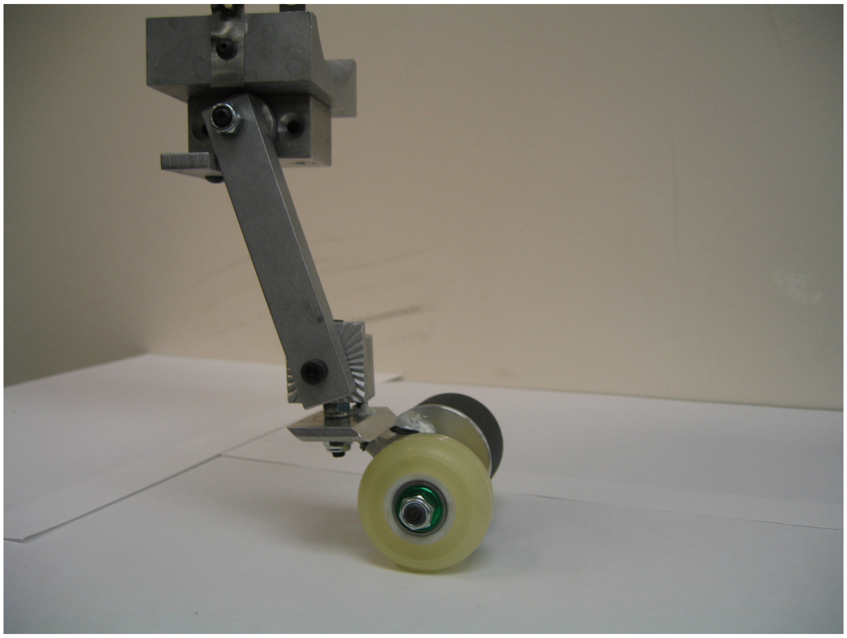

Figure 2.9 photograph of a TCDL prototype.

2.5.3 Design Disadvantages

Driving tests revealed several flaws in the TCDL concept. The driving testing consisted of pulling the TCDL with an EPW over variety of indoor and out door surfaces, including door thresholds, curb cuts, hallway, sidewalks, grass, and others. The trailing caster performed well on hard smooth surfaces; however, the small caster size was less than ideal for rough surfaces and obstacles. The spring loaded arm kept the TCDL in contact with the ground and the slightly exaggerated trail on the caster kept flutter to a minimum at low speeds. Conversely, at higher speeds the TCDL had a tendency to bounce and flutter over rough surfaces, which indicated that the trail and spring arm were not enough to compensate for the conditions caused by the small, hard wheel.

The small size of the wheel also caused the spring arm to catch on some obstacles, especially abrupt drop offs. In this situations where the drop off was great enough to exhaust the arms reach, the TCDL would be temporarily left hanging until the weight of the wheelchair would come to rest on the TCDL, which often bent the arm. In attempt to correct this problem the range of motion of the spring arm was limited and the thickness of the arm was increased. The design modifications proved successful in allowing the TCDL survive the drop off situation.

Another problematic driving situation was backing into curbs of the exact height of the caster fork. If the curb was lower than the caster fork the wheel and the articulation of the arm would allow the TCDL to clear the obstacle. If the curb was higher, the load would be carried by the now thicker spring arm. In the caster fork curb contact scenario, the entire load caused by the impact was carried by the stem bolt, often shearing it off. An illustration of the three scenarios is given in figure 2.10.

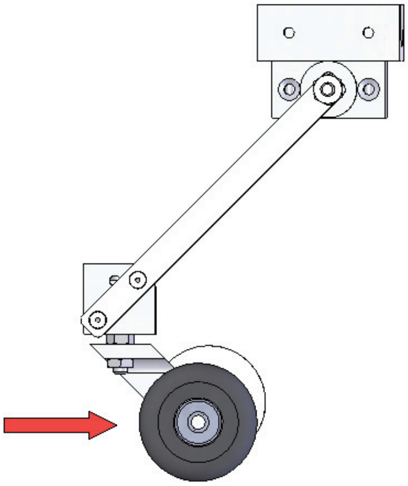

Figure 2.10 depicts the lower than the fork reverse impact scenario where the spring arm articulates and allows the TCDL to clear the obstacle.

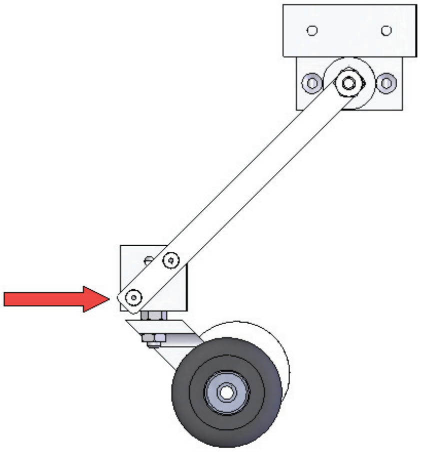

Figure 2.11 depicts the higher than the fork reverse impact scenario where the spring arm absorbs the impact, most likely stopping the EPW.

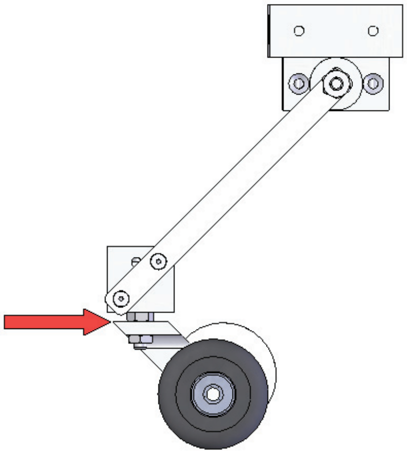

Figure 2.12 depict the equal to fork height impact scenario where the load is carried by the stem bolt, most likely shearing it.

Again the increasing the dimensions of the component, in this case the diameter of the stem bolt, seemed a reasonable solution. However, it was clear that this type of logic would lead to an ultra robust TCDL which would transmit loads to the attachment point of the EPW, potentially damaging it. Other failure modes that were encountered during testing of the TCDL included: deformation of the arm axle due to a lateral force, and failure of the bracket.

2.6 CONCLUSION

None of the described concepts proved to be a viable candidate for long-term logging of EPW usage. A reliable way of attaching to wide variety of EPWs was a common problem for all the concepts. The most promising concept, the TCDL, did work under controlled conditions; however, was no suitable for some commonly encountered condition in the real-world. The primary reason the TCDL was not practical was the small caster could not conquer some common obstacles. Knowledge gained from the TCDL development was employed to produce caster data logger (CDL), which is described in the following chapter.

3.0 CASTER DATA LOGGER

3.1 SECTION INTRODUCTION

None of the four original concepts proved to be viable option for logging EPW usage; however, the knowledge gained from these designs and experiments was used to conceive a new concept. This section describes the Caster Data Logger (CDL) from its conception to its first use for field data collection at 2006 NVWG.

The concept of the CDL was based on the idea that the manufactures original caster wheels could be replaced with a specially instrumented wheel, of similar dimensions, that could count wheel revolution. The sensors and electronics are based on a set of three reed switches, mounted inside the caster hub that revolve around a magnet, which is fixed to the stationary axle. The reed switches are connected to a circuit board and a battery, which also revolve around the axle. When the magnet passes over one of the reed switches, the switch is closed, causing the microcontroller on the circuit board to record the date, time, and switch number.

3.2 DESIGN CRITERIA

The design criteria stated in Chapter 2.1 was again employed for the CDL. Some of these criteria were further refined to more accurately define the requirements for the CDL concept. The detailed criteria include:

-The device must capture and store distance and speed traveled by the EPW

-The device should have a battery life of at least 90 days

-The device should easily be attached and removed from the EPW

- Installation of the CDL should not be more complicated the changing a normal wheel

-The device must not damage the EPW

-The device must not compromise the safety of the EPW user

-The CDL must be as durable as the manufactures' original wheel

-The CDL must attach to the EPW as securely as the manufacture's original wheel

-The device should attach to a wide variety of EPWs

-The device must not interfere with the user's activities in any matter

3.3 METHODS

3.3.1 Prototype CDL v1.0

The purpose of CDL v1.0 was to create a proof of concept prototype that could be instrumented to an EPW and collect data under controlled laboratory conditions. The end goal of this prototype was to test the feasibility of changing the caster wheel and to verify that EPW usage data could be collected in this fashion.

The instrumented hub was based on three major dimensional constraints. First, a qualitative examination of popular EPW models was conducted and a 200mm by 50mm tire hub was chosen as the dimensional constraint for the outer dimensions of the hub. The second design constraint was the 1.75 inch diameter of the MDL circuit board. The MDL board was adapted for this application due to its reliability and to expedite development. The third constraint was the 5/8 inch inner diameter bearings required to fit the largest EPW axles. Base on these dimensions, and that the geometry should maximize interior space for electronics, while maintaining a wall thickness of at least 0.2 inches, the hub was designed. A solid model for the hub was created using Solid Works 2004 (Solid Works Corp. Concord, MA), as shown in figure 3.1.

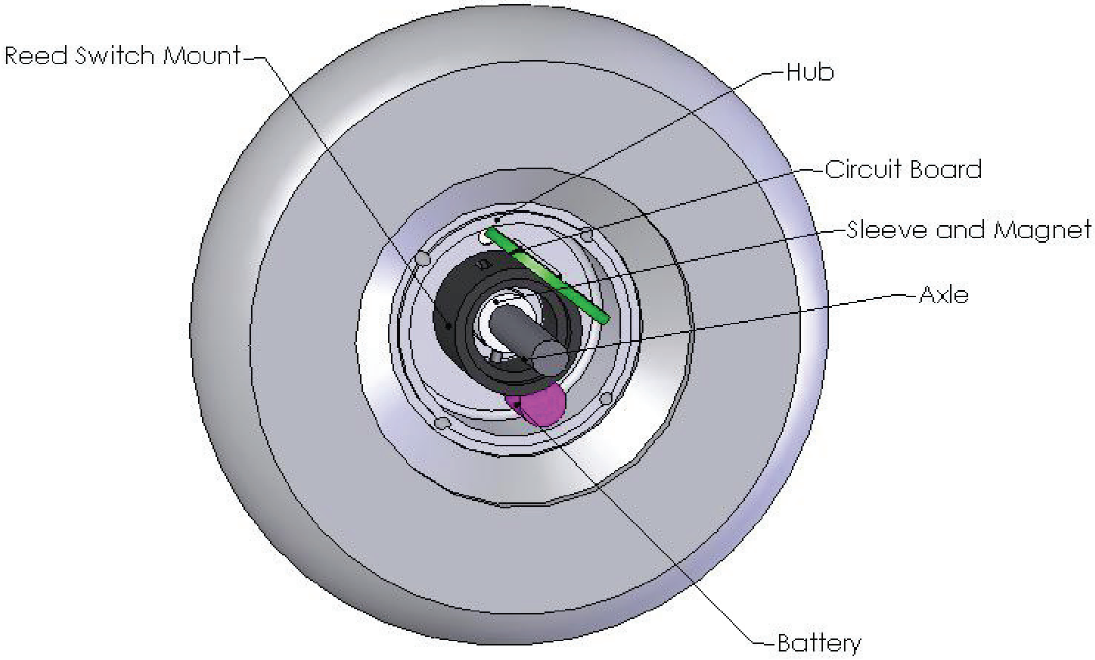

Figure 3.1 is an annotated solid model of inside of the CDL v1.0 assembly.

A hollow cylinder to seal around the axle was designed using the dimensions of the hub and 5/8 inch axle with a 1/8 inch thick magnet attached to it. Three narrow slots 120º apart and 1/8 inch deep were incorporated into the outer face of the cylinder for precise mounting of the reed switches. A flat face was created on the cylinder to create more space for the circuit board and a half circle was cut into the cylinder to receive a ½ AA battery. The inner diameter of each end the cylinder was increased to receive the hub. The battery was held in contact with the terminals by a “C” shaped piece.

The two halves of the hub were fabricated out of aluminum stock and machined to rough dimensions using a CNC mill, with code generated using Feature CAM (Delcam USA Salt Lake City, UT). The piece was then turned on a lathe to exact tolerances. Aluminum was chosen as the material for the hub because its high strength would provide more than adequate structural properties in spite of geometry that was not optimized for overall structural strength. The tube was made from round acetyl plastic stock on the lathe and the other features were subsequently cut using a mill.

The three phases of testing on the CDL v1.0 were carried out using an Invacare TDX (Invacare Elyria, OH), which is a mid-wheel drive EPW with cantilevered caster forks. The installation phase began with setting the circuit board with the correct time and data. Next the front wheels of the EPW, with a user in it, were elevated 1 inch off the ground using wooden blocks and the front right wheel was removed. Then the shallow half of the hub was set in place, followed by the positioning of the magnet on the axle. Subsequently, the tire and the deep half containing the electronics of the hub where placed on the axle. The correct position of the magnet was verified by checking the indicator LED, the hub was screwed together, and the lock nut holding the wheel on was replaced.

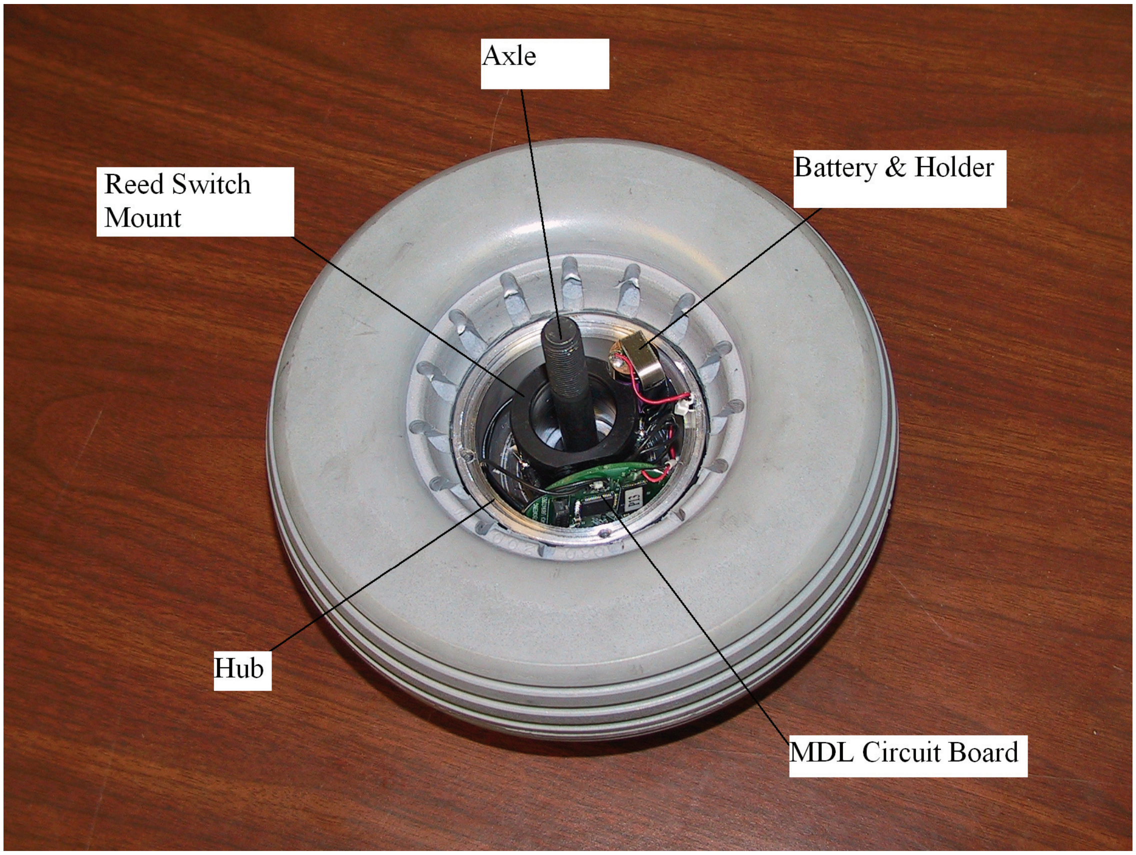

Figure 3.2 is photograph of the inside of the CDL v1.0, showing the reed switch mount in black, the MDL circuit board, and battery holder.

The second phase of testing started when the EPW was taken off the blocks and the wheelchair was driven around by the user. The wheelchair was driven around indoors for four hours while the user completed normal office tasks. The CDL removal phase test occurred at the end of four hours when EPW and user were place on blocks, the locknut was removed, and entire hub-tire assembly was removed. The original caster was then replaced. The hub was disassembled; the data were downloaded and analyzed using a Matlab (MathWorks, Inc Natick, MA) program developed for the MDL.

The result of CDL v1.0 installation test revealed that the battery would momentarily disconnect during installation. In this situation, it was required that the installation procedure was repeated from the beginning; a successful installation took nearly an hour. During the data logging phase the software reset itself several times due to momentary power disconnects during the first hour. However, the last three hours resulted in analyzable data, free of resets. Removal of the data logger and replacement of the original wheel took less than 15 minutes.

3.3.2 Prototype CDL v2.0

The purpose of CDL v2.0 was use the knowledge acquired from testing the CDL v1.0 to create a data logger was more suitable for reliable, long-term use, under a variety of conditions. In order to accomplish these goals the battery holder was redesigned, the hub was simplified from three to two pieces, the MDL board was better secured, and geometry that could be efficiently machined was used when possible.

The EPW trial using the CDL v1.0 revealed that "C" battery holder was inadequate. From these trials it was apparent that being able to access the battery without disassembling the CDL would be beneficial. A "flashlight" style battery holder was chosen, as shown in figure 3.3. The battery would slide down a tube with the positive contact at the bottom. Closing the circuit would be a conical spring and a copper contact. When the plug was threaded down the spring attached to the cooper contact would compress against the battery. As the plug was tightened the cooper plate contacted a spring washer, which was connected via wire to the negative terminal of the MDL board.

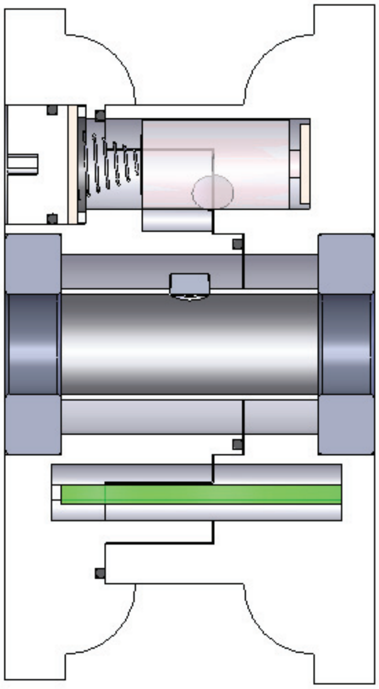

Figure 3.3 is a solid model of the CDL v2.0 showing the cross sectional view of the "flashlight" style battery holder.

The two halves of the hub were modified to include the tube that held the reed switched in the previous version, reducing the number of parts. Holes for mounting the reed switches were in one half. The halves of the hubs were also design so that they would interlock on multiple surfaces, improving the structural qualities of the hub. A thin pocket was integrated within the hub to house the MDL board securely. An additional slot was built-in to cleanly route the wires from the switches to the board.

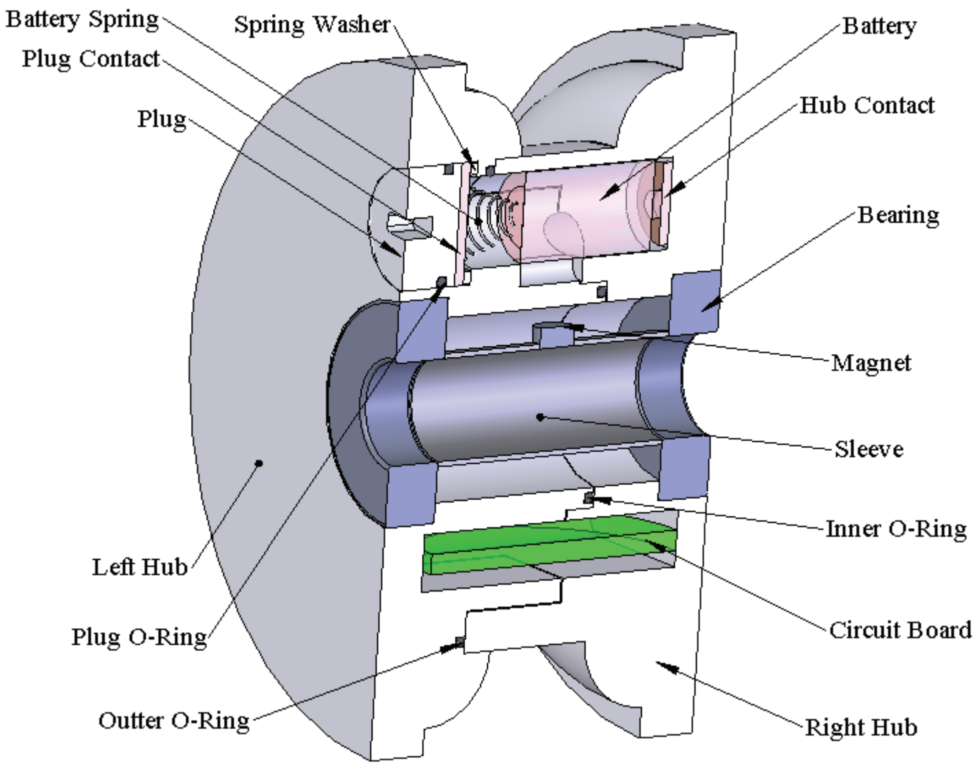

Figure 3.4 is solid model of the inside of the CDL v2.0 showing the annotated, cross sectional view of the inside of the device.

Another addition to the CDL v2.0 was the magnet sleeve. Most EPW caster axles are smaller than 5/8 inch in diameter, so a sleeve was needed to adapt them to the 5/8 inch bearing. The sleeve also served two other purposes: maintaining the spacing between bearings and as method for positioning the magnet. As a spacer, the sleeve keeps the bearing inline and allows the inner races of the bearings to be squeezed without improperly thrust loading the radial bearings.

3.3.3 Prototype CDL v2.1

The purpose of CDL v2.1 was to adapt CDL v2.0 for manufacture out of acetyl plastic. Since the design of CDL v2.0 achieved most of the design goal for that iteration, little was change for

CDL v2.1. The most notable change was the addition of T-nuts in place of directly threading the plastic. Tolerances were adjusted to ensure that the halves of the hub would fit tighter than the aluminum version. Manufacturing the CDL out plastic instead of aluminum would reduce the cost of the raw materials and greatly reduce the machining time. The downside of using plastic is a reduction in the strength of the device.

In order to validate the strength of the plastic CDL fatigue testing was performed. Standards do not exist for individual wheelchair components, so tests were adapted from the ANSI/RESNA standards for entire wheelchairs. A custom test platform was designed and fabricated for testing single caster on the double drum tester. The platform was constructed with three piece of steel angle iron welded into a "U" shape. On each leg of the "U" a steel tube was welded to interface with fixtures on the double drum. A caster spindle barrel was fabricated from machined steel tubing and two 5/8 inch inner diameter radial bearings. The spindle barrel was welded to the frame and a steel caster fork was bolted to the barrel.

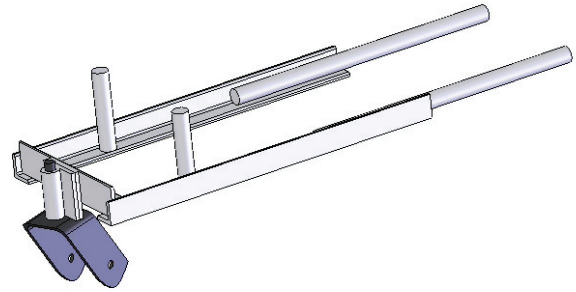

Figure 3.5 Solid model of double drum test platform.

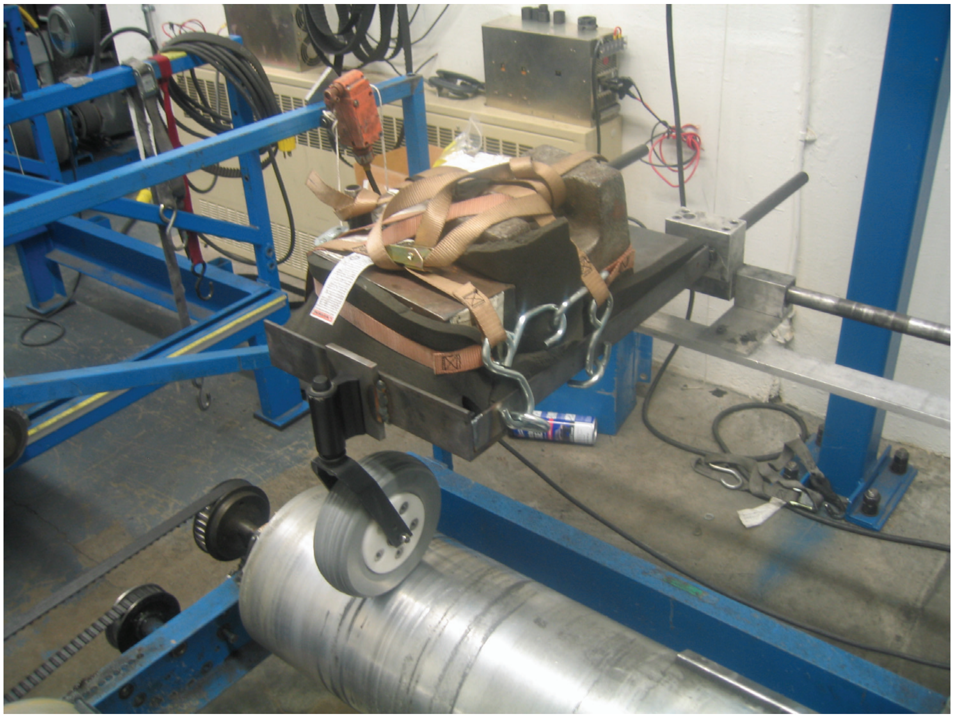

Figure 3.6 Photograph of the test platform, loaded with weights and fixed to the double drum tester.

Once the test platform was created and fixed to the double drum tester, the CDL v2.1 was bolted to the caster fork. Prior to testing, acceptable performance criteria were created. The passing condition for the caster was to complete 200,000 cycles with ½ inch slats without any mechanical failure. A crack in the plastic, permanent deformation of the hub, fractured bolt, or bearing seizure was to be considered mechanical failure. The test platform was loaded with 200 pounds of steel weights to simulate the load of the wheelchair and it occupant. The 200 pounds assumes a 400 pound wheelchair piloted by a 400 pound user with equal weight distribution on 4 wheels.

The CDL v2.1 was subjected to the aforementioned test and completed the 200,000 cycles with little signs of wear and no mechanical failures.

3.3.4 Mass production: CDL v2.2

The purpose of CDL v2.2 series of data loggers was to manufacture a short run of devices for data collection at the NVWG. The aim for the NVWG usage study was to recruit at least 10 subjects, so the manufacturing goal was to produce 15 CDLs. In order to produce this many devices efficiently and with sufficient quality control, computer-aided manufacturing (CAM) software and computer numerical control (CNC) machining techniques were employed. The round stock for the each half of the hub was rough cut band saw and turned to exact thickness on the lathe. A program was created using FeatureCAM to general tool paths to turn outer profile of the CDL on the CNC lathe. Once the program was executed, the part was flipped and the opposite was face cut to dimensions. Once the lathe operations were completed, the parts were positioned on the CNC mill to cut the pockets inside the hub, spot drill the bolt holes, and cut the counter sinks for the T-nuts. The halves on the hubs were paired and the hole for the battery holder was bored. Machining of the other parts was performed using manual machining techniques. Once all components were fabricated, the CDLs were assembled, including the mounting of the reed switches and the soldering their leads to the MDL board. Photographs of the inside and outside of the completed CDLs are shown in figure 3.7 and 3.8 respectively.

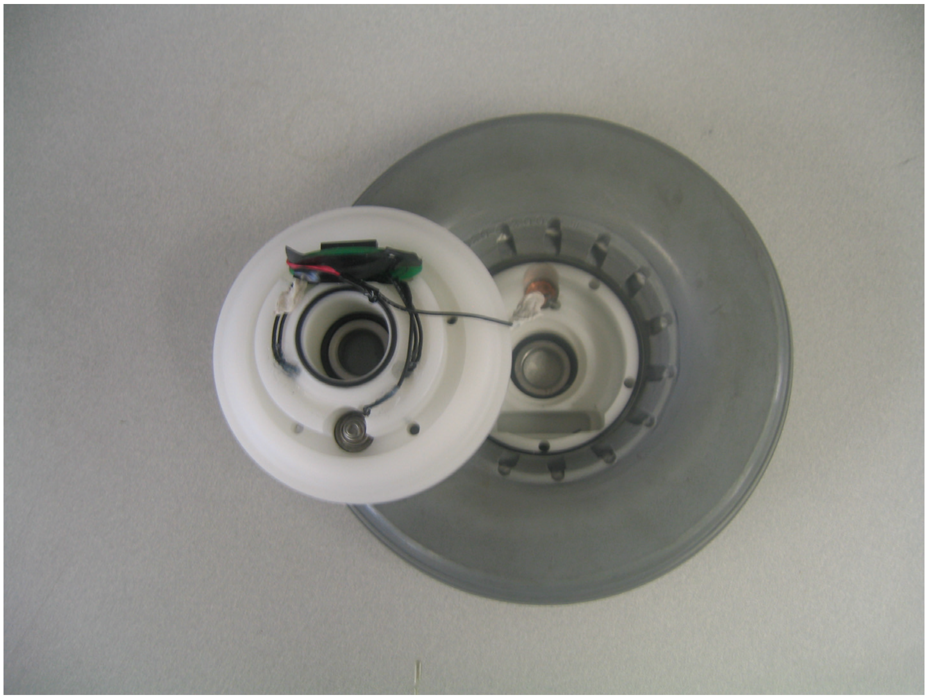

Figure 3.7 Photograph two halves of the CDL v2.2 hub with inside exposed.

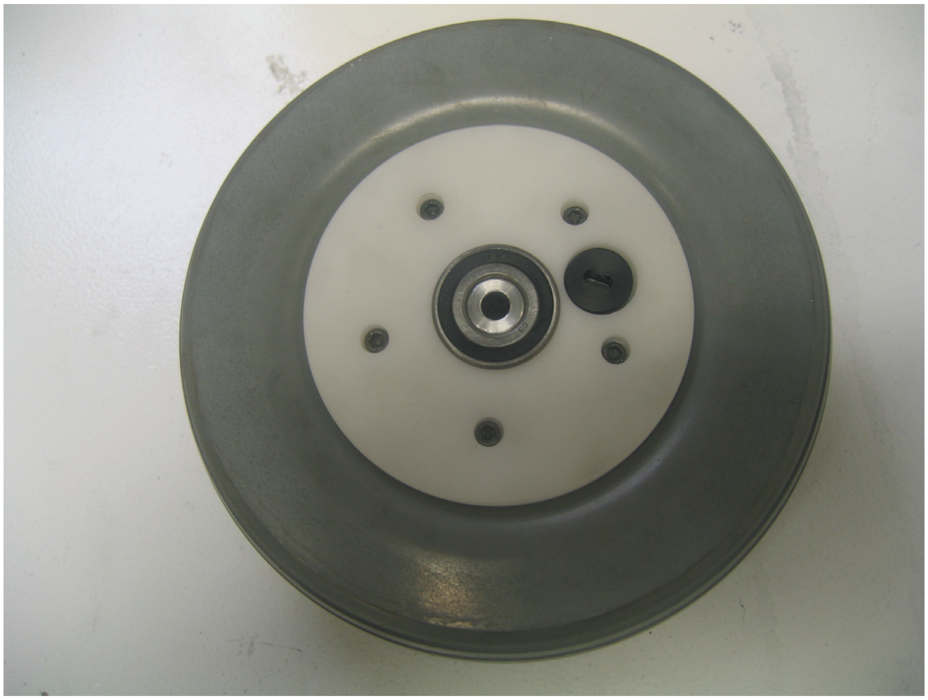

Figure 3.8 Photograph of the assembled CDL v2.2 with battery holder side up.

In addition to the instrumented CDLs, a matching non-instrumented hub was designed and fabricated. The purpose of this "dummy" hub was to ensure that the caster tires on the EPW would have the same tread wear; therefore, having similar rolling resistance. The dummy hub had the same outer geometry as the instrumented hub; however, the internal geometry differs, as to save material and machining time. A solid model of the dummy hub is given in figure 3.9.

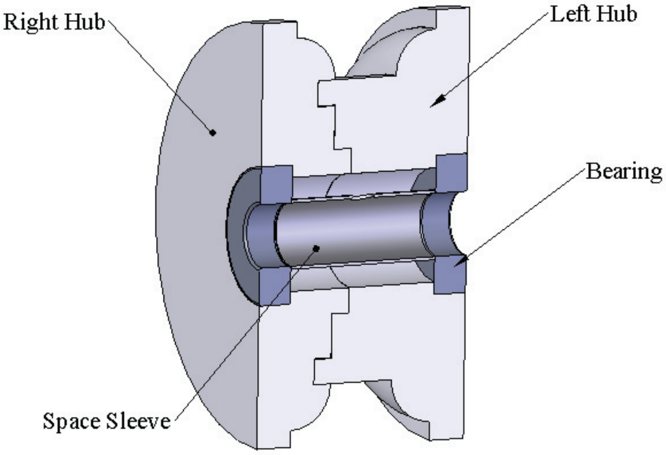

Figure 3.9 An annotated, cross section view of the dummy hub solid model.

3.3.5 National Veterans' Wheelchair Games Protocol

Ten subjects were recruited at the 2006 NVWG in Anchorage, AK to participate in this study. In order to participate, the subjects must have been at least 18 years old and used an EPW as their primary means of mobility. The age of the participants ranged from 71 to 36 years with a mean age of 55±10 years. The time the participants have used a wheelchair ranged from 40 to 2 years and had a mean of 23±13 years. All subjects were veterans and had a diagnosis of: spinal cord injury (n=8), amputation (n=1), and CVA (n=1). A summary of the demographic information is given in table 3.1; the home setting was self reported by each participant.

Table 3.1 summary of subject's demographic information

Variable		Number of Subjects	Percentage
Ethnic Origin			
	African American	2	20%
	Caucasian	8	80%
Gender			
	Male	10	100%
Veteran			
	Yes	10	100%
Disability/Injury			
	SCI - Cervical Level	6	60%
	SCI - Thoracic Level	2	20%
	Amputation	1	10%
	CVA	1	10%
Self Reported Home Setting			
	Rural	2	20%
	Suburban	3	30%
	Urban	5	50%

Informed written consent was obtained from each subject. Next, each subject was asked to complete a demographic survey, which was originally described in Tolerico et al. While the questionnaire was being completed, the caster wheels of the participant's chair where were elevated off the ground and both manufacturer's wheels were removed. One side of the manufacturer's wheel was replaced with a CDL and the other side was replaced with a dummy hub. Upon completion of CDL installation the participants were given their manufactures wheels, a return addressed, postage paid box to return the CDL in, and were instructed to have the it remove three weeks from the installation date.

Figure 3.10 Photograph of the aluminum CDL v2.0 installed on a rear wheel drive EPW.

Upon the return of the CDL from the participants the raw data were downloaded from the device using custom software developed for the MDL. Five days of data from the week of NVWG and 5 days from the following week were chosen for analysis. Matlab and Excel were used to compile descriptive statistics regarding EPW usage during the aforementioned times.

3.4 RESULTS

Nine of the 10 CDLs were returned by the subjects. Of the returned CDLs, 4 contained a full set of data, 2 had a partial set of data, three returned with no valid data, and 1 was not returned. Physical evaluation of the CDLs, with no or partial data set, revealed that a magnet position malfunction caused the interruption in data collection. None of the CDLs experience any mechanical failure, nor did any have a moisture leak. The results data analysis showed that the as a group the subject traveled an average distance of 7751 ± 3439m (n = 5) per day during the 5 days at the NVWG and had an average speed of 0.85±0.1 m/s^2. In the home setting the subjects as a group traveled a distance of 3397±1300 m (n = 4) and an average speed of 0.73±0.14 m/s^2. Table 3.2 gives the average distance per day and average driving speed for each subject.

Table 3.2 Average distance traveled and average drive time for individual subjects at the NVWG and during the following week. Distance and Speed are given in average ± standard deviation.

Participant	NVWG average distance per day (m)	NVWG average speed (m/s^2)	Week after average distance per day (m)	Week after average speed (m/s^2)
1	9666±3259	0.86±0.09	2656±1197	0.59±0.04
2	6907±3814	0.83±0.14	3667±1304	0.64±0.04
3	9245±1324	0.82±0.03	4193±1626	0.76±0.5
4	3277±1797	0.87±0.17	3072±742	0.92±0.04
5	9665±1703	0.89±0.06	-----------	-----------

3.5 DISCUSSION

The CDL v1.0, despite some technical shortcomings, demonstrated that the concept could be utilized to collect EPW usage data. The exercise was also useful in determining what features needed to included in the next generation. The lengthy installation demonstrated that the caster must be pre-assembled in order to keep the installation to an acceptable time. The tests also highlighted the need for a robust battery connection.

Solid modeling, CAM, and CNC design and fabrication techniques greatly aided the prototyping and mass production process. Solid modeling allowed for experimentation with various geometries without actually fabricating them, which more than likely shorted the development process by a few prototype iterations. CAM and CNC enabled more complicated geometries to be constructed and provided extremely repeatable results. For the CDL v2.2

production run, the components were interchangeable from CDL to CDL. This type of quality control would be tedious and extremely time consuming if completed without this type of automation.

The addition of the dummy hub was necessary to ensure safe driving. If a new tire was paired with a worn tire, the uneven rolling resistance could cause the EPW to veer in one directing when the user intended to travel in a straight path. The user would be forced to compensate, make driving cognitively more complex, which for some users could hamper their ability to safely manipulate the EPW. Also it allows for exchange of the original caster tires of similar size with CDL tires that are not completely identical, increasing the number of compatible EPW models without the need for additional types of tires.

The selection of acetyl plastic as primary construction material proved successful. It could be machined much faster than aluminum and the raw materials cost less. The casters made of acetyl plastic completed double drum testing with little to no signs of wear. The NVWG study confirmed that the material and geometry are suitable for real-world driving. None of the returned CDLs experienced mechanical damage or seal leaks suggesting high degree of durability, especially given the activities associated with participating at and traveling to and from the NVWG.

The design improvements to the CDL v2.x series greatly reduce the amount of time need to install the CDLs over the previous version. The quick installation could be completed outside a controlled laboratory environment, as demonstrated by recruitment at the NVWG. Similarly, the participants were able to or have someone in their community successfully remove the CDLs and replace them with the original wheels. Both of these points suggest that these devices could be utilized in a variety of settings. The CDLs that did not experience electronic failures contained 3 weeks worth of data, indicating that longer studies are possible, as expected. Several of the CDLs did experience an electronics failure, which upon inspection was revealed to be a slight shift of the magnet sleeve. The CDL with some additional upgrades could be a reliable tool for objectively measuring EPW usage.

The EPW usage data is intended to serve as pilot data for a larger forthcoming study and due to the small sample size inferential statistics were not performed. However, these preliminary results do hint that participants traveled farther and faster during the NVWG than in the following week. This result is as expect, given that by their nature the NVWG encourage activity. They also reduce barriers to travel, with accessible venues and transportation. These barriers may exist in the participants communities and could partially account for the decreased in daily distance traveled. A similar study with a larger sample size may be able to identify some of these barriers through the use of demographic survey. The results do provide objective, real-world driving environment data on how much EPWs are used. These numbers could be used to influence the design EPWs components, such as frames, suspensions, batteries, and cushions.

The results of this study are limited due to small sample size, the relatively brief amount of time data was collected, and focus on specific population. Thus broader generalizations cannot be made; however, further study could address these issues.

3.6 CONCLUSION

An instrumented caster was developed that had the ability to collect EPW usage data in a community setting. The device could be installed outside of the laboratory, in a short period of time and did not interfere with the participant's activities. Its structural performance was demonstrated in bench testing and in real-world use. However, the device did have electronics reliability issues. In order for the CDL to useful research tool, the causes of the problems need to be thoroughly investigated and corrected.

4.0 REFINEMENT

4.1 SECTION INTRODUCTION

This section describes the modifications made to the CDL v2.2 following the 2006 NVWG protocol. It illustrates the methods by which the problems with the CDLs were diagnosed and continues with an explanation of the design modifications. It also describes bench tests by which the durability and accuracy of the device were verified.

As reported in chapter 3.4, 9 of the 10 CDLs were returned from the NVWG protocol. Upon return any data was on the device was downloaded, decoded, and examined for consistency. The battery leads were tested using a multi-meter for connectivity, individual reed switches were checked for proper operation, and it was verified the MDL board would reboot, indicating that the board had sustained no damage. In addition to inspection of the electrical components, the state of the magnet was noted.

On three of the returned CDLs, the magnet had become dislodged from the magnet sleeve. All three occurrences happened in a relatively short period of time, less than three days, indicating the magnets were not correctly pressed into the aluminum sleeve.

Visual inspection of the sensor data showed intermittent sensor dropout in several of the CDLs. A sensor would be present in the data, dropout for a period of time, and appear later in the data set. Close physical examination of the affected CDLs showed that the hub could shift laterally on the bearing and the sleeve, changing the position of the magnet. The shift was caused by two factors: the magnet sleeve being slightly oversized in length and the bearing boars being cut too deep. The overall error was 0.050 inch or less, which helped conceal the error during manufacture. Also during manufacture, when the bearing was first pressed fit, it would not shift; however, as the bore in the plastic opened up over time the caster could shift on the bearings. A solid model illustrating this is given in figure 4.1. The shift problem was compounded by variability in the reed switch positioning. The reed switches were glued into holes using room temperature vulcanizations (RTV). Although the holes were of equal depth, variability existed in where the switches were position within the hole. The number 0 sensor hole adjacent to the MDL board pocket was partially exposed allowing for more accurate positioning of the reed switch, and as a result no sensor dropout occurred for this switch on any of the CDLs, allowing the data to be analyzed.

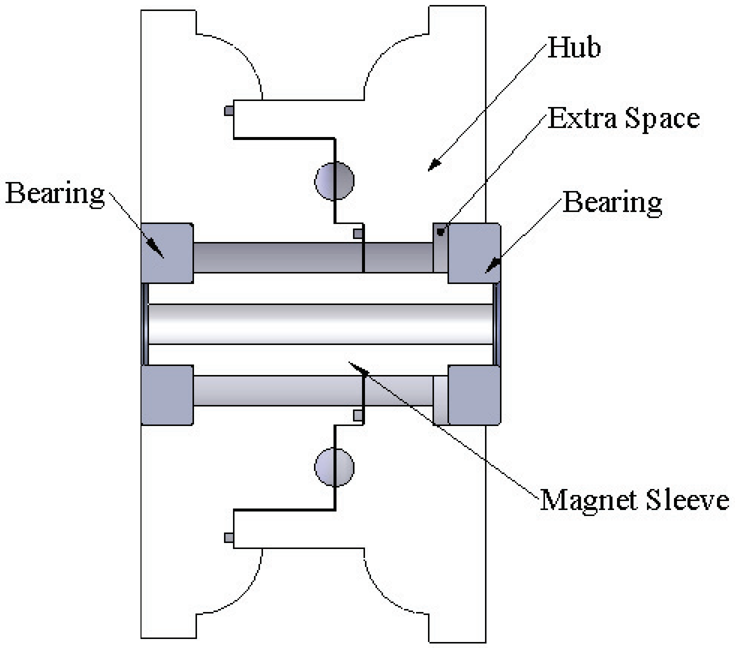

Figure 4.1 Cross sectional, solid model of the CDL demonstrating the magnet shift.

Sensor dropout also affected the normal startup procedure of the CDLs. A roll-start feature was included in original MDL operating system, which required a series of consecutive reed switch activations within a given time before data is stored to flash. If one sensor was dropping out the software could not escape roll-start mode.

A power interruption problem during high shock conditions was discovered during bench testing. During double drum testing, occasionally the shock of the caster hitting a slat would cause enough of battery disconnect that the processor would freeze to due to the drop in voltage. The drop was not significant enough to reset the processor.

4.2 METHODS

4.2.1 Design

The evaluation of the returned CDLs revealed issues with the magnet shifting and some of the magnets falling out. The first design change was to increase the diameter of magnet sleeve. Originally the sleeves were machined from ¾ inch aluminum round stock and the magnet was to protrude from the outer face of the cylinder, as shown in figure 4.2. For the redesigned sleeve, 1 inch aluminum round stock was specified and the magnet was pressed in the cylinder until face of the magnet was even with face of the sleeve, as shown in figure 4.3. The magnet holes were undersized by 0.040 inch and magnets were pressed using an arbor. The change in magnet position decreased the distance between the magnet and the reed switches.

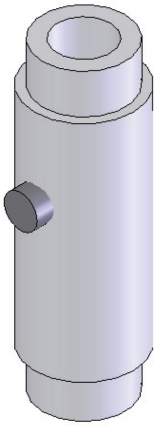

Figure 4.2 Solid model of the original magnet sleeve with a protruding magnet

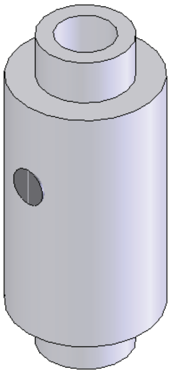

Figure 4.3 solid model of the redesigned magnet sleeve with a flush magnet

The second magnet design modification was to correct the shifting of the magnet sleeve. First the tolerance on the length of the new magnet sleeves was more tightly controlled. Second, the length of the magnet field was increased by placing two magnets side by side axially on the sleeve, as shown in figure 4.4.

Figure 4.4 photograph of the magnet sleeve with increased magnetic field length

In order to address the problem of momentary battery disconnection, it was proposed that the addition of a capacitor across the power terminals could provide enough stored charge to keep the circuit powered during a periods of high shock to the battery holder. It was assumed that the battery disconnect would not last longer 0.1 seconds. Then the resistance of the MDL board was estimated by powering the board with a power supply that had voltage and current output indicators. The power supply was set to voltage control mode and the output voltage was set to 3.6 volts. The current draw was then recorded and the estimate of the resistance was calculated using Ohm's Law. Using the time, t = 0.1 seconds, the resistance, R, of the board, the capacitance of the capacitor was calculated the time constant relationship given in equation 4.1.

$$t = RC \qquad \text{Equation 4.1}$$

The calculation resulted in a nominal capacitor value of 100µf. A 100µf electrolytic capacitor was soldered across the battery terminal, as shown in the schematic in Figure 4.5.

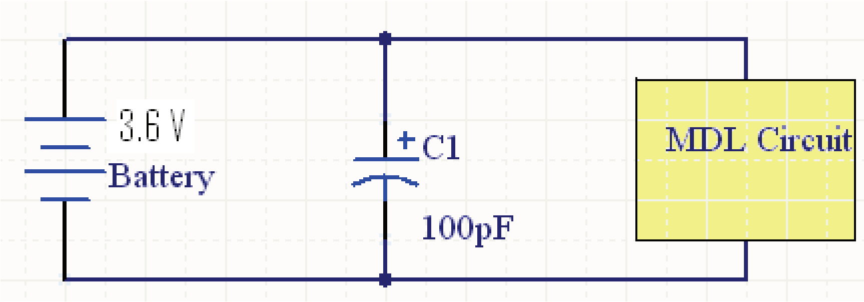

Figure 4.5 schematic of modified power circuit

The final design modification was to the MDL software. The operating system code was amended to permanently disable the role start function. The implication of this was that anytime a reed switch was activated the processor would record that event and toggle the greed LED.

4.2.2 Testing

In order to verify the reliability of the measurements of the CDL and to uncover any potentially dangerous structural flaws, the CDL was subjected to a series of bench tests.

The precision and accuracy of the CDL was testing using a modified double drum test. The test platform for double drum testing as described in chapter 3.3.3 was utilized, only it was not loaded with weight. The slats were removed from double drum roller and the platform was fixed double drum tester frame. The CDL was then used to record the distance traveled in 10,000 cycles of the rollers, three times. The theoretical distance traveled by CDL was calculated using from the measured diameter of the rollers, the measured diameter of the CDL tire, number of cycles, and the circumference formula. The average and standard deviation of the three trials were calculated and compared to the theoretical value. This test is also an indication of the success of the re-designed magnet sleeve. Since the caster is always in same orientation, the sensor order is known; hence, any sensor dropout would indicate continued problems with the magnet alignment.

An additional trial of the 10,000 cycle double drum test with slats was performed to determine how slat impacts affected accuracy. The theoretic circumference of the roller with double was computed and this value was compared to the value measured by the data logger.

The double drum test with slats revealed battery disconnect problem, so it was employed to test upgraded power circuit. The test platform was again utilized and was load with enough weight to keep the wheel from bouncing off the roller when encountering a slat. The passing criteria for the test would be to complete 50,000 cycles without any processor resets or freezes.

In order to better understand how the CDL responds to high impact loads the device was assessed using a pendulum impact tester. The impacted tester consists of frame that suspends a weighted pendulum, with a load cell attached to the impact end of the pendulum, as shown in figure 4.6. Where the pendulum is at its lowest point rest a rigid bracket on which to attach caster fork stems. Since the CDL has unique dimension a custom fixture was welded out of steel, as shown in figure 4.7. The pendulum can be raised using a ratchet strap and released using hand-held trigger. The force applied by the pendulum can be varied by changing the height and or the weight of the pendulum. The caster is tested by gradually increasing the impact force over several releases of the pendulum until failure occurs. During each impact the analog data from the load cell is collected using a data acquisition card and a laptop PC with Virtual Bench (NI) software. Using the Virtual Bench Software the sample frequency was set 1000 Hz and was set to write the scaled voltages to a text file. The force versus time data was plotted using Excel and the loading phase of the highest load drop fitted with a linear regression to estimate the loading rate.

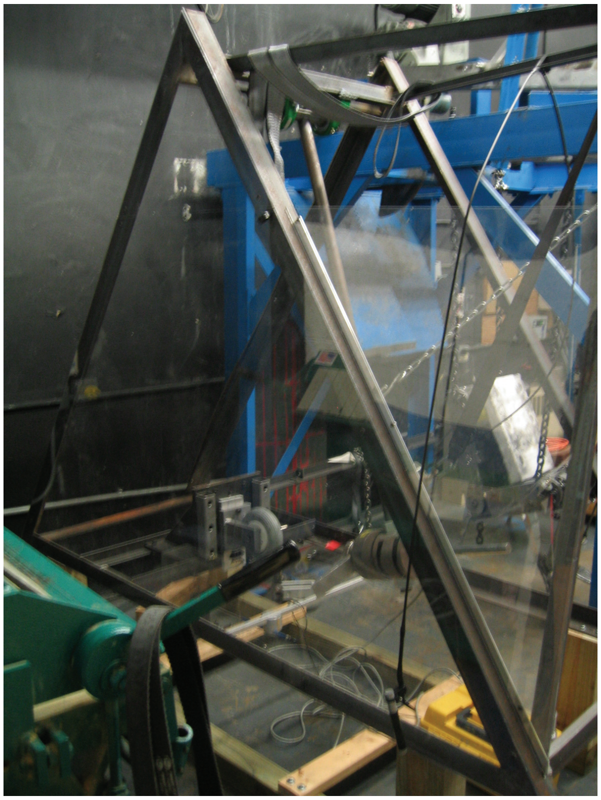

Figure 4.6 Photograph of pendulum impact tester with the CDL

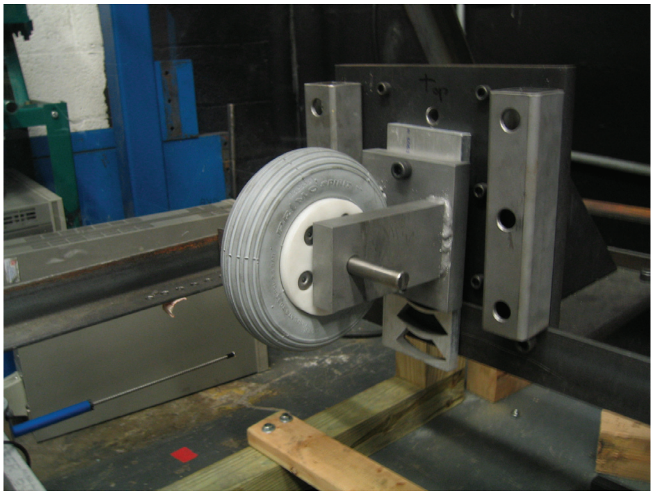

Figure 4.7 Close-up photograph of the custom fixture for CDL on the impact tester

It is highly probable that in real-world driving conditions the CDL will be exposed to or submerged in water. To test the CDL's ability to withstand these types of conditions a CDL was submerged in 12 inches of water for one hour to determine if water could leak into the electronics compartment. At the end of the hour the data logger was removed from the water, disassemble, and inspected for leaks.

4.3 RESULTS

The design upgrades proved to be successful. The redesign of the magnet sleeve and the increased length of the magnetic field corrected the sensor dropout problem. The addition of the capacitor was a shown to be successful by the slated double drum test. The CDL completed the 50,000 cycles without any processor resets or freezes. The water submersion test revealed no water leaks into the electronics compartment.

The three un-slated double drum trials resulted in an average distance measured of 8630±1.29m. With a caster wheel diameter of 0.1933m and a roller diameter of 0.2747m, the theoretical distance measured by the CDL was 8629m. Comparing the measured distance to the theoretical distance resulted in a %0.01466 error. In the slated double drum test, a distance of 8839 m was measured and compared to the theoretical measurement of 8827 m, which yields a %0.1398 error.

The impact pendulum tester was not capable of causing structural failure to the CDL. The pendulum was loaded with the maximum amount of weight available and was dropped from an angle of 75° from vertical. This drop resulted in a maximum load of 11,060 N; the force verses time curve for this drop is given in figure 4.8. From the linear regression, the loading rate was estimated at 931 N/msec with an R^2 value of 0.945; a plot of the loading phase data and the linear regression is given in figure 4.9.

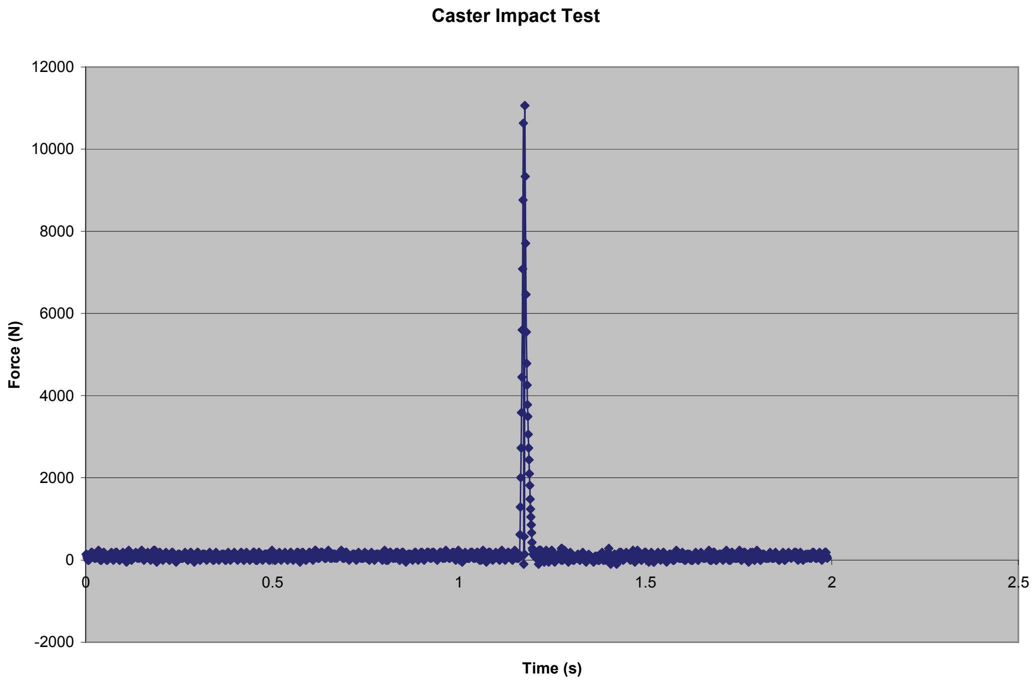

Figure 4.8 Force vs. time plot for highest load pendulum drop

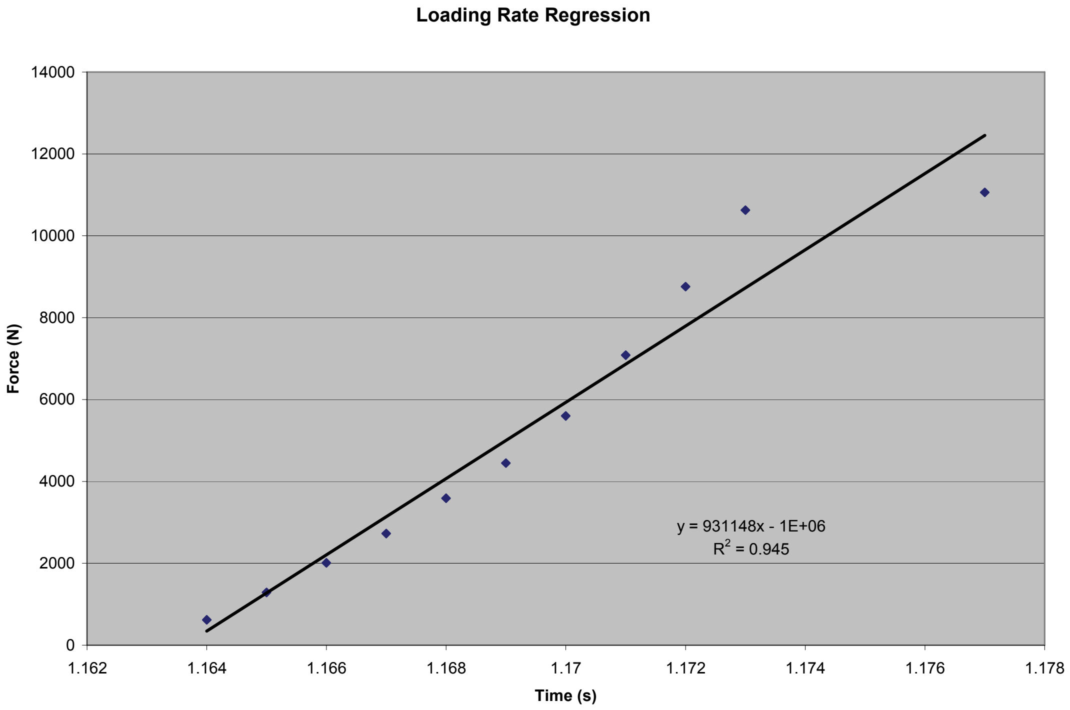

Figure 4.9 Force vs. time plot with a linear regression for the load phase of the highest load pendulum drop

4.4 DISCUSSION

As demonstrated by testing, the design changes proved to be successful. The redesigned magnet sleeve with the increased magnetic field length eliminated the problem of sensor dropout, as verified with slated and un-slated double drum tests. The addition of capacitor provided the processor with enough power during momentary power interruptions to prevent resets or freezes. The results of these tests strongly suggest that CDL will reliably collect data under field conditions and the malfunctions that occur during the NVWG study have been corrected. It is important that the device work perfectly, as not to use any more resources or subjects time than is necessary for completion of the protocol.

The water submersion test revealed that no water leaked into the electronics compartment of the CDL. This result is as expected, since no malfunction of this type occurred at during NVWG study and that design included robust seals. The test does indicate that the CDL could withstand some extreme water submersion situations.

The result of the un-slated double drum tests strongly suggests that the CDL is both accurate and precise. The average measured value was very close to the theoretical value with a percent error of less than two-hundredths of a percent over a distance of 8629m, indicating a high degree of accuracy. The low standard deviation suggests that the measurements also have a high degree of precision. One likely source of error is the resolution of the CDL, which is 0.203m for this tire, so depending on the start and position of the CDL, distance could be lost or gained. Another likely source of error is when the double drum was shut down during the experiment for inspection of the CDL, the CDL went into hibernate mode, and one sensor hit was lost during wakeup. Other less likely sources of error for this test include: measurement error of the CDL tire and the roller and the tire slipping on the CDL hub.

The slated double drum accuracy test was more likely to reveal error caused by tire slipping on the hub or the roller. However, the error of less than two-tenths of a percent would suggest that tire slippage is not a major source of error under theses conditions either.

The pendulum impact test demonstrated the acetyl plastic CDL could survive high loads applied at high loading rates, as observed during frontal vehicle crashes. The most impressive finding was that the CDL could not be broken by the pendulum impact testing equipment used in this experiment. The highest load recorded was 11,060 N, which caused no visible signs of structural damage to the CDL. This load is much higher than the minimum 8000 N normal load that Bertocci et al (2003) suggests that wheelchair caster assemblies be designed for in order to withstand a 20g/48kph frontal vehicle collision. The loading rate of 931 N/msec was much high than those reported by Bertocci et al (1999), which ranged from 89-218 N/msec, indicating the loading rate was more than sufficient to reveal any structural flaws. Based on available literature (Bertocci et al 1999) the acetyl plastic CDL should perform as well or better than the caster wheel it is replacing during high loading, high loading rate conditions.

The impact testing only subjected the caster to loads normal to the axle. The CDL could be subjected to off axis loading; however, these loading conditions would not like be as severe. Given that the caster is free to rotate, the caster will either: rotate to an orientation where the load is normal to the axle or rotate to an orientation where the load is in line with the axle. In the latter scenario the fork and the stem bolt would carry most of load.

Since failure was not reached during the pendulum impact tests, the failure mode of the CDL is not known. Some failure modes may be more favorable than others. For instance, a plastically deformed a caster, or a wheel with a “flat spot”, might be drivable for a short distance or keep the EPW from submarining during a vehicle collision. Conversely, if the caster hub shatters, the EPW not likely to be drivable for even short distances and would cause submarining during a vehicle collision. A favorable design would have a failure mode similar to the one described in the flat spot scenario.

4.5 CONCLUSION

Design modifications were successful in correcting the reliability flaws of the CDL v2.2. Bench testing indicated that the CDL was both accurate and precise at measuring distance traveled. Reliability testing verified the electronic are able to withstand repeated shock. Impacted testing showed that the CDL is as or more likely to survive a high loading at a high loading rate than the caster wheel it is replacing. Overall, the bench testing verifies that the CDL is safe and reliable data collection tool.

5.0 FUTURE DIRECTIONS

5.1 CHAPTER INTRODUCTION

In this chapter recommendations for future development and potential for data collection are discussed. Having verified that the CDL is an accurate and reliable method for logging EPW usage, the areas for future development should focus on making the device user-friendly and improving the electronics. Designing a CDL that can be used by a broader group of users should be a design priority for the next generation of CDLs. The CDL v2.2 series of data loggers although shown to be reliable and accurate, are complicated to use and maintain. Ideally, the next generation of CDLs will be used by researchers and clinicians in variety of settings. They may use them to collect data for research protocols or to get an objective measure of outcomes for individual clients. The following chapter describes the design features that could be included to make the CDL more usable and more useful. It also recommends a battery of bench tests that the next generation CDLs must pass to ensure safety and reliability.

5.2 DESIGN CRITERIA

In addition to the previously stated design criteria, additional design criteria were developed that should guide the development of the next generation of CDLs. These criteria focus on making the CDL user-friendly and were developed after informal consultation with researchers who may use these devices for future studies. The criteria are:

-Battery access should require minimal effort

-Downloading data should not require decompressing the tire

-Downloading data should not require removing the CDL from the participants EPW

-Graphic user interface software for downloading should be written

-Detailed documentation must accompany the CDL

5.3 DESIGN RECOMMENDATIONS

5.3.1 Recommended concept

One design aspect of the CDL v2.2 is that the tire must be compressed to bolt the halves of the hub together. The CDL v3.x series could address this issue using a three part hub. The new CDL would have a central hub, which would provide the basic structure of the caster, a back tire piece that is bolted on and would hold the tire, and a front plug that could be removed to access the electronics and the battery, as shown in figure 5.1. With this type of setup, the tire could be pre-compressed during the manufacturing stage and would not need to be changed unless the user desires to do so. All the electronics would be mounted on the front plug, which would be threaded into the central hub allowing for easy removal with a custom tool. If the researcher or clinician is not interesting in changing tires, they could be provide a set of tires, each pre-compressed with a central hub and a tire piece, and one plug with electronics, that could be interchanged between the tire set.

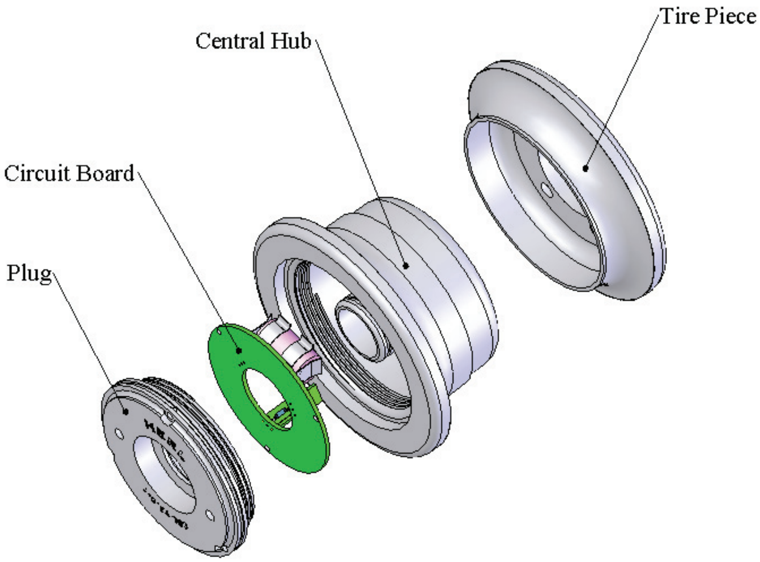

Figure 5.1 Exploded conceptual solid model of CDL v3.0

Unlike the previous generation, the CDL v3.0 could have consolidated electronics. In the CDL v2.x series, the battery, switches, and MDL board were arranged in various locations around the hub and were connected via soldiered wires. This not only increased the complexity of the manufacturing process, but also created greater potential for electronics failure. Having a new board specific for the CDL v3.0 would allow for the battery and switches to mount directly to a printed circuit board, eliminating the need for wires and the potting of switches, increases reliability. A conceptual solid model of the proposed printed circuit board is given in figure 5.2.

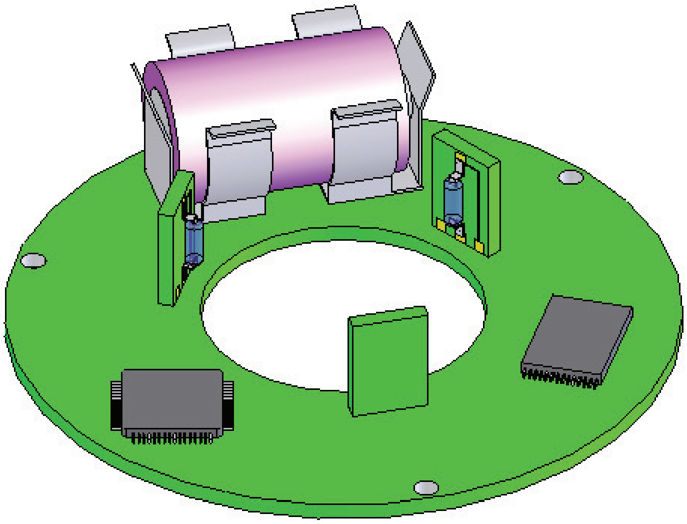

Figure 5.2 Conceptual solid model of the CDL v3.0 printed circuit board

Modern techniques for rapid prototyping could drastically alter both the design of the CDL and the manufacturing process. Technologies such as Stereolithography (SLA) and Selective Laser Sintering (SLS) are capable of producing functional three dimensional parts from solid models. In respect to design, any shape that can be created using solid modeling can be produced with SLA or SLS, which is a significant advantage over machining techniques. Even with CNC machining methods complex contours and 90° corners are sometimes difficult or impossible to cut, and even when possible can be tedious and time consuming. The disadvantage is that the material properties of the plastics used in SLA and SLS are not as favorable for structural components as acetyl plastic. However, with geometry that minimizes stress points and thorough bench testing of the components, a structurally sound CDL could be produced using one of these technologies. In respect to manufacturing, SLS and SLA have two distinct advantages over machining: they require less labor, and can produce exact replications with almost no dimensional variation. Both the SLA and the SLS only require labor at the beginning and the end of the build process and can run unattended. The reduction in labor time could offset the higher cost of SLA and SLS raw materials. Since the both machines use computer driven lasers, parts can be made in perfect replication and can be efficiently made on demand without worry of variation between runs. With machining techniques, large production runs are more conducive to maintaining part precision across higher numbers of devices.

Figure 5.3 Photograph the CDL 3.0 concept fabricated using SLA

5.3.2 Recommended electronics upgrades

Additional electronic features could add to the utility of the CDL and make it easier to use. Two of the main drawbacks of the current electronics are that communication with the device is not as easy as it could be and that it is impossible to synchronize with other devices. Additional features that could resolve these issues include a real-time clock, an external Universal Serial Bus (USB) interface, and a Bluetooth interface.

The electronics could benefit from a real-time clock. The currently used MDL circuit features a crystal oscillator and time is counted with the processor relative to the start time. If power is disconnected all subsequent data is invalid because the time the processor was off is not accounted for. With a real-time clock, the processor could be shut down and restarted and the clock would account for the elapsed time. The current crystal oscillator does have some error and over long period of times, time is lost. For tracking EPW usage and relating it to days, this error is acceptable; however, if for example, vibration data was to be synchronized with the CDL data, an error of a couple of seconds would be unacceptable. A real-time clock would also aid in commencing the synchronization of two or more devices.

A complimentary feature to the real-time clock is a Bluetooth chip for short range wireless communication. The ability to communicate with other devices via a standardized protocol would lead new applications for the CDL. One application would be to use Bluetooth to share clock information between devices. One device could serve as the master and the rest of the devices would be slaves. When the data collection is initialized the master could send its clock information to the other device, and the slave device would update their clocks. The Bluetooth chips would be shut down to conserve power, and woke up at a given interval to monitor and correct clock error relative to the master device's clock. A more study specific application would be to use Bluetooth to transmit caster wheel speed data to a controller on the frame of the EWP, which would be useful in detecting drive wheel slippage. The Bluetooth protocol includes a 128 bit encrypted communication mode, thus some privacy protection for the data. Overall, the benefit of this technology is that utility can be added to the CDL in a scaleable and generic manner depending on the application.

In the MDL circuit, data is downloaded through the JTAG interface of the microcontroller, converted on an external download board to RS-232, and then was transmitted to a PC. Concerns with type of interface include: the size of standard RS-232 connector, and RS-232 ports becoming a less common standard feature on PC computers, especially laptops. A USB interface would solve these concerns; USB ports are commonly incorporated on nearly all computers, and the USB standard includes a miniature connector. The chip for the USB transceiver could be wired on the CDL printed circuit board and powered through the computer's USB port. The miniature USB connector would allow an external port be built into the CDL, in turn allowing data to be downloaded without removing the CDL from a wheelchair. This would be especially useful in longer studies, were data could be downloaded periodically for analysis.

5.3.3 Recommended software upgrades

In addition to electronics upgrades, some software improvements could be made to both the operating system and the PC interface program. If the suggested electronics upgrades are complete the operating system will need to be programmed to support these devices. In particular, the data download process will need to be coded to pass through the microcontroller's asynchronous serial port instead of the JTAG port to support USB transmission. Code will also need to be written to support the Bluetooth chip.

For the CDL to be used by a broader audience of users, the PC interface program needs significant development. The program written for the MDL has a line command interface and tends to be difficult to use. The program also has some errors, which can make use frustrating.

A graphical user interface program could make the program more intuitive to use. The addition of menus and tool bars would save the user from memorizing the line commands. The upgraded program could also be used to coordinate synchronization between the CDL and various other devices.

A detailed user's manuals should be included with the software and describe all aspect of using the CDL. The manual should include pictorial and written descriptions of CDL installation, types of EPWs it is compatible with, written and pictorial descriptions of the interface software, and a trouble shooting section. In addition to the manual, a training video may be helpful.

5.4 RECOMMENDED TESTING

5.4.1 Safety

The safety of study participants is paramount; therefore, thorough bench testing should be completed before the next generation is released for data collection. Fatigue testing should follow in the spirit of the ANSI/RESNA double drum and curb drop tests. The logic for this testing is to demonstrate that the CDLs are an equivalent replacement of the original caster wheels. The conditions for the double drum test should be the same as described those described in chapter 4.2.2. Again the caster must complete 200,000 cycles of the reference drum. In addition to the previously described test conditions, the hub should be fitted with lowest profile tire it is designed for. For a CDL constructed with a new material the test should be performed with three different CDLs to ensure that structural properties do not vary significantly from device to device.

The curb drop test should also be performed on the next version of the CDL. The curb drop test was not previously performed on the CDL v2.2, so a method of testing would need to be devised. One option would be to use an old EPW, and load it with a test dummy. This method would most closely match the ANSI/RESNA test conditions; however, with repeated testing of different casters, it can be assumed that EPW components are going to fail and significant time would be spent repairing the EPW. A second option would be to build a custom platform out of steel, to which weight could be added. The third option would be to use a materials testing machine to simulate the cyclic loading of the curb drop. For all methods, a 400 pound occupant and a 400 pound wheelchair should be assumed and the caster should be fitted with the lowest profile it is designed for. The passing criteria would be 6,666 cycles. Again, for new materials the test should be performed on three different CDLs.

In order to test impact strength, the next CDL should be subjected to the pendulum impact test. The test should be performed in accordance with protocol described in chapter 4.2.2. The lowest profile tires should be used and if a new material is utilized, the test should be repeated on three different casters. The passing criteria for this test should be load of greater than 8000N without failure as recommended by Bertocci et al (2003). The 8000N load is based on 20g/48kph vehicle crash test scenario, which should be the worst loading situation the CDLs would be expected to survive.

Base on testing parameters, the CDL should not be used with bariatric wheelchairs unless the device passes the tests under higher loading conditions. The 400 pound user and 400 pound wheelchair criteria was selected by adding additional weight to likely conditions, providing some factor of safety. The other limitation is that study participants should be asked to report any high speed vehicle collisions, so their CDL can be replaced. The pendulum impact tests show that the CDL v2.2 could survive high loading conditions, but it may significantly weaken the CDL and to error on the side of caution, the casters should be replaced. Given the infrequent occurrence of collisions of this type and that more than likely other components of the EPW will fail under these conditions, the scenario is not a major concern, but it should be noted.

5.4.2 Reliability

The CDL v3.x series should have the same or better electronics reliability characteristics the previous generation. To ensure reliability, the CDL needs to be subjected to a slated double drum test, an un-slated double drum test, and a water submersion test.

The purpose of the slated double drum test is to make sure that electronic do not fail under repeated shock conditions. The most likely failure mode for this test is the battery connection. The protocols for this test should follow as described in chapter 4.2.2. The rational for setting 50,000 cycles as passing criteria is that it represents one-quarter of the CDLs expected life, which is longer than any single protocol duration. In between uses, the CDL components should be inspected and maintained as needed.

The purpose of the un-slated double drum test is to assess the CDL for accuracy and precision. At least three trials of 10,000 cycles should be completed and the trials should be compared against each other and the theoretical results as described in chapters 4.2.2 and 4.3. This test represents the best case scenario for error; under real driving conditions partial rotations may be lost during change of direction and the tire slipping on the hub is more likely on real obstacles than on rollers. However, these factors are highly dependent on the user's environment, activities, and driving habits and, are nearly impossible to account for.

The water submersion test is to verify that the CDL does not leak water. A water depth of 12 inches was selected base on the idea that water of that depth would more than likely disable an EPW and users would avoid negotiating an obstacle of that magnitude. An hour time period was arbitrarily chosen as representative of more than just brief submersion.

5.5 RECOMMENDATION FOR FUTURE DESIGN PROJECTS

The development of the CDL and prior design concepts took place over two and half years and required significant resources. Some aspects of the design process proceeded in an efficient fashion, while other aspects could have benefited from better design process. In the first phase of work, mainly encompassing the evaluation of concepts, as described in chapter two, demonstrated both bad and good design process. The use of solid models and computer models was very useful in determining what concepts had potential and which ones that were flawed. However, once the TCDL concept was chosen the design process broke down. Due to tight deadlines, the design went into mass production before thorough bench and field testing could be performed, resulting in a poor product. Had sufficient testing been conducted on the TCDL the concept would likely have been abandoned before the replication of several identical devices.

These lessons were heeded in second round of design with CDL. Multiple iterations of the CDL were completed and various methods of testing were conducted along the way. In six months, three iterations of the CDL were produced before the production of the field ready models began, allowing many of the design flaws to be discovered and corrected in an efficient manner. Starting with a less than perfect but quickly producible design in the CDL v1.0, proved to be a very useful way of assessing the concept's potential and demonstrating what would be needed in a next generation device.

The lessons learn from the development of the CDL can be generally applied to future projects of similar nature. The first guideline is that multiple prototype iterations of a design should be fabricated and tested before mass production; solid models and computer simulations should be employed to reduce the number of iterations necessary to arrive at a field ready product. Second, prototypes should be thoroughly tested at each stage, under appropriate conditions. Lastly, for all projects, especially ones with strict deadlines, a team approach is necessary to produce a quality product. The greatest time saver in a development project is catching flaws and anticipating weaknesses before they are implement; the inclusion of more engineers and end users in the process increases the likelihood that weaknesses will be discovered while the design is in the "on paper" phase and not in the production phase.

A flow chart that ties the aforementioned guidelines together is given in figure 5.4. The flow chart begins with a concept and suggests that simulations should first be used to evaluate a concept, followed by the fabrication of a proof of concept model and the preliminary evaluation of it. If the concept is deem not feasible at any point in this phase, a new or modified concept should be chosen and the process should start over again. If the preliminary evaluation suggests a concept will be successful, a functional prototype should be fabricated. The functional prototype should be able to be deployed into the device's intended environment; however, it may be lacking in user friendliness and may not be designed to be produced in quantity. The functional prototype should be bench tested in controlled situations as well as limited testing in environment the device is intended to operate. This stage should include as my iterations as necessary for verifying the device works. The final step before production should be to create a single prototype that can be accurately and readily reproduced with available methods. This prototype is to ensure that design flaws are carried into the final productions run. This phase can also be used optimize the manufacturing protocol for time and quality, which may include the fabrication of jigs, fine tuning of CNC programs, and ordering the most appropriately dimensioned raw materials. A final round of testing should again be included before a series of identical devices are replicated, as to ensure any changes in design or fabrication techniques do not cause any unexpected deviations in device performance. For less complex designs the functional and production ready prototypes may be combined into one step.

Although the design process flow chart is presented in a generalized format, it should be noted that it is intended to serve as guideline for the development of devices where a small number of field ready, identical prototypes are to be made. It is not intended as a complete method for arriving at commercial product, rather it is a framework for developing a limited number of identical functional devices in an efficient manner, while maintaining quality.

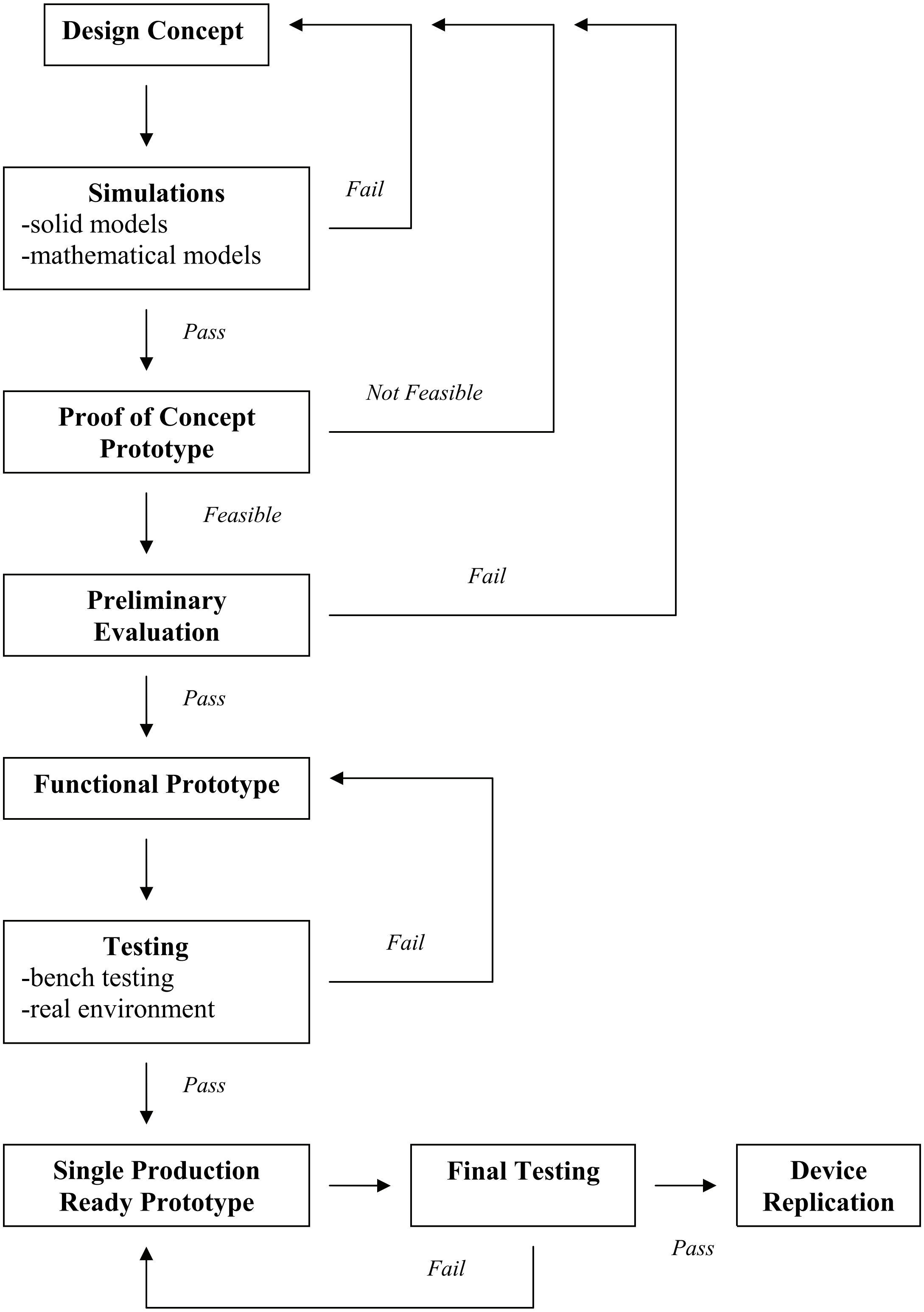

Figure 5.4 Flow chart outlining the step of an ideal design process

5.6 CONCLUSION

Guidelines have been described for the design and bench testing of the next generation of CDLs. The design goals of the next generation of CDLs should focus on making it user-friendly and increase its functionality. If improvements can be made in these areas the CDL could be used by a broad audience of researchers and clinicians for a variety of research purposes and clinical measures. The device described in this manuscript satisfies the original design criteria to a high degree and has demonstrated the potential to be prolific data collect instrument. However, the success and significance of this study will largely depend on the impact of the novel research and clinical measures made possible through the use of the next generation of Caster Data Logger.

APPENDIX A

CDL V2.X DRAWINGS

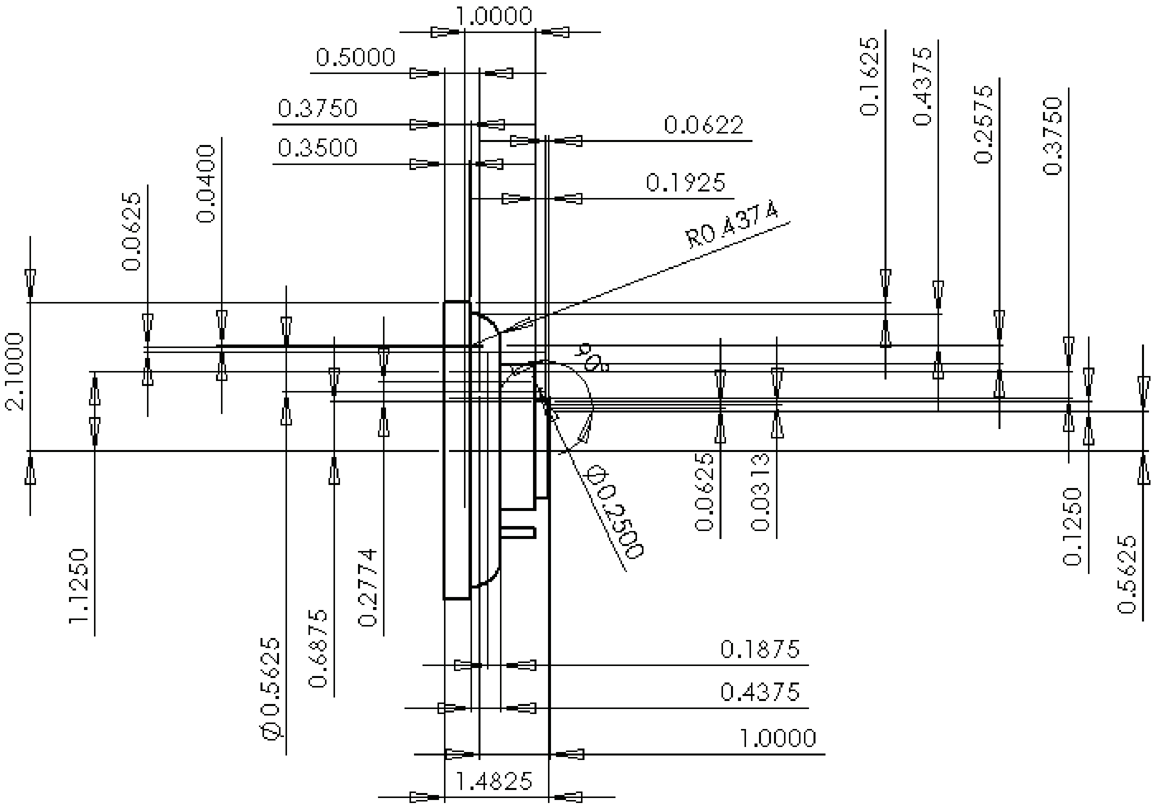

Figure A.1 Mechanical drawing of the side view of the part *left hub.sld*

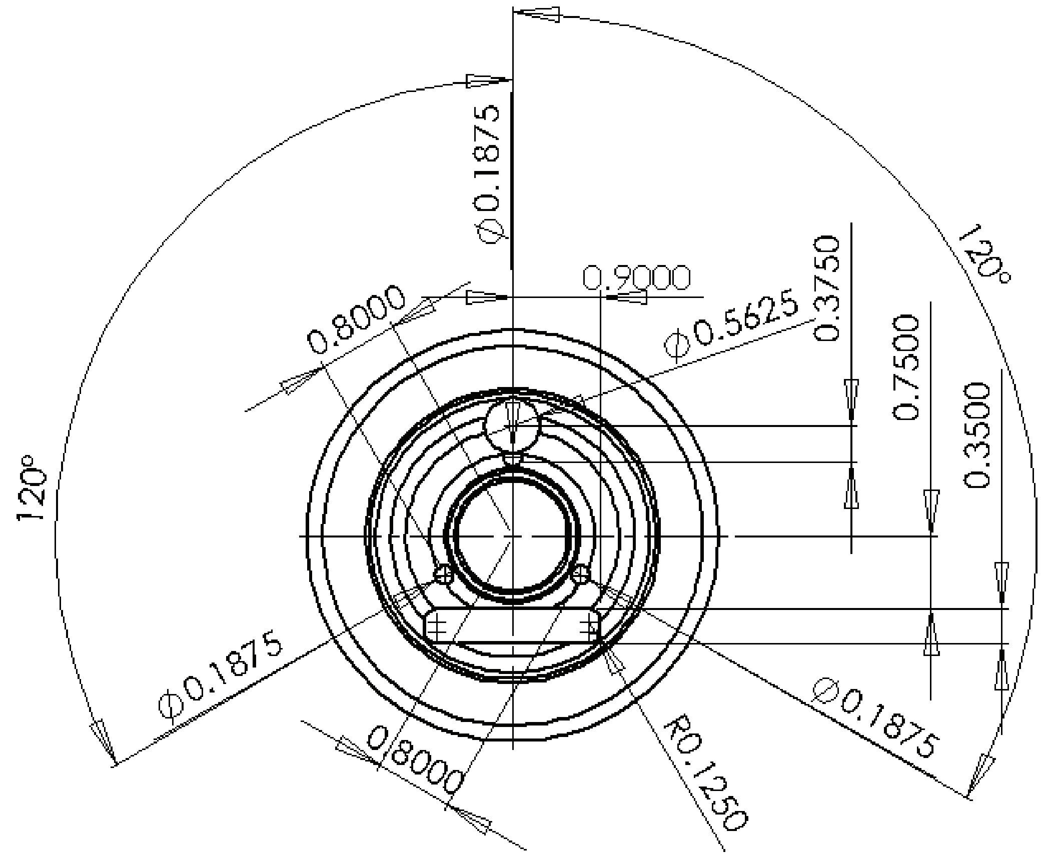

Figure A.2 Mechanical drawing of the inside view of the part *left hub.sld*

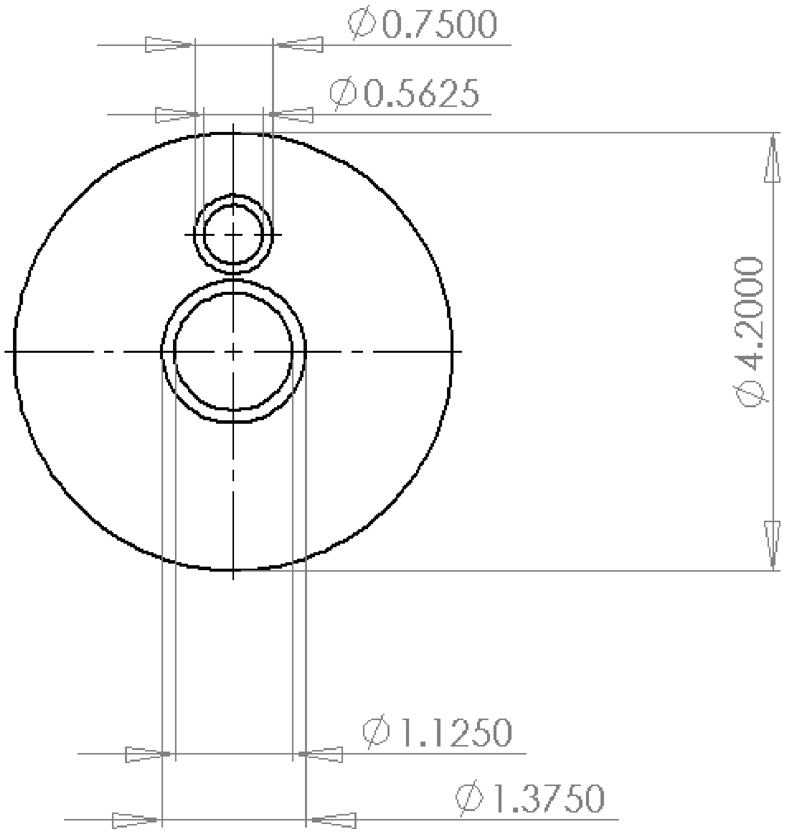

Figure A.3 Mechanical drawing of the outside face of the part *left hub.sld*

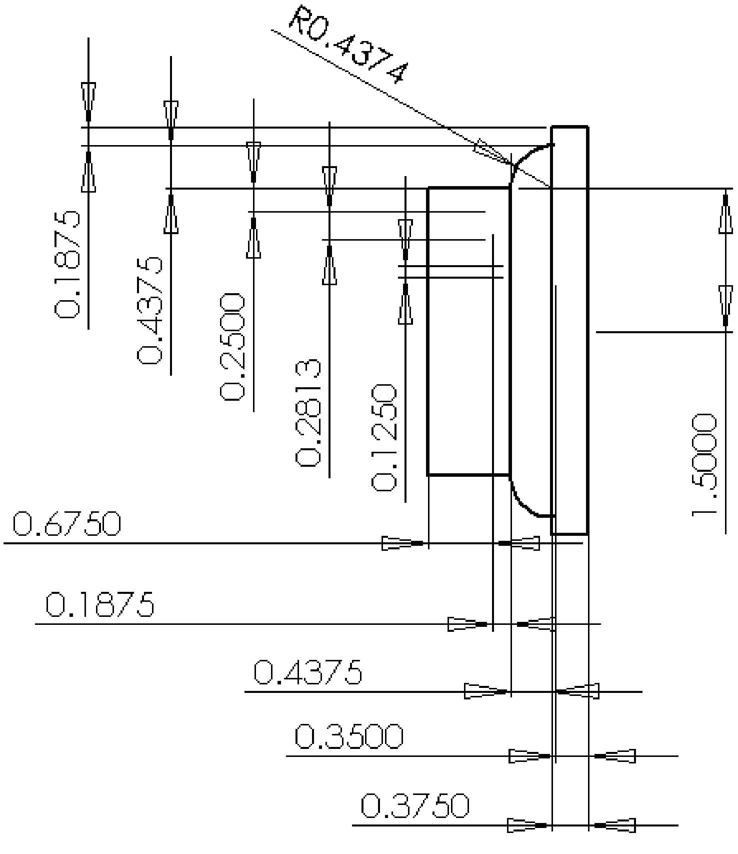

Figure A.4 Mechanical drawing of the side view of the *right hub.sld*

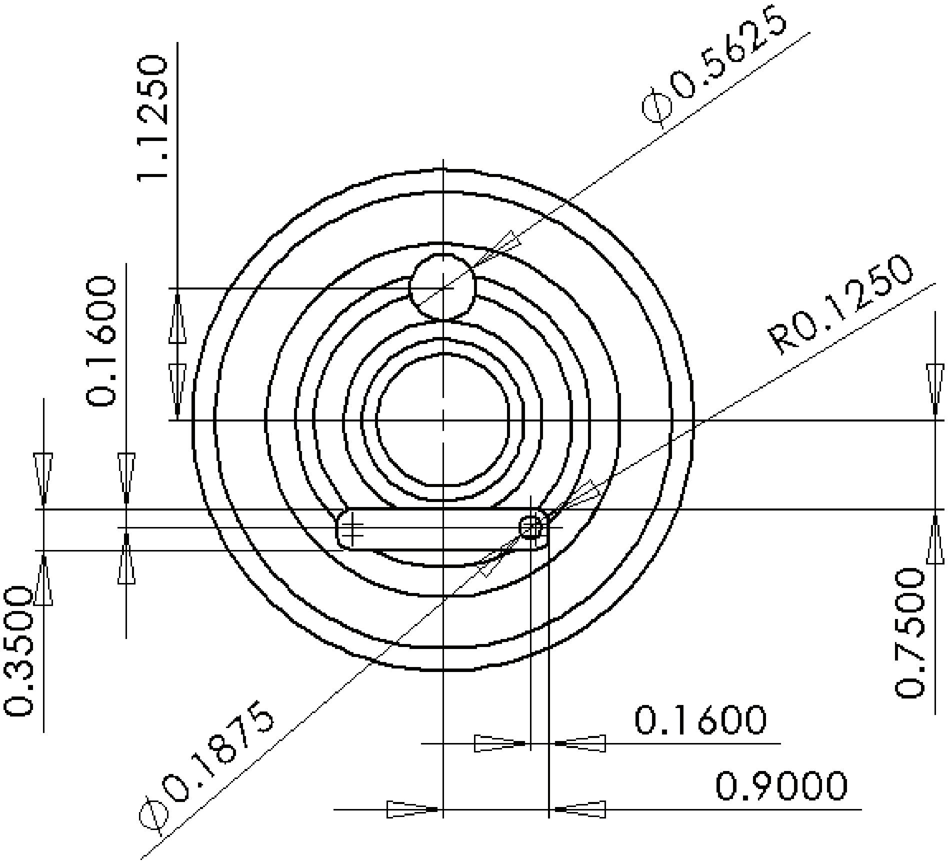

Figure A.5 Mechanical drawing of the inside of the part *right hub.sld*

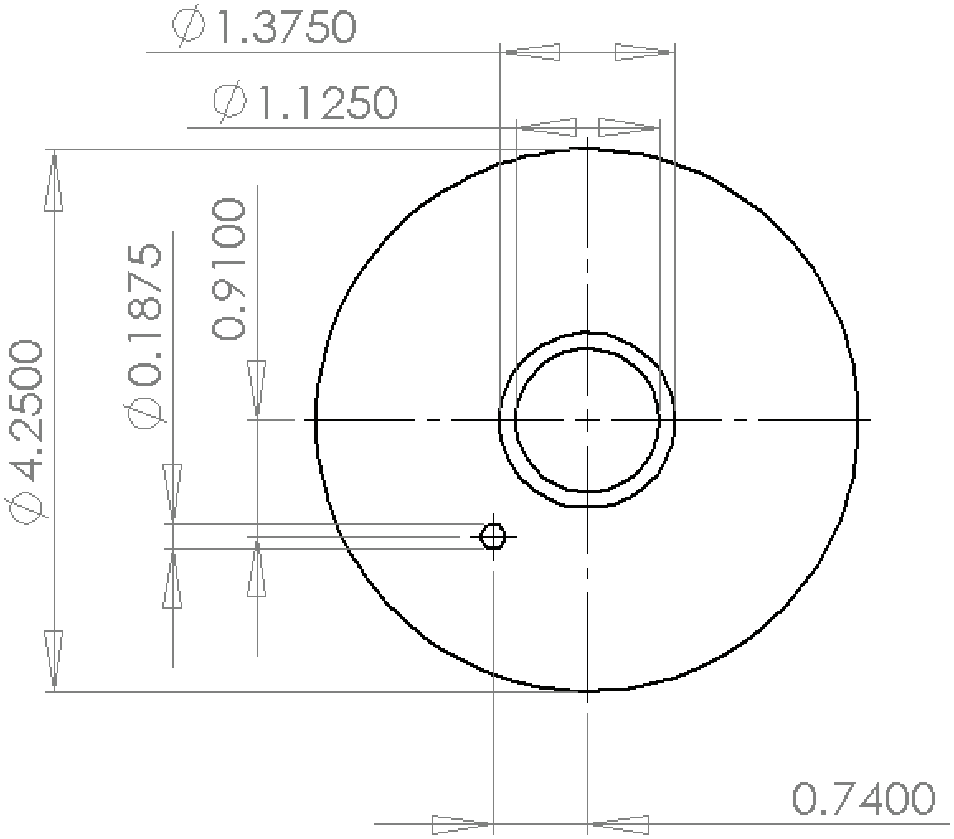

Figure A.6 Mechanical drawing of the outside face of the part *right hub.sld*

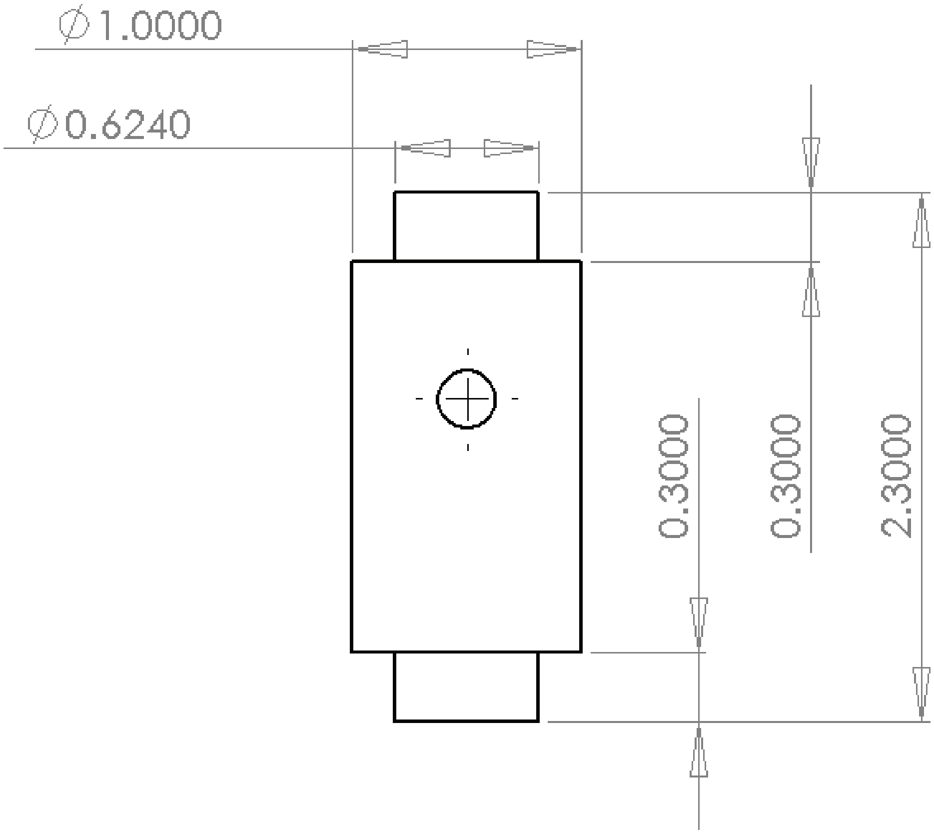

Figure A.7 Mechanical drawing of the side view of the part *magnet sleeve.sld*

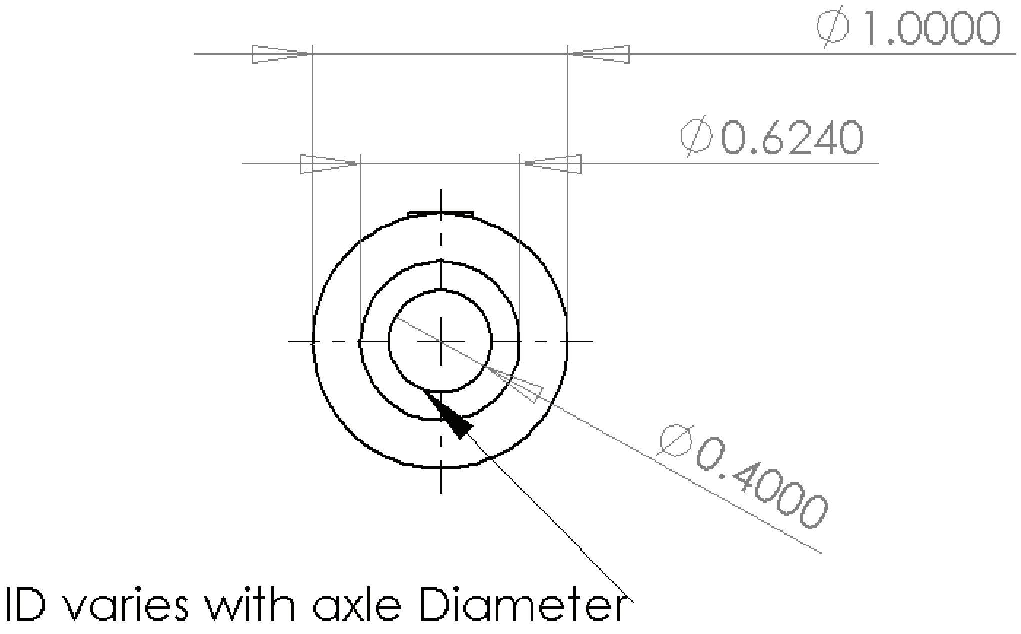

Figure A.8 Mechanical drawing of the top view of the part *magnet sleeve.sld*

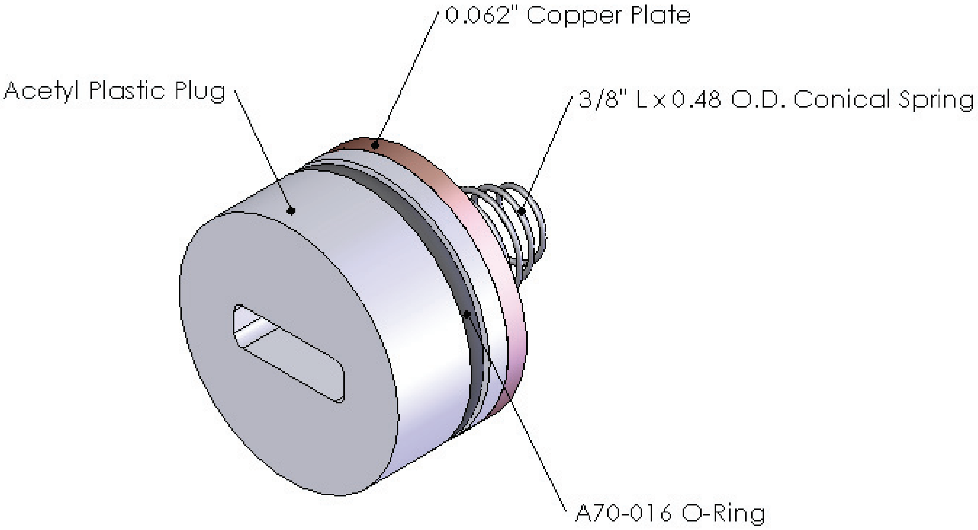

Figure A.9 An annotated isometric view of the solid model assembly *battery plug.asm*

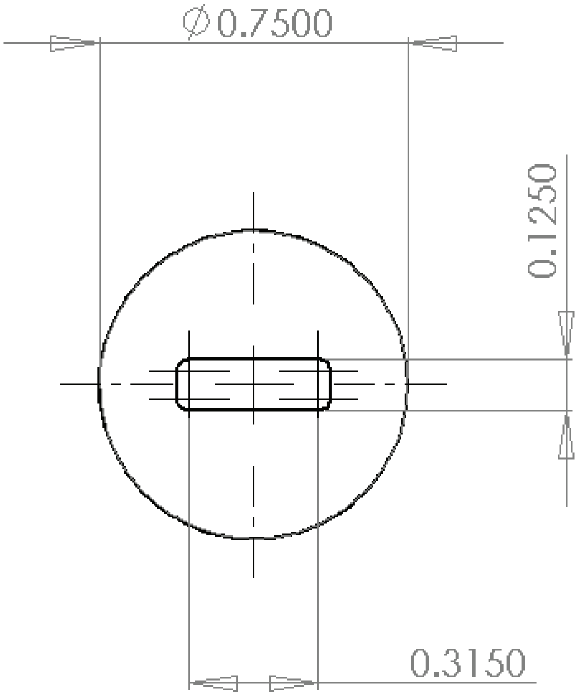

Figure A.10 Mechanical drawing of the top view of the part *battery plug.sld*

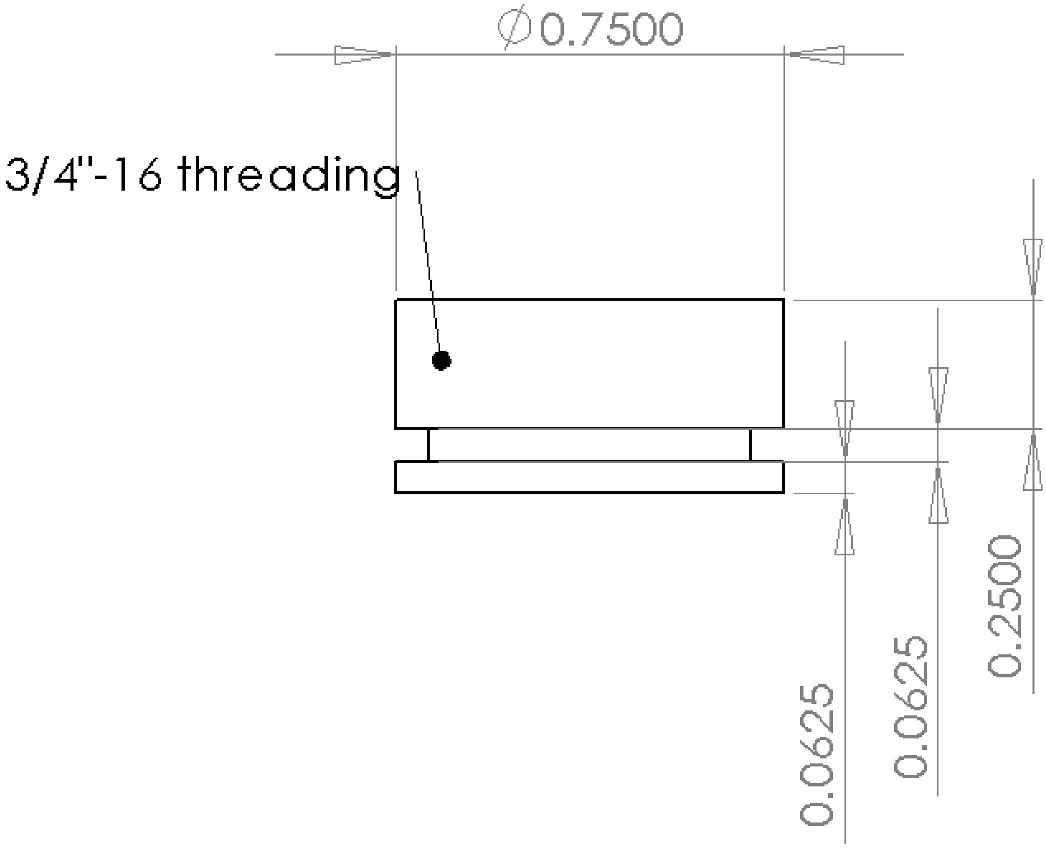

Figure A.11 Mechanical drawing of the side view of the part *battery plug.sld*

APPENDIX B

DUMMY HUB DRAWINGS

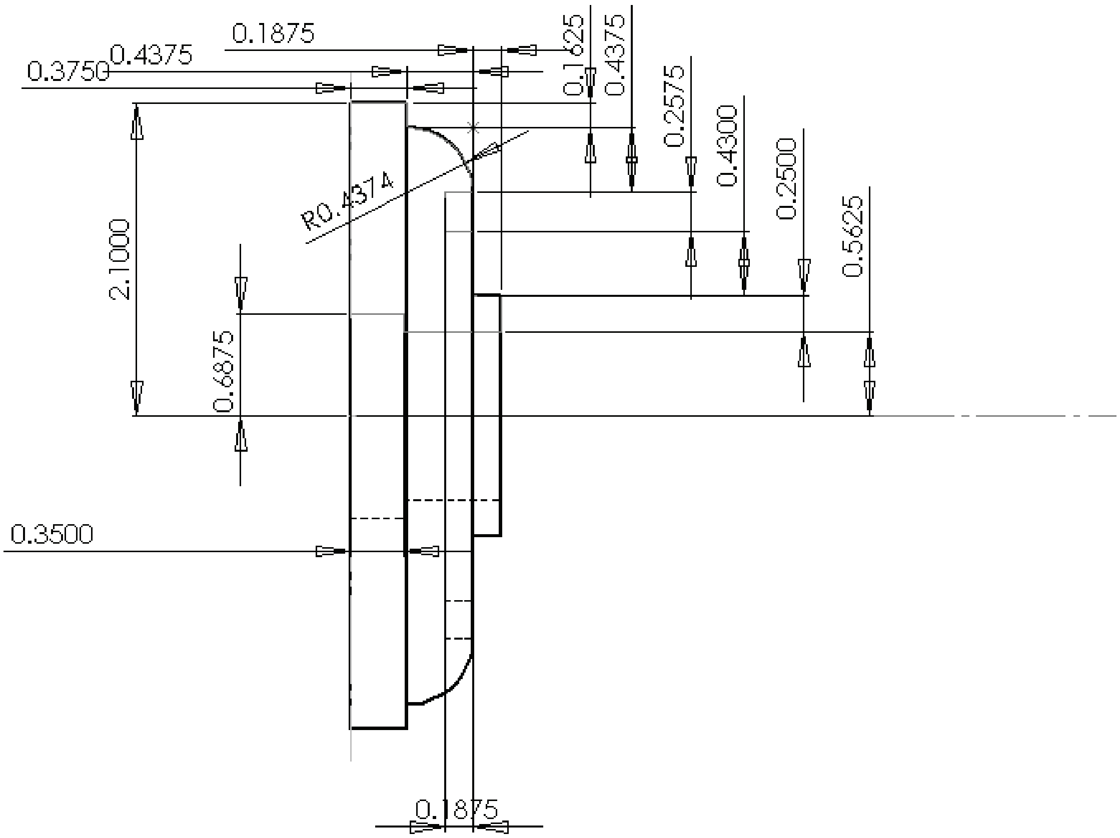

Figure B.1 Mechanical drawing of the side view of the part *left dummy hub.sld*

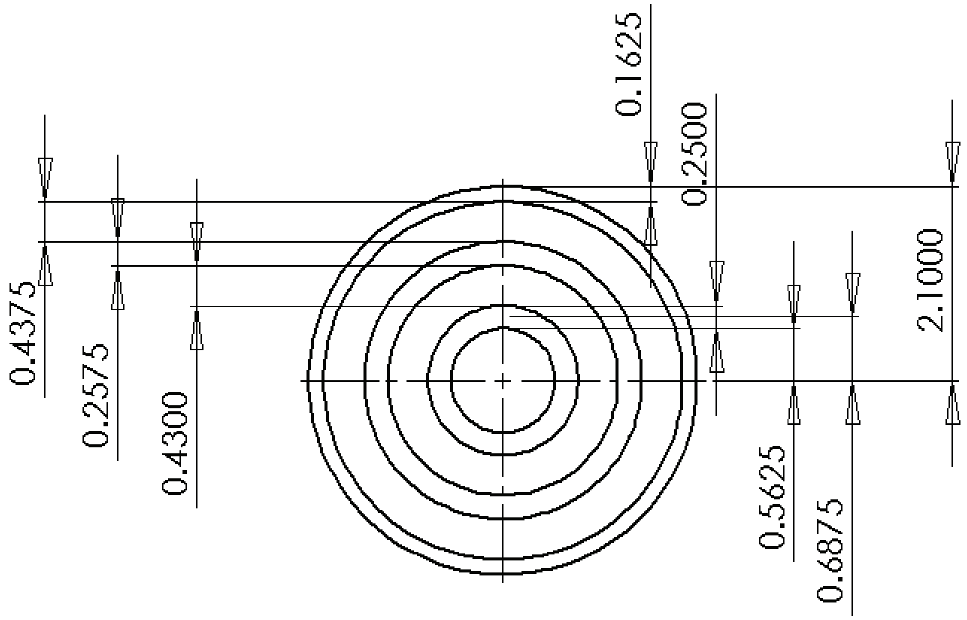

Figure B.2 Mechanical Drawing of the inside view of the part *left dummy hub.sld*

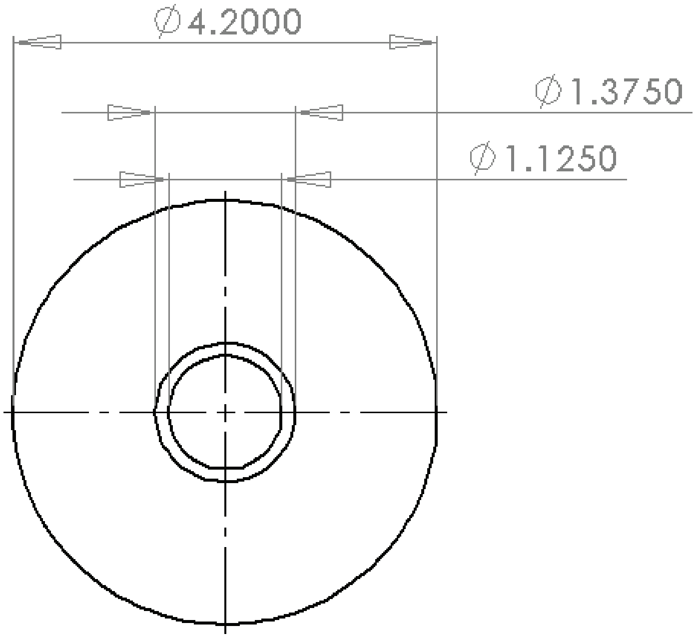

Figure B.3 Mechanical drawing of the outside face of the part *left dummy hub.sld*

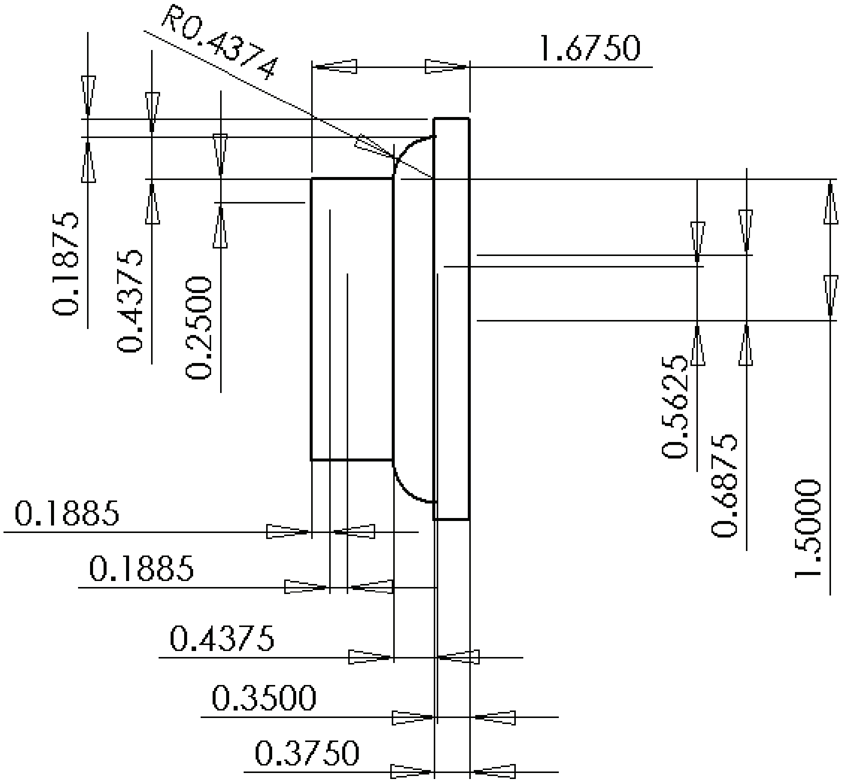

Figure B.4 Mechanical drawing of the side view of the part *right dummy hub.sld*

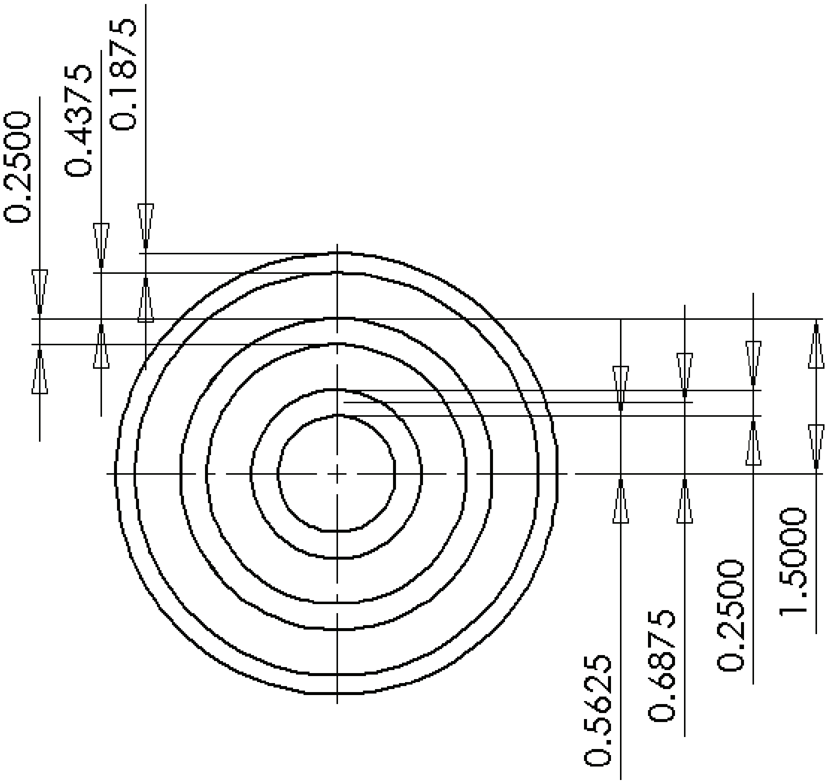

Figure B.5 Mechanical drawing of the inside of the part *right dummy hub.sld*

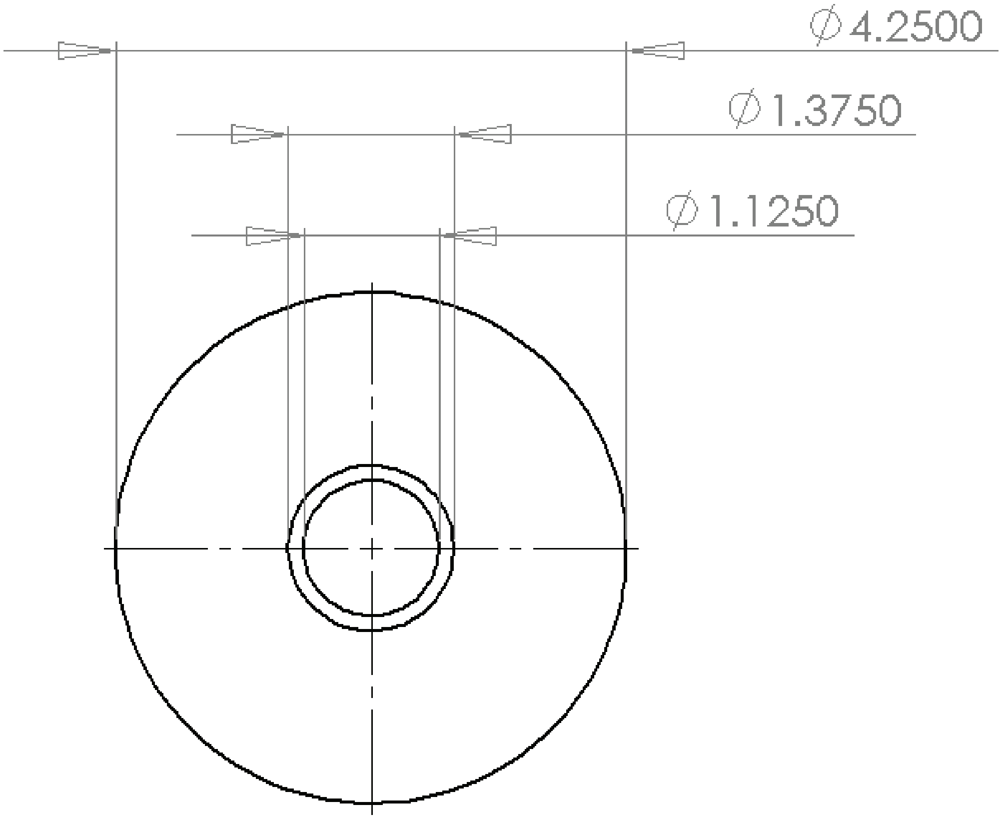

Figure B.6 Mechanical drawing of the outside face of the part *right dummy hub.sld*

APPENDIX C

CDL V2.2 MECHANICAL PARTS LIST

Material	vendor	vendor part #	Unit def	Unit cost ($)
4.5" Dia Delrin Round stock	McMaster	8572K37	$/ft	97.86
5/8" ID, 1 3/8 OD ABEC-1 Bearings	McMaster	60355K37	1 bearing	6.57
8-32-Tee Nuts w/out prongs	McMaster	90598A041	100/pack	13.1
.588 ID wave spring	McMaster	9714K33	25/pack	8.06
O-ring 70 neoprene -039	McMaster	94115K039	30/pack	13.35
O-ring 70 neoprene -025	McMaster	94115K025	100/pack	13.43
O-ring 70 neoprene -016	McMaster	94115K016	100/pack	3.42
12"x12"x0.062" electrical grade Cu	McMaster	8963K42	1 sheet	21.32
Conical Springs 3/8" L	McMaster	1692K17	3-pack	12.05
2" L 8-32 Socket head screws	McMaster	91251A205	25/box	5.13
1" Dia Aluminum round stock	McMaster	1615T29	72"	42.08
1/2 AA 3.6V Tadiran Batteries	Digikey	439-1004-ND	10	50.88
1/4" dia 1/8" thick magnets	Digikey	469-1004-ND	10/pack	1.88

APPENDIX D

QUESTIONAIRE

Wheelchair Driving Characteristics
During and Post National Veterans Wheelchair Games

Date: ___/___/______

Name: ____

Address:____

City: ____________________ State: __________________ Zip Code:____________
Telephone number: ___________________________Email:_____________________

Gender: ☐ Male (1) ☐ Female (0) Date of Birth: ___/___/______ Age: ______

Disability or Injury Level: _______________________

Date of Disability Onset or Injury: ___/___/______

Veteran Status: ☐ Yes, I am a US Veteran. (1) ☐ No (0)

Ethnic Origin: ☐ African American (1)
☐ Hispanic (4)
☐ Asian American (2) ☐ Native American (5)
☐ Caucasian (3) ☐ Other (6): _____________

Body weight: ____________

Primary Residence Setting: ☐ Rural (0) ☐ Urban (1) ☐ Suburban (2)

Are you currently employed (full or part time)? ☐ Yes (1) ☐ No (0)

Can you use transportation independently? ☐ Yes (1) ☐ No (0)

Are you able to ambulate (with or without the use of assistive devices)? ☐ Yes (1) ☐ No (0) If **YES**, in a typical day, how often do you ambulate?
☐ 8 hours or more (1) ☐ 6-7 hours (2) ☐ 4-5 hours (3) ☐ 2-3 hours (4)
☐ 1 hour or less (5) ☐ Other (6): ___________

How does the accessibility of your community environment influence your daily activities?

☐ Helps a lot (0)
☐ Helps some (1)
☐ Has no effect (2)
☐ Limits some (3)
☐ Limits a lot (4)

Information Regarding Your Wheelchair(s)

Type of **Primary** Wheelchair: ☐ Manual (1) ☐ Power (0)

Wheelchair Make: _____________________________ Model: ______________________

If Power Wheelchair:

Average Amount of Time Before You Charge Your Battery? _________ hours

What kind of power base do you have?

☐ Front wheel drive ☐ Mid-wheel drive ☐ Rear wheel drive

What kind of seating system does your power wheelchair have? ***(check all that apply)***

☐ Power recline ☐ Power leg elevator

☐ Power tilt ☐ No features

☐ Power seat elevator ☐ Other: ___________________________

Age of **current** primary wheelchair: ____________ years

Number of years since you started using a wheelchair: __________ years

Overall, how satisfied are you with your **primary** wheelchair?
☐ Very satisfied
☐ Satisfied
☐ Neither satisfied, nor dissatisfied
☐ Dissatisfied
☐ Very dissatisfied

Type of **back-up** wheelchair:
☐ Manual (1) ☐ Power (0) ☐ Do not use or own a back-up wheelchair (2)

On average, how often do you use your **back-up** wheelchair?
☐ At least once a week (0)
☐ Several times a month (1)
☐ Several times a year (2)
☐ Do not use or own a back-up wheelchair (3)

Which events are you participating in at the NVWG?

NVWG Events	**Which wheelchair/equipment will you be using?** *(Please check the appropriate box)*
1.	☐ Primary ☐ Sports/backup ☐ Not applicable ☐ Other equipment: ___________________
2.	☐ Primary ☐ Sports/backup ☐ Not applicable ☐ Other equipment: ___________________
3.	☐ Primary ☐ Sports/backup ☐ Not applicable ☐ Other equipment: ___________________
4.	☐ Primary ☐ Sports/backup ☐ Not applicable ☐ Other equipment: ___________________
5.	☐ Primary ☐ Sports/backup ☐ Not applicable ☐ Other equipment: ___________________

Do you regularly participate in sports or other recreational activities at home?

☐ Yes (1) ☐ No (0)

If **YES**, please indicate below the activities you participate in.

Type of sport or recreational activity	# days per week	# hours per day	Wheelchair/equipment used? *(Please check the appropriate box)*
			☐ Primary ☐ Sports/backup ☐ Other equipment: __________________ ☐ Not applicable
			☐ Primary ☐ Sports/backup ☐ Other equipment: __________________ ☐ Not applicable
			☐ Primary ☐ Sports/backup ☐ Other equipment: __________________ ☐ Not applicable
			☐ Primary ☐ Sports/backup ☐ Other equipment: __________________ ☐ Not applicable
			☐ Primary ☐ Sports/backup ☐ Other equipment: __________________ ☐ Not applicable

BIBLIOGRAPHY

[1] Cooper RA, Cooper R, and Boninger ML. Trends and Issues in Wheelchair and Seating Technologies. *Assistive Technol*, in press.

[2] Aronovitz LG. CMS Did Not Control the Rising Power Wheelchair Spending. *Testimony Before the Committee on Finance, US Senate*. April 23, 2004 GAO-04-716T

[3] Brandt A, Iwarsson S, Stahle A. Older Peoples's Use of Powered Wheelchairs for Activity and Participation. *J Rehabil Med.* 2004; 36: 70-77.

[4] Meyers AR, Anderson JJ, Miller DR, Shipp K, Hoenig H. Barriers, Facilitators, and Access for Wheelchair Users: Substantive and Methodologic Lessons from a Pilot Study of Environmental Effects. *Soc Sci & Med*. 2002; 55: 1435-1445.

[5] Hoenig H, Landerman L, Shipp KM, George L. Activity Restriction Among Wheelchair Users. *J Am Geriatr Soc*. 2003; 51(12): 1244-1251.

[6] Whiteneck G, Meade MA, Dijkers M, Tate DG, Bushnik T, Forchheimer MB. Environmental Factors and Thier Role in Participation and Life Satisfactions After Spinal Cord Injury. *Arch Phys Med Rehabil.* 2004; 85: 1793-1802.

[7] Chaves ES, B.M., Cooper R, Fitzgerald SG, Gray DB, Cooper RA. Assessing the influence of Wheelchair Technology on Perception of Participation in Spinal Cord Injury. *Arch Phys Med Rehabil*. 2004; 85: 1854-1858.

[8] Kennedy P, Lude P, Tayor N. Quality of Life, Social Participation, Appraisals and Coping Post Spinal Cord Injury: A Review of Four Community Samples. *Spinal Cord*. 2006; 44: 95-105.

[9] Tudor-Locke CE, Meyers A. Challenges and Opportunities for Measuring Physical Activities in Sedentary Adults. *Sports Med*. 2001; 31(2): 91-100.

[10] Vyssotski AL, Serkov AN, Itskov PM, Dell'Omo G, Latanov AV, Wolfer DP, Lipp H-P. Miniaure Neurologgers for Flying Pigeons: Multichannel EEG and Action and Field Potentials in Combination with GPS Recording. *J Neurophysiol*. 2006; 95: 1263-1273.

[11] Witte TH, Hirst CV, Wilson AM. Effect of Speed on Stride Parameters in Racehorses at Gallop in Field Conditions. *J Exp Biol*. 2006; 209: 4389-4397.

[12] Yao J, Warren S. Applying the ISO/IEEE 11073 Standards to the Wearable Home Health Monitoring Systems. *J Clin Monit Comput*, 2005; 19: 427-436.

[13] Miyazaki S. Long Term Unrestrained Measurement of Stride Length and Walking Velocity Utilizing a Piezoelectric Gyroscope. *IEEE Trans Biomed Eng*. 1997; 44(8): 753-759.

[14] Herren R, Sparti A, Kamiar A, Schutz Y. The Prediction of Speed and Incline in Outdoor Running in Humans Using Accelerometry. *Med Sci Sport Exerc*. 1999; 31(7): 1053-1059.

[15] Culhane KM, Lyons GM, Hilton D, Grace PA, Lyons D. Long-term Mobility Monitoring of Older Adults Using Accelerometers in a Clinical Environment. *Clin Rehabil.* 2004; 18: 335-343.

[16] Postma K, Berg-Emons van den HJG, Bussmann JBJ, Sluis TAR, Bergen MP, HJ Stam HJ. Validity of the Detection of Wheelchair Propulsion as Measured with an Activity Monitor in Patients with Spinal Cord Injury. *Spinal Cord*. 2005; 43: 550-557.

[17] Schneider PL, Crouter SE, Lukajic O, Bassett DR. Accuracy and Reliability of 10 Pedometers for Measuring Steps over a 400-m Walk. *Med Sci Sports Exerc*. 2003; 35(10): 1779-1784.

[18] Crouter SE, Schneider PL, Karabulut M, Bassett DR. Validity of 10 Electronic Pedometers for Measuring Steps, Distance, and Energy Cost. *Med Sci Sports Exerc*, 2003; 35(8): 1455-1460.

[19] Melanson EL, Knoll JR, Bell ML, Donahoo WT, Hill JO, Nysse LJ, Lanningham-Foster L, Peters JC, Levine JA. Commercially Available Pedometers: Considerations for Accurate Step Counting" *Prev Med*. 2004; 39: 361-368;

[20] Foster RC, Lanningham-Foster LM, Manohar C, McCrady SK, Nysse LJ, Kaufman KR, Padgett DJ, Levine JA. Precision and Accuracy of an Ankle-Worn Accelerometer-Based Pedometer in Step Counting and Energy Expenditure *Prev Med*. 2005; 41: 778-783.

[21] Felton G, Tudor-Locke C, Burkett L. Reliability of Pedometer-Determined Free-Living Physical Activity Data in College Women. *Res Q Exerc Sports*. 2006; 77(3): 304-308.

[22] de Blok BMJ, de Greef MHG, ten Hacken NHT, Sprenger SR, Postema K, Wempe JB. The effects of a Lifestyle Physical Activity Counseling Program with Feedback of a Pedometer During Pulmonary Rehabilitation in Patients with COPD: A Pilot Study. *Patient Educ and Couns*. 2006; 61:48-55.

[23] Speck BJ, Looney SW. Self-Reported Physical Activity Validated by Pedometer: a Pilot Study. *Public Health Nurs*. 23(1); 88-94.

[24] Chan CB, Ryan DAJ, Tudor-Locke C. Relationship between Objective Measure of Physical Activity and Weather: a Longitudinal Study. *Int J Behav Nutr Phys Activ*. 2006; 3(21).

[25] Jago R, Watson K, Baranowski T, Zakeri I, Yoo S, Baranowski J, Conry K. Pedometer Reliability, Validity and Daily Activity Targets Among 10- to 15-Year Old Boys. *J Sports Sci*. 2006; 24(3): 241-251.

[26] Knapik JJ, Darakjy S, Hauret KG, Canada S, Marin R, Jones BH. Ambulatory Physical Activity during United States Army Basic Combat Training. *Int J Sports Med*. 2007; 28: 106-115.

[27] Mermon D, Rissel C, Phongsavan P, Smith BJ, Van Kemenade C, Brown WJ, Bauman AE. Promoting Walking with Pedometers in the Community. *Am J Prev Med*. 2007; 32(4): 290-297.

[28] Spaeth DM, A.J., Cooper RA. Application of a Commercial Datalogger for Rehabilitation Research. *Proc of the 23rd Annual RESNA Conf*. 2000; Orlando, FL.

[29] Cooper RA, T.T., Cooper R, Dvorznak M, Fitzgerald SG, Ammer W, Guo S, Boninger ML. Driving Characteristics of Electric-Powered Wheelchair Users: How Far, Fast, and Often Do People Drive?. *Arch Phys Med Rehabil*. 2002; 83: 250-255.

[30] Spaeth DM, C.R., Albright S, Ammer W, Puhlman J. Developement of a Miniature Data Logger for Collection Outcome Measures for Wheeled Mobility. *Proc of the 27th Annual RESNA Conf*. 2004; Orlando, FL.

[31] Fitzgerald SG, Arva J, Cooper RA, Dvorzvak MJ, Spaeth DM, Boninger ML. A Pilot Study on Community Usage of a Pushrim-activated, Power-assisted Wheelchair. *Assistive Technol*. 15(2): 2003; 113-119.

[32] Kaminski BA. Application of a Commercial Datalogger to Electric Powered and Manual Wheelchairs of Children. University of Pittsburgh, 2004.

[33] Tolerico ML. Investigation of the Mobility Characteristics and Activity Levels of Manual Wheelchair Users In Two Real World Environments. University of Pittsburgh, 2005

[34] Cooper RA, Robertson RN, Van Sickle DP. Wheelchair Impact Response to ISO Test pendulum and ISO Standard Curb. *IEEE Trans Rehabil Eng*. 1994; 2(4): 240-246.

[35] Bertocci GE, Hobson DA, Digges KH. Developement of Transportable Wheelchair Design Criteria Using Computer Crash Simulation. *IEEE Trans Rehabil Engr*. 1996; 4(3): 171-181.

[36] Bertocci GE, Esteireiro J, Cooper RA, Young T, Thomas C. Testing and Evaluation of Wheelchiar Caster Assemblies Subjected to Dynamic Crash Loading. *J Rehabil Res Dev*. 1999; 36(1): 32-41.

[37] Bertocci GE, van Roosemalen L. Wheelchair Caster Loading During Frontal Impact. *Assistive Technol*. 2003; 15: 105-112.

[38] Cooper RA, Wolf EJ, Fitzgerald SG. Evaluation of Selected Sidewalk Pavement Surfaces. *J Spinal Cord Med*. 2004; 27(5): 468-475.