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# Design of a Power-Assist Hemiplegic Wheelchair

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**DESIGN OF A POWER-ASSIST HEMIPLEGIC WHEELCHAIR**

by

Keith Nicholas Liadis

A Thesis

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in

Mechanical Engineering

May 2006

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# I Abstract

Current one-handed manual wheelchairs are difficult to propel because one arm can only provide half the power that is ascertained in a two-handed manual wheelchair. A power-assisted hemiplegic (one-sided paralysis) wheelchair was developed that can effectively be propelled with one arm while remaining maneuverable, lightweight, and foldable. An existing manual wheelchair was minimally modified and fitted with power-assisted components that could alternatively be attached to a wide range of manual wheelchairs. The design implements a motor and gear train to power the wheel on the user's affected side, encoders on both rear wheels to track wheel position, and a heel interface on the footrest to control steering. A controls program was developed that analyzes wheel position and steering to respond to the motion of the hand-driven wheel. Extensive testing was performed to ensure design integrity. Testing results showed that the prototype successfully met and exceeded predetermined design specifications based on industry standard testing procedures. The design has the potential to deliver increased freedom to a considerable consumer base.

## II Acknowledgements

Two years ago I was graduating from WPI with my bachelor's degree. My plan was to start working right away and find time to take grad classes at night. As graduation day grew near without a position lined up, Professor Hoffman approached me to ask if I was interested in "Plan B". Two years later, I am graduating with my master's degree, an amazing job, a wedding date, a new home, and last but certainly not least, a potentially groundbreaking thesis project capable of improving the lives of countless people. So to Professor Hoffman, I sincerely thank you for the opportunities, financial support, and guidance that you have so graciously provided me with.

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# III Table of Contents

<b>I</b>	<b>ABSTRACT</b>	i
<b>II</b>	<b>ACKNOWLEDGEMENTS</b>	ii
<b>III</b>	<b>TABLE OF CONTENTS</b>	iii
<b>IV</b>	<b>LIST OF FIGURES</b>	vii
<b>V</b>	<b>LIST OF TABLES</b>	viii
<b>1</b>	<b>INTRODUCTION</b>	1
<b>2</b>	<b>BACKGROUND</b>	2
2.1	<b>Specialty Disabilities</b>	2
2.1.1	Need for Specialized Wheelchairs	2
2.1.2	Difficulties with Producing Specialized Wheelchairs	3
2.2	<b>Hemiplegic Disabilities</b>	4
2.2.1	Stroke	5
2.2.2	Causes of Stroke	5
2.2.2.1	Effects of Stroke	7
2.2.2.2	Stroke Mobility Research	8
2.2.3	Additional Causes of Hemiplegia	8
2.3	<b>Current Hemiplegic Wheelchairs</b>	9
2.3.1	Dual-rim Wheelchairs	9
2.3.2	Hemiplegic Lever-arm Wheelchairs	10
2.3.3	Conceptual Wheelchair Designs	12
2.3.3.1	University of Cambridge Thesis Research	12
2.3.3.2	WPI MQP Work	13
2.4	<b>Standard Wheelchair Research</b>	13
2.4.1	Current Advancements in Wheelchairs	13
2.4.1.1	Manual Wheelchairs	14
2.4.1.1.1	Lightweight and Foldable Designs	14
2.4.1.2	Power Assist Wheelchairs	15
2.5	<b>Motor Drives</b>	16
2.5.1	Brushed DC Commutator Motor Drives	16
2.5.2	Brushless DC Electronically Commutated Motor Drives	18
2.5.3	DC Stepper Motor Drives	18
2.6	<b>Encoder Feedback</b>	19
2.6.1	Absolute Encoder	20
2.6.2	Incremental Encoder	20
2.6.2.1	Quadrature Encoder	21
2.7	<b>Wheelchair Testing Standards</b>	21
<b>3</b>	<b>METHODS</b>	<b>23</b>
3.1	<b>Task Specifications</b>	24

<b>3.2</b>	<b>Ideation of a Hybrid Manual/Powered Wheelchair</b>	27
3.2.1	Propulsion	27
3.2.1.1	Propulsion Design Concepts	27
3.2.1.1.1	Torque Responsive Drive	28
3.2.1.1.2	Position Responsive Drive	29
3.2.2	Steering	29
3.2.2.1	Steering Design Concepts	30
3.2.2.1.1	Additive Steering Concept	30
3.2.2.1.2	Multiplicative Steering Concept	31
3.2.2.1.3	Pirouette Steering	32
3.2.3	Braking	33
3.2.4	Finalized Design Concept	33
<b>3.3</b>	<b>Component Design Conception</b>	34
3.3.1	Wheelchair Frame	34
3.3.2	Motor and Gear Train	35
3.3.3	Motor Amplifier	36
3.3.4	Controls System	37
3.3.5	Power System	37
3.3.6	Encoders	38
3.3.7	<i>Steering Interface</i>	39
3.3.7.1	Thigh Interface	40
3.3.7.2	Foot Interface	40
3.3.7.3	Hand Interface	41
3.3.8	Manual Wheel Locks	41
<b>4</b>	<b>PROTOTYPE DESIGN</b>	42
<b>4.1</b>	<b>Controls System</b>	42
4.1.1	Hewlett Packard Quadrature Encoders	42
4.1.2	PC/104 Control Hardware	43
4.1.2.1	Panther PC/104 Processor	44
4.1.2.2	RTD Incremental Encoder PC/104 Board	45
4.1.2.3	Measurement Computing DAC Board	46
4.1.2.4	Tri-M PC/104 DC/DC Power Supply	47
4.1.3	PC/104 Control Software	47
4.1.3.1	Straight-Line Driving	49
4.1.3.2	Steering	50
4.1.3.3	Pirouette Function	51
4.1.4	Advanced Motion Controls Brushless Servo Amplifier	52
4.1.5	Power System - NiCad Rechargeable Cells	53
<b>4.2</b>	<b>Mechanical Components</b>	53
4.2.1	Wheelchair Frame - Invacare Manual Wheelchair	54
4.2.2	Hand-Driven Wheel Side Components	56
4.2.2.1	Wheel Interface	57
4.2.2.2	Encoder Mount	58
4.2.2.3	Encoder Axle	59
4.2.3	Motor-Driven Wheel Side Components	60
4.2.3.1	Gearbox	60
4.2.3.1.1	Brushless DC Motor	60
4.2.3.1.2	Gear Train	62
4.2.3.1.3	Gearbox Modifications	65
4.2.3.1.3.1	Upper Gearbox Cover	68
4.2.3.1.3.2	Lower Gearbox Cover	70

4.2.3.1.4	Gearbox Mount	71
4.2.3.2	Wheel and Axle Interface	72
4.2.4	Steering Interface	74
4.2.5	Controls Component Mounting and Wiring	77
<b>5</b>	<b>TESTING AND ANALYSIS</b>	<b>79</b>
<b>5.1</b>	<b>Standards-Based Testing (ISO and ANSI/RESNA)</b>	79
5.1.1	Determination of Static Stability (ISO 7176-1, ANSI/RESNA WC-1)	79
5.1.2	Determination of the Effectiveness of Brakes (ISO 7176-3, A/R WC-3)	81
5.1.3	Determination of Dynamic Stability (ISO 7176-2, A/R WC-2)	82
5.1.4	Determination of Obstacle-Climbing Ability (ISO 7176-10, A/R WC-10)	83
5.1.5	Dimensions, Mass, & Turning Space (ISO 7176-5, A/R WC-05)	85
5.1.6	<i>Other Testing</i>	87
<b>5.2</b>	<b>Controls System Testing</b>	87
5.2.1	Straight-Line Driving Test	87
5.2.2	Figure-Eight Obstacle Maneuvering Test	88
<b>6</b>	<b>DISCUSSION</b>	<b>90</b>
<b>7</b>	<b>CONCLUSIONS</b>	<b>95</b>
<b>8</b>	<b>FUTURE RECOMMENDATIONS</b>	<b>97</b>
	<b>REFERENCES</b>	<b>99</b>
	<b>APPENDIX A – CALCULATIONS</b>	<b>101</b>
	Center Distance and Belt Length	101
	Motor Torque Requirement	103
	Drive Wheel RPM Requirement	104
	Gear Train Ratio	104
	<b>APPENDIX B – COMPONENT SPECIFICATIONS</b>	<b>105</b>
	HP Quadrature Encoders (HEDS-5500 A06/A14)	105
	Versalogic Panther PC/104 Processor (EPM-CPU-6/7)	106
	RTD DM6814 Quadrature Encoder Input PC/104 dataModule	107
	Measurement Computing PC104-DAC06 Analog Output Board	108
	Tri-M HE104-DX Power Supply	109
	Advanced Motion Controls B30A8 Brushless Servo Amplifier	110
	<b>APPENDIX C - COST ANALYSIS</b>	<b>111</b>
	<b>APPENDIX D – PART DRAWINGS AND ASSEMBLY</b>	<b>112</b>
	Overall Assembly	112
	<b>Motor-Driven Side Components</b>	113
	Gearbox Housing – Modified	114

Upper Gearbox Cover – Modified	115
Encoder Spacer – Motor-Side	116
Encoder Axle – Motor-Side	117
Lower Gearbox Cover	118
Frame Clamp – Lower Gearbox Cover	119
Modified Gear – Plastic/Metal	119
Modified Gear – Metal Wheel Interface	120
Bearing Spacer – Metal Wheel Interface	120
Wheel Axle Spacer – Metal Wheel Interface	121
Wheel Axle Spacer – Wheel Hub	121
<b>Hand-Driven Side Components</b>	122
Encoder Block – Hand-Driven Side	123
Encoder Block Clamp	124
Encoder Axle – Hand-Driven Side	124
Large Pulley – Modified	125
Large Pulley Mount	125
<b>Steering Interface Components</b>	126
Heel Disc	127
Heel Disc Spacer	128
Encoder Block – Steering Interface	129
Encoder Axle – Steering Interface	130



## IV List of Figures

Figure 1 - Modular Seating (Sunrise Medical, 2005) .....	4
Figure 2 - Causes of Ischemic Stroke (diseases-explained, 2005).....	6
Figure 3 - Causes of Hemorrhagic Stroke (diseases-explained, 2005).....	6
Figure 4 - Body Function Affected by a Stroke (diseases-explained, 2005) .....	7
Figure 5 - Lifestand Dual-Rim Wheelchair (LifeStand, 2005).....	10
Figure 6 – Thompson Lever Drive Wheelchair (e-bility, 2005).....	11
Figure 7 – University of Cambridge Thesis: Dual-Rim Project (Lesley, 2001).....	12
Figure 8 - Terminator Titanium Ultralight Wheelchair (Invacare).....	14
Figure 9 - iGLIDE Ascending Mount Washington (Independence Technology, 2004)...	15
Figure 10 - Brushed DC Commutator Motor Overview (Marshall, 2005).....	17
Figure 11 - Absolute Encoder Track Segments .....	20
Figure 12 - Quadrature Encoder Tracks.....	21
Figure 13 - Multiplicative Steering Concept (Left-side Paralyzed).....	32
Figure 14 - Assorted Wheel Interfaces .....	35
Figure 15 - Encoder Precision - CPR.....	39
Figure 16 - HP Quadrature Encoder (HEDS-5500 A14/A06) .....	43
Figure 17 - PC/104 Stack (EPM-CPU-6/7) .....	43
Figure 18 – Panther PC/104 Board (EPM-CPU-6/7).....	44
Figure 19 – Incremental Encoder dataModule® (DM6814HR).....	45
Figure 20 – Encoder Wiring Diagram .....	46
Figure 21 - Measurement Computing DAC Board (PC104-DAC06) .....	46
Figure 22 - Tri-M Power Supply Board (HE104-DX).....	47
Figure 23 - Controls System Block Diagram – Testing Stage.....	48
Figure 24 - AMC Brushless Servo Amplifier (B30A8).....	53
Figure 25 – Original Invacare Wheelchair (L218LA286) .....	54
Figure 26 - X-Frame Folding Mechanism .....	55
Figure 27 - Leg Rest Interface .....	55
Figure 28 – Available Frame Space for Attachment of Components.....	56
Figure 29 – Hand-Driven Side Encoder Setup .....	57
Figure 30 – Available Frame Space for Encoder Block .....	58
Figure 31 - Encoder Mount Cross Section.....	59
Figure 32 - Encoder Axle.....	59
Figure 33 - Brushless Motor .....	60
Figure 34 – Drive System Stall Torque Calculation.....	61
Figure 35 - Drive System RPM Calculation.....	61
Figure 36 - Bearing Bores with Inset O-rings.....	62
Figure 37 - Original Gear Train (Left) vs. Modified Gear Train (Right) .....	63
Figure 38 - Modified Gear Shaft and Encoder Axle.....	63
Figure 39 - Modified Final Gear and Wheel Interface .....	64
Figure 40 - Initial Gearbox Redesign.....	66
Figure 41 - Original Gearbox Base.....	66
Figure 42 - Final Modified Gearbox.....	67
Figure 43 - Final Gearbox Base.....	68

Figure 44 - Upper Gearbox Cover .....	69
Figure 45 - Gearbox Encoder Mount .....	70
Figure 46 - Lower Gearbox Cover Alignment Holes .....	71
Figure 47 - Redesigned Clamping Feature .....	72
Figure 48 - Cross Section of Motor-Side Wheel Interface .....	72
Figure 49 - Wheel Spacer Cross Sections .....	73
Figure 50 - Steering Interface Assembly .....	74
Figure 51 - Steering Interface Cross Section .....	75
Figure 52 - Steering Interface Views .....	76
Figure 53 - Legrest Wiring Connection .....	76
Figure 54 - Controls Backpack Mount.....	77
Figure 55 - Wiring Connectors .....	78
Figure 56 - Power Switches .....	78
Figure 57 - Static Stability Test Setups.....	80
Figure 58 - Brake Holding Test Setup .....	81
Figure 59 - Turning Space Test Setup .....	86
Figure 60 - Straight-Line Marker Mount Test Fixture.....	88

## V List of Tables

Table 1 - Steering Lookup Table .....	50
Table 2 - Pirouette Function Lookup Table.....	52
Table 3 - Static Stability Test Results.....	80
Table 4 - Brake Holding Test Results.....	82
Table 5 - Dynamic Stability Test Results .....	83
Table 6 - Obstacle Traversal Test Results .....	84
Table 7 - Figure-Eight Test Results .....	89

# 1 Introduction

Advancements in assistive technology for individuals using wheelchairs are continuously being introduced into the medical field. These advancements, for the most part, focus on advanced technologies, such as the use of composite materials for lightweight and durable wheelchair frames and gyroscopic sensors for self-balancing purposes. While these advancements are extremely beneficial to society, there is a large population of wheelchair users that are often overlooked. Hemiplegic (paralysis on one side of the body) disabilities are particularly common, especially with stroke victims, and provide a large demand for wheelchairs that cater to their needs. While powered wheelchairs can be used effectively by hemiplegic users, they are expensive, difficult to transport, and do not require physical activity. A lightweight, foldable manual wheelchair that can be efficiently maneuvered and transported by a hemiplegic user while remaining relatively inexpensive would be extremely beneficial to the hemiplegic population.

A manual chair has three fundamental functions that need to be addressed during the design process: propulsion, braking, and turning. While these wheelchair functions are easily controlled in two-hand operated wheelchairs, their implementation in hemiplegic-friendly wheelchairs is much more complex. In a standard wheelchair, all three of these functions are controlled by the amount of throw put into the individual push rims. In a one-hand operated manual chair, the ability to control each wheel independently diminishes greatly. The user is reduced to half the strength they could effectively use with both hands which results in decreased amounts of stamina. Different hemiplegic manual wheelchair designs have been implemented; however none have been able to effectively solve these issues to the point where they have become mainstream models.

The goal of this thesis was to design and prototype a power-assist wheelchair that effectively targeted these three fundamental functions while maintaining the maneuverability and amount of stamina associated with two handed wheelchair operation. Through the use of Pro/Engineer, MATLAB, and other analytical software and methods, an optimized design was produced, fabricated, and tested to ensure these goals were successfully met.

## **2 Background**

In order to efficiently design a product that would target the needs of hemiplegic wheelchair users, detailed background research was conducted on disabilities and wheelchair design to ensure optimal design choices were made. The following sections will illustrate these research findings.

### ***2.1 Specialty Disabilities***

The term disability pertains to a wide range of mental and physical impairments that inhibit the ability of an individual to perform normal everyday functions. There are many common conditions that lead to disabilities, such as muscular dystrophy, attention deficit disorder, paraplegia, trauma, and cerebral palsy. These conditions have been researched heavily to create assistive products to reduce associated limitations. Unfortunately, minimal research has been conducted to design and develop assistive products for less common conditions due to a smaller demand population. Companies tend not to pursue research and development efforts for small demand products because the costs of research and development are hard to recoup with lesser sales.

#### **2.1.1 Need for Specialized Wheelchairs**

Disabilities can be categorized into many different areas. One such common category is disabilities that lead to wheelchair use. In the interests of this research, this category will be broken down even further into disabilities that lead to specialized wheelchairs. A specialized wheelchair meets the needs of specific disabilities and includes features not normally found in manual or powered wheelchairs.

Manual wheelchairs are very effective at targeting a widespread population of individuals requiring assistive mobility products. They are low cost, lightweight, and sustain exercise because of their manual operation. The average manual wheelchair accommodates users who have moderate upper body strength, normal targeting skills,

and weigh less than 250 pounds. Unfortunately, not every individual falls into this category leaving a substantial population to search for additional mobility options.

Powered wheelchairs on the other hand are expensive, heavy, and do not promote exercise because of their powered drive system. The typical powered wheelchair user has very limited or no movement in both their lower and upper body, and weighs less than 250 pounds. Powered wheelchairs can accommodate the majority of mobility disabilities, but because of their cost, size, and weight, are often not suitable.

The need for specialized chairs that effectively target individuals with specialized disabilities who cannot benefit from standard manual and powered wheelchairs is strong, but in low numbers. Wheelchair manufacturers have had a difficult time meeting this demand.

### **2.1.2 Difficulties with Producing Specialized Wheelchairs**

The main problem wheelchair companies have in producing specialized wheelchairs is that while there is a high demand, the demand is for all kinds of different needs. One simple wheelchair redesign would not cover all the different specialized disability needs. In order to meet this demand, there would need to be a whole spectrum of chairs ranging from pediatric to bariatric chairs, hemiplegic to triplegic chairs, stand-up to fully reclining chairs, etc. The cost to conduct the research and development necessary to produce these relatively low volume wheelchairs would not be justified for an assistive technology company.

To alleviate this problem, many wheelchair companies are reaching out to specialized users by making their wheelchairs module-based, where options can be easily adapted into the chair to meet their specialized needs. Modular-based chairs not only help meet this demand, but they also make it very easy for non-specialized wheelchair users to customize their chairs. For example, a common modular option is seating in which a user can choose the seat cushion and/or backrest to be used on their chair based on their individual preferences (Figure 1).



Figure 1 - Modular Seating (Sunrise Medical, 2005)

While there are many products currently on the market that target specialized demands, there are still multitudes of demands that are not being met.

## ***2.2 Hemiplegic Disabilities***

Hemiplegia/hemiparesis is one such disability in which the needs of the individuals are not being adequately met by current manual or power wheelchair designs. Hemiplegic disability leads to some form of paralysis that affects either the left or right hemisphere of the body. Hemiplegia refers to the complete loss of movement on one side of the body, while hemiparesis refers to reduced mobility on one side of the body (Molson, 2000).

The result of this disability creates a need for a wheelchair, however this need falls somewhere between a manual and power wheelchair. While the individual retains full motion on one side, they cannot easily manipulate a manual wheelchair since two arms are generally required for operation. Enough motion is retained that a power wheelchair would be in excess since it would remove the opportunity for the user to maintain physical activity since only slight hand movements are required to operate them. Powered wheelchair users are strongly encouraged to maintain physical activity in their functioning limbs to prevent muscle atrophy because a power wheelchair promotes such low levels of physical activity,

Hemiplegia is a disease caused by neurological problems. One half of the body is affected because one half of the brain loses some amount of capability related to motion. The main cause of hemiplegia is stroke (Molson, 2000).

## **2.2.1 Stroke**

The American Stroke Association reports that on average, 700,000 stroke incidences occur every year. In 1999, over one million people were reported living with physical handicaps that were a result of stroke. The severity of stroke has led to stroke being labeled the third most common cause of death in the United States and the leading cause of disabilities in adults. In 2002, one in every fifteen deaths in the U.S. was due to stroke. (American Heart, 2005)

Stroke refers to the incidence when blood flow to the brain is altered. This can occur due to blockage or a blood vessel bursting. An ischemic stroke occurs when blood flow is blocked from reaching the brain, while a hemorrhagic stroke occurs when a blood vessel bursts in the brain. Both forms result in the death of brain cells, which ultimately affects the functioning of the brain. A brief attack that does not produce significant side effects since blood flow is only momentarily interrupted, is called a transient ischemic attack (TIA). (NINDS, 2005)

## **2.2.2 Causes of Stroke**

Of the three main types of stroke, ischemic stroke is the most common, comprising approximately 83% of all occurrences. An ischemic stroke occurs when blood flow is blocked from reaching the brain due to a blocked blood vessel. Ischemic stroke usually results from a blood clot that reaches the brain and lodges in an artery. Commonly, a clot will form somewhere else in the body due to an injury, and will travel to the brain where the clot is trapped in smaller blood vessels found in the brain (referred to as Cerebral Embolism). Another typical cause of ischemic stroke is atherosclerosis, a condition that causes blood vessels to harden and form a plaque due to deposits of calcium, blood platelets, cholesterol, fatty substances, or other random substances that lodge in the inner lining of arteries. Blood clots tend to form in these areas, and if this occurs in the brain, brain cells that are deprived of oxygenated blood die (referred to as Cerebral Thrombosis). Brain cells can die within only a few seconds of interrupted oxygen flow. (diseases-explained, 2005)

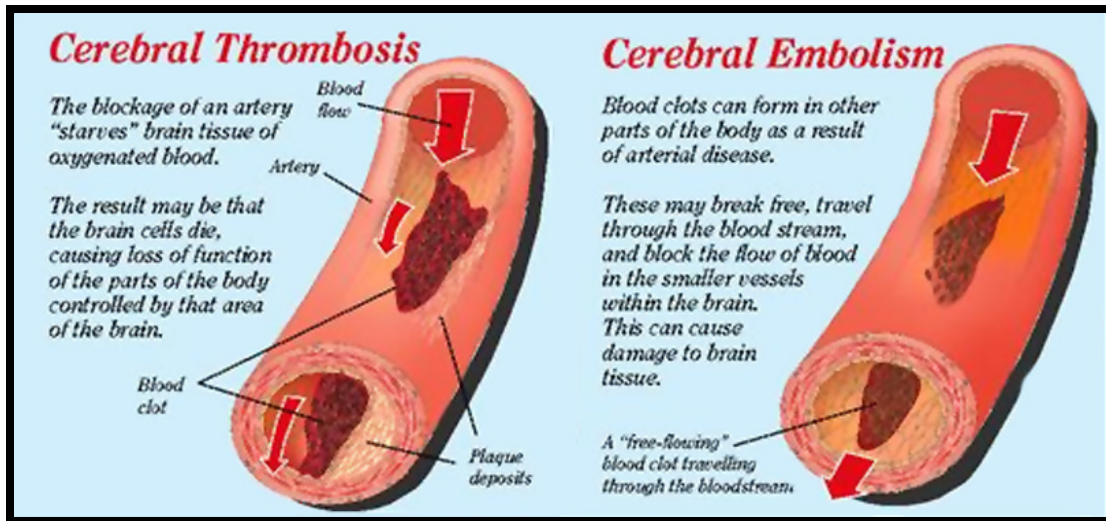


Figure 2 - Causes of Ischemic Stroke (diseases-explained, 2005)

Hemorrhagic stroke occurs when blood flow breaches the walls of blood vessels in the brain. The immersion of blood in the brain creates excess pressure on brain tissue because the skull limits expansion of the brain cavity. This excessive pressure can also result in the death of brain cells. (diseases-explained, 2005)

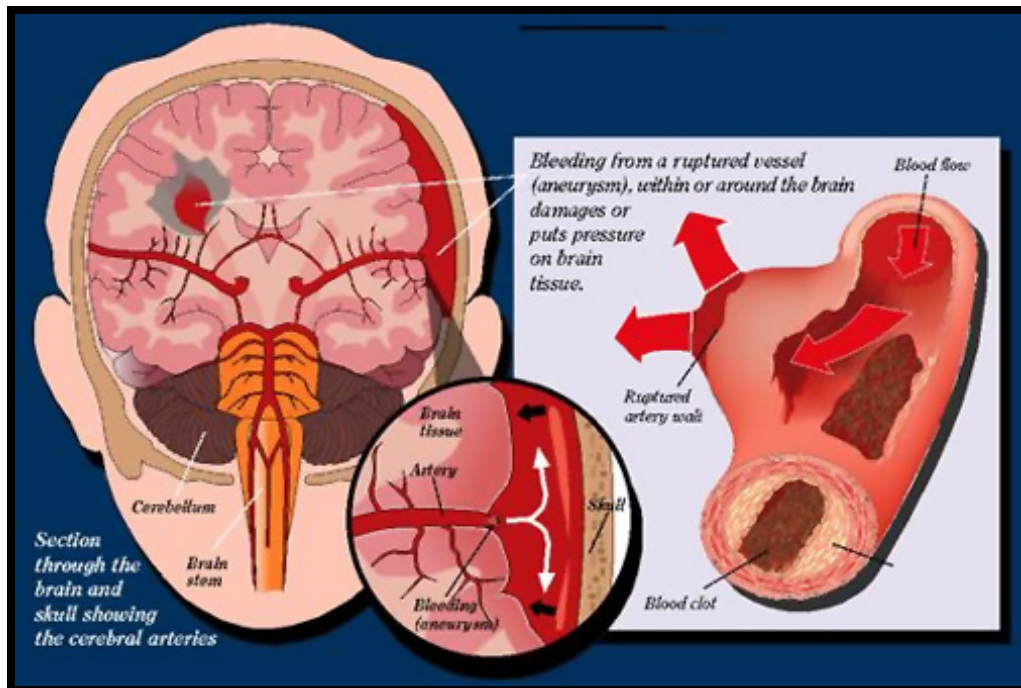


Figure 3 - Causes of Hemorrhagic Stroke (diseases-explained, 2005)

Factors that can increase the risk of stroke are: atherosclerosis, obesity, heart disease, smoking, high blood pressure/cholesterol, cocaine use, alcohol abuse, diabetes,



increased age, clot-promoting medication, the use of estrogens, gender, polycythemia, head injury, and race (diseases-explained, 2005). African-Americans tend to be the most at risk for strokes, followed by American Indians and Asians. The leading cause of stroke is high blood pressure. Studies have shown that around one out of every three adults has high blood pressure. (American Heart, 2005)

### 2.2.2.1 Effects of Stroke

Stroke can affect individuals in a multitude of different ways depending on where the brain is damaged, and how severe the damage is. Each side of the brain controls one side of the body, and interestingly enough, each side controls the opposite hemisphere. It is easy to determine which side of the brain is affected after a stroke by assessing the symptoms of the stroke victim. Common physical affects are loss of movement or feeling in one side of the body, loss or impaired vision, and diminished balance. Common psychological affects include memory loss, irritability, loss of depth perception, and decreased communication skills. Figure 4 describes common problems that occur when specific regions of the brain are affected.

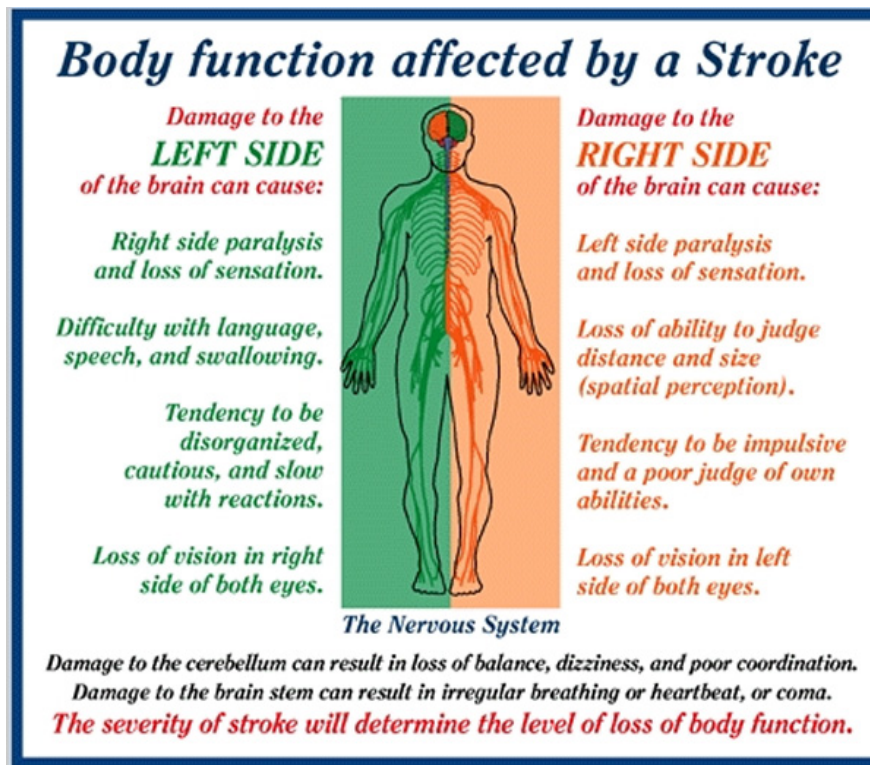


Figure 4 - Body Function Affected by a Stroke (diseases-explained, 2005)

The severity of a stroke depends on the type of attack that occurs. A transient ischemic attack (TIA) is the least threatening type of attack. This attack occurs quickly, usually within a couple of minutes, but symptoms can last up to a full day. This type of attack is technically not a stroke since no permanent damage occurs, but is often referred to as a “mini-stroke” (Campellone, 2005). A TIA can become an ischemic stroke if not treated promptly since irreversible damage can occur if normal blood flow to the brain is not restored.

When an attack lasts longer than a day, but no permanent damage is suffered, the attack is referred to as a reversible ischemic neurological deficit (RISND). This attack is also technically not a stroke, but can lead to a stroke if not treated properly as well. An attack is considered a stroke when damage becomes irreversible.

One of the most common affects of stroke is hemiplegia/hemiparesis, and is the motive that drove the research conducted in this thesis. Studies have shown that in stroke survivors over the age of 65, approximately one half of the victims suffer from hemiparesis after a period of six months. It is also shown that assistive devices are needed by 30 percent of all stroke survivors to continue to be mobile. (American Heart, 2005)

### **2.2.2.2 Stroke Mobility Research**

With stroke being a leading cause of disabilities, extensive research has been conducted to help reduce the impact of stroke on activities of daily living. Countless devices and methods have been developed through this research, and many have been successful. Exercise is one of the most important ways to accelerate stroke paralysis rehabilitation and thus is a primary focus of researchers. Unfortunately, with all the advancements being made in stroke mobility, limited advancements have been made to increase hemiplegic wheelchair mobility.

### **2.2.3 Additional Causes of Hemiplegia**

Cerebral Palsy is another main contributor of hemiplegia. Cerebral Palsy develops in children usually around birth when damage occurs in the brain. Unfortunately there is limited knowledge of the cause of cerebral palsy. The condition is linked to damage of the brain that occurs either during maturation in the womb, during the birthing process, or

shortly thereafter due to medical complications. Motor skills are reduced, often in one side of the body and can result in various levels of hemiparesis/ hemiplegia. The condition is life long, is not transferable, and does not become more severe over time. (CHASA, 2004)

Alternating Hemiplegia is another disorder that causes paralysis on one side of the body. This disorder develops early on in a child's life, often within four years of birth, and causes random stages of paralysis that usual develop during sleep. The condition does not result in mental retardation and currently has unknown causes. (NINDS, 2005)

## ***2.3 Current Hemiplegic Wheelchairs***

The few hemiplegic wheelchairs that are currently available were researched to determine where and if any improvements could be made to existing designs, as well as to obtain ideas for designing an original hemiplegic wheelchair design.

The common disadvantage found with all purely manual hemiplegic wheelchairs is that using only one arm to propel a wheelchair always results in lowered performance as compared to two-handed manual wheelchair operation. These wheelchairs either require one arm to provide the power of two arms, or institute mechanical advantage which lowers the required arm strength but decreases the distance traveled. Without some type of stored energy, these wheelchairs cannot perform equally with standard manual wheelchairs.

### **2.3.1 Dual-rim Wheelchairs**

Dual-rim wheelchairs are not often utilized because of the difficulty associated with their operation. Not only are dual-rim wheelchairs hard to propel physically, but propulsion is also challenging mentally. It takes considerable cognitive ability to operate two rims with one hand, and learn how to effectively turn and maneuver with this type of design. A dual-rim chair propels one wheel with a normal rim and the other wheel by feeding the axle through the center of the chair to the other side, and attaching a second

rim to the axle. The two rims have different diameters and are offset from one another to allow for individual manipulation (Figure 5).



**Figure 5 - Lifestand Dual-Rim Wheelchair (LifeStand, 2005)**

These wheelchairs are difficult to propel because one arm is doing the work for both arms. There is no mechanical advantage available in this type of design, making it a challenge for users to operate it, especially since the majority of hemiplegic users are older and have decreased strength in their non-disabled arm. While these chairs lack in practical functionality, they are useful because even the limited functionality allows users to exceed their current abilities.

### **2.3.2 Hemiplegic Lever-arm Wheelchairs**

Lever-arm wheelchairs are designed to tackle the issue of user strength required for operation of the wheelchair. A lever is attached to the hub of the wheel to replace the hand rim and is operated by pumping the lever-arm. By extending the length of the lever arm to nearly double the radius of a standard wheel rim, half the strength is needed to propel a single wheel. In the case of a hemiplegic lever-arm wheelchair, only one lever-arm is used to drive one wheel. Steering is achieved by coupling a linkage from the lever-arm to the front caster on the same side as the lever-arm, and is activated by twisting the handle on the lever arm.

The added mechanical advantage of the lever arm is advantageous when facing slopes and other environments when a significant propelling force is required for

traversal. The disadvantage is that for the decreased effort required to propel the chair, the amount of corresponding wheel rotation is decreased by the same ratio.

Operation is relatively ergonomic because the lever incorporates a one-way clutch that allows the chair to be propelled with a cranking operation. The clutch can be reversed by flipping a switch found on the lever-arm so the user can operate the chair in reverse. The cranking motion allows the user to maintain constant contact with the propelling interface while propelling the chair in any direction. Having a constant grip reduces the chance of developing injuries to the wrist from the repetitive impacts associated with hand-rim operation.

Since the propelling apparatus incorporates a one-way clutch, problems occur in terms of braking. Instinctually, when a user needs to stop, they pull back on the lever-arm. This does not produce expected results though because of the clutch. The brake is built into the lever; however, the lever has to be pulled all the way back or all the way forward to engage it. Engaging the brake by pulling backwards may be beyond the range of motion of some users.

Another problem with this type of wheelchair design is that only one side of the chair operates all of the three fundamental functions. If the wheelchair is used on uneven terrain, and an operating wheel lifts off the ground, the wheelchair effectively loses functionality and can possibly strand its user or result in undesired motion. Despite its significant downfalls, the overall concept is much easier to operate than a dual-rim chair, providing more flexibility to the user (Figure 6).



**Figure 6 – Thompson Lever Drive Wheelchair (e-bility, 2005)**

### **2.3.3 Conceptual Wheelchair Designs**

Despite the limited amount of research being applied to these problems, a few universities, including WPI, have researched solutions in recent years. These projects are directed at improving current manual hemiplegic wheelchair designs.

#### **2.3.3.1 University of Cambridge Thesis Research**

Thesis work has been performed at the University of Cambridge in the U.K. to improve the dual-rim wheelchair. The functions of the individual rims on their wheelchair were altered to perform differently. Instead of propelling individual wheels, one rim was used to propel both wheels in the forward/reverse direction, while the second rim was used to perform pirouettes in place (Figure 7). Steering (while moving) was achieved by coupling the caster to the footrest. The user steered the wheelchair by turning their ankle to change the caster's direction, and thus could effectively maneuver while moving. The chair is very innovative, and has potential in the market; however, it does not provide a solution for the additional strength needed to operate the chair. The team at the University of Cambridge applied for U.K. patents in 2001, and the most recent project updates showed that the patents were pending. (Lesley, 2001)



**Figure 7 – University of Cambridge Thesis: Dual-Rim Project (Lesley, 2001)**

### **2.3.3.2 WPI MQP Work**

Students at WPI completed their Major Qualify Project (MQP) on a lever-arm based hemiplegic wheelchair in 2005. The project effectively demonstrated a proof of concept lever-arm chair that confronted the issue of reversal of direction. Instead of using a switch to reverse the output of the lever-arm, the lever arm could be physically shifted left and right to engage separate wheel hubs. The two wheel hubs were attached to the wheel axle via opposing cam clutches that allowed the cranking motion to propel the chair in only one direction.

Braking was accomplished by pulling the lever arm back past the normal propulsion operating range, which engages a break on each wheel. The steering design on this wheelchair was not effective.

While this wheelchair improved upon reversal of motion in comparison with existing hemiplegic lever-arm wheelchairs, the MQP did not tackle the issues involved with only propelling and steering one side of the chair as previously discussed.

## **2.4 *Standard Wheelchair Research***

Many improvements have been made to wheelchairs since they first became available to allow for extensive versatility and user freedom. These advancements had a significant impact on the design of the mobility device designed in this thesis and were researched to aid in its development. A number of current advancements were incorporated into the final design of the wheelchair.

### **2.4.1 Current Advancements in Wheelchairs**

Advancements in manual and power assist wheelchairs were researched as applicable to the project's application to identify possible solutions to the design problem.

### **2.4.1.1 Manual Wheelchairs**

Manual wheelchairs have a very basic look; however they can include some very innovative features. From folding capabilities to lightweight composite materials, considerable advancement has been made recently to further expand manual wheelchair capabilities.

#### ***2.4.1.1.1 Lightweight and Foldable Designs***

In order to propel a manual wheelchair, a user not only has to move their weight, but they have to move the weight of the wheelchair as well. As material science continues to improve, materials become lighter and stronger for applications such as this. Aircraft-grade aluminum and titanium frames allow top end full functioning manual wheelchairs to weigh as little as 15 pounds including wheels and essential accessories (Figure 8). (Invacare, 2005)



**Figure 8 - Terminator Titanium Ultralight Wheelchair (Invacare)**

Foldable models have become the standard in the manual wheelchair market. By incorporating a folding mechanism into a wheelchair, the ability to transport the chair improves considerably. Many of these wheelchairs also include quick release mechanisms to allow the wheels to be taken off for even easier storage. These features allow wheelchairs to be effortlessly stored in trunks of cars with minimal storage space or behind the front seat of full-size sedans.



### 2.4.1.2 Power Assist Wheelchairs

A new state-of-the-art wheelchair concept that is rapidly becoming available is the power-assist wheelchair. As technology has become more advanced, it has become possible for wheelchairs to be designed that accurately and effectively augment user forces on the wheels. In the case of the INDEPENDENCE iGLIDE Manual Assist Wheelchair (iGLIDE) (Figure 9), torque sensors are incorporated into the push rims to measure the applied tangential forces. This torque is amplified through motors attached to the wheels to make operation of the wheelchair substantially easier. The chair easily ascends ramps and traverses grass, an ability previously unheard of in the manual wheelchair world. The power-assist also helps to slow down the chair when opposing force is applied to the push rims, which is a significant safety feature. The additional components are light enough that they do not interfere with the operation of the wheelchair, however can make normal wheelchair operation more difficult when the power-assist is turned off. (Independence Technology, 2004).



**Figure 9 - iGLIDE Ascending Mount Washington (Independence Technology, 2004)**

Certain power-assist wheelchairs claim to be “hemiplegic-friendly”, however do so by only transferring torque signal from one side to the other for straight line driving. In order to turn, the user has to switch off the power, turn to the desired direction, and switch the power back on to drive in a straight line. This is time consuming and difficult to maneuver. On uneven terrain, the wheelchair does not drive straight due to the differing torques on each wheel.

## **2.5 Motor Drives**

Stored energy has been identified as the only means of creating a hemiplegic manual wheelchair that could perform as well as a standard two-handed manual wheelchair. The most effective means of storing energy for transportation is to utilize battery powered motors.

Wheelchairs can be driven by a variety of motor drives depending on their application. Motor drives were researched to determine what type of motor and gear combination could provide optimal drive systems for wheelchair use. Items of interest were torque, speed, noise, power consumption, size, and weight. Research was limited to the category of direct current (DC) permanent magnet (PM) motors. DC PM motors were selected because they can easily be run off batteries and are smaller, lighter, and require less energy than pure electromagnetic excitation motors. (Miller, 1989)

### **2.5.1 Brushed DC Commutator Motor Drives**

Brushed commutator motors are used widely for their low cost and low technology. Powered wheelchairs have used brushed DC commutator motor drives for a long time because of their high torque and speed capabilities. These motors can be run by simply applying a voltage across their terminals. A brushed motor works by applying a voltage across a commutator that is attached to the motor's rotor. As the commutator rotates, it rubs against a pair of stationary brushes that are connected to the positive and negative terminals of the motor. The commutator is split into regions that as they rotate are either connected to a positive brush, a negative brush, or open space. The commutator sections are soldered to a wire coil such that one end of the coiled wire connects to one commutator section and the other end of the wire connects to the opposing commutator. This creates a connection between the terminals when the sections are in contact with the brushes. Surrounding the armature is a pair of permanent magnets with opposing poles facing into the armature. The alternating electrical field produced by the commutator and brushes produces an alternating magnetic field in the wire coils so that one end will be repelled from one magnet and attracted to the other and vice versa on the other end of the coil. The commutator is arranged in such a way that when the ends of the wire coil

approach their respective attracting magnet, the commutator sections switch which brushes they are rubbing against, which changes the electromagnetic field in the wire coil. The momentum of the armature causes the rotor to continue in the direction it was traveling as opposed to stopping and reversing direction. This process repeats as the armature rotates creating the rotating motor behavior. (Kenjo and Nagamori, 1985).

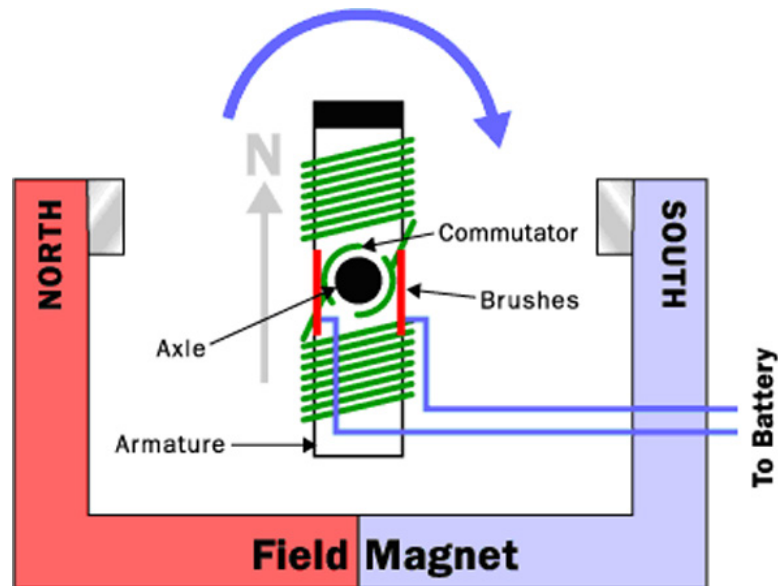


Figure 10 - Brushed DC Commutator Motor Overview (Marshall, 2005)

Speed of commutated motors can be controlled using a speed controller that controls the applied voltage, or by means of a pulse width modulated (PWM) controller that cycles the delivery of a constant voltage to the motor in an on/off method. PWM control is preferred because power loss is reduced in typical varying speed controlled conditions which results in less heat dissipation. (Electro-craft,1977).

Brushed motors can be noisy depending on their size and speed. The brushes rub against the commutator, which creates enough friction to produce noise. Over time the brushes can wear and/or bend so that they do not create a solid contact with the commutator. This creates a need for the motors to be serviced. Another associated problem with the brushes is that because of effects such as friction and contact resistance, there are significant power losses compared to brushless DC motors.

## **2.5.2 Brushless DC Electronically Commutated Motor Drives**

In recent years, brushless DC motors have become the new standard for powered wheelchairs, in particular ones utilizing rare earth magnets. These motors run more efficiently than their brushed DC counterparts because there are no contacting parts in the motor. Wear in the system only occurs in the rotor bearings, not in the internal motor elements. An additional benefit is that brushless motors are quiet since there is no noise created from components interacting with each other. (Bauer and Stone, 1998)

The configuration of a general brushless DC motor is opposite that of a brushed DC motor. Whereas the permanent magnets surround the rotor in the brushed configuration with the wire coils attached to the rotor, the brushless configuration is reversed. A non-mechanical system is employed to create commutation in the motor to replace the function of the rotating commutator. This method is known as electronic commutation and is more difficult to control because the motor has to “know” when to switch the electromagnetic field in the coils. Switching has to be carefully orchestrated to create a smooth flowing transition of magnetic poles around the rotor at varying speeds. The transition of magnetic fields causes the rotor to follow the field as it rotates around the motor housing. Electronic commutation is controlled by an outside controller that converts an input signal for the motor into these modulated rotating field output signals. (Geiras and Wing, 2002)

A brushless motor requires feedback for the controller to ensure rotor position as it commands motion. The feedback is presented in the form of hall sensors and/or encoders, creating more accurate motion. This feedback makes the brushless motor drive system a great candidate for precision motion control. A drawback is that the controller and motor combination are generally more expensive because of the advanced logic and additional hardware used to control the motor. (Geiras and Wing, 2002)

## **2.5.3 DC Stepper Motor Drives**

Stepper motor drives have shown potential in the wheelchair market because of their ability to be driven in precise increments. Stepper motors offer higher torque at lower speeds in comparison to brushless motors, and do not require feedback sensors to

ensure correct positioning. These motors can be problematic however if loads present themselves that exceed the motors capabilities. In this case, the motor can lose its tracking capability and incorrectly position itself. They can also be jittery in their motion and for the most part are used only in low load applications such as printers and measuring instruments.

Stepper motor packaging is also an interesting feature for wheelchair design. A specific type of stepper, known as a pancake stepping motor, can be designed into a thin wafer-shaped housing. This configuration would be very advantageous for mounting directly to a wheel hub if it could handle high loads effectively.

## ***2.6 Encoder Feedback***

Current powered and power-assist wheelchairs utilize encoders to assist in controlling wheelchair motion. This type of control is classified as closed loop and is essential to a position controlled drive system. In terms of a wheelchair drive system, rotary encoders are an optimal form of feedback for creating a closed loop system. By tracking the rotation of the drive wheels, the wheelchair can actively adjust for changes in environment that counteract the commanded speed of the individual wheels. This change can be looped into the control system to compensate for these changes by sending adjusted signals to the motors. Encoders were researched to determine if they would be a suitable means of controlling a hemiplegic power-assist wheelchair.

Rotary encoders track angular position by monitoring a subdivided disc. In an optical encoder, the disc is subdivided into alternating transparent and dark segments. A light source is directed at the disc, and as the disc turns, an optical sensor mounted on the opposite side of the disc monitors the light passing through the transparent segments. Another method that accomplishes the same objective is mounting the light source and sensor on the same side of the disc and replacing the transparent segments with reflective segments so the light will be reflected from the light source to the sensor. The sensors interpret the light source as an on signal, and no light source as an off signal. The way in which the segments are broken up and read defines the type of optical encoder. The two general types are absolute and incremental encoders.

### 2.6.1 Absolute Encoder

Absolute encoders are the more expensive of the two types of encoders. These encoders are used in situations where knowing the exact position of a rotating object is necessary even when they have been turned off and on. These encoders work by employing multiple tracks on the disc. Each disc has a unique pattern on each segment so that at any given segment a different combination of on and off signals is being transmitted by individual sensors on each track (Figure 11). The controller takes these on/off signals and generates a code based on that segment's thumbprint. Since each segment is unique, each segment has its own individual code. The controller then knows where the disc is positioned based on the outputted code.

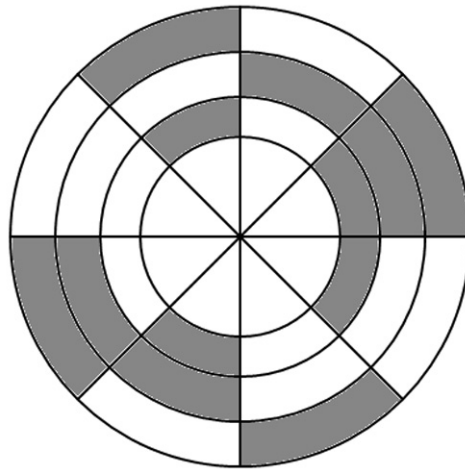


Figure 11 - Absolute Encoder Track Segments

### 2.6.2 Incremental Encoder

Incremental encoders are made using a single row (track) of segments. The most basic incremental encoder utilizes a single track with an optical sensor to read the segments (or ticks) as they pass by. The encoder sends a signal to the control system every time it passes a tick mark. The controller then counts how many tick marks were passed in a given time interval to determine relative position, speed, and acceleration. The position is only relative because every tick mark is the same and the encoder cannot differentiate between individual ticks. Since the optical sensor is only counting the number of ticks it detects, this basic type of incremental encoder can not decipher what

direction the wheel is traveling in. Resolution of the encoder is determined by how many segments the disk is broken up into and is generally referred to as counts per revolution (CPR).

### 2.6.2.1 Quadrature Encoder

A quadrature encoder is a type of incremental encoder that allows the controller to know not only how far the encoder wheel has traveled, but also in what direction it has traveled. This task is accomplished by introducing a second track and second optical sensor into the system. The second track is offset by ninety degrees from the first track (Figure 12). As the disc rotates, each sensor outputs a square wave to separate channels, A and B. Because the tracks are offset, the signal outputs are ninety degrees apart in a given period. As the sensors pass by the ticks, if channel A comes ninety degrees before channel B, the controller senses that the rotation is in one direction. If A comes ninety degrees after B, it senses that the rotation is in the opposite direction. The controller will use this knowledge to either add or subtract the ticks to the relative position. (Gieras and Wing, 2002)

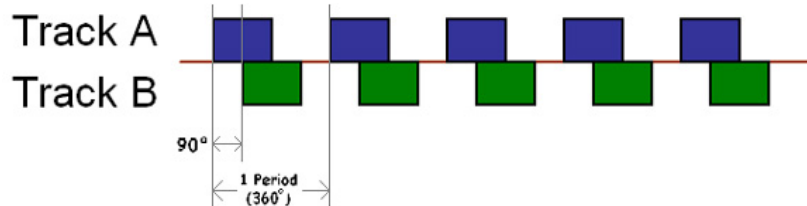


Figure 12 - Quadrature Encoder Tracks

## 2.7 Wheelchair Testing Standards

Powered and power-assist wheelchairs are subject to significant standardized testing before they are marketed. The reasoning behind this is that clinicians need a way to properly choose a wheelchair for their patients. By reporting the results of these tests, a clinician can better prescribe a wheelchair that meets their patient's needs. In addition, since wheelchairs need to be prescribed to a user by a medical professional, the Food and

Drug Administration (FDA) has to first give approval (fda.gov, 2006). The FDA uses the results from these standardized tests as a basis for their decision.

The most common testing standards used by wheelchair manufacturers are developed by the International Organization for Standardization (ISO) and those jointly developed by the American National Standards Institute and the Rehabilitation Engineering & Assistive Technology Society of North America (ANSI/RESNA). These organizations have developed standards that are applicable to all types of wheelchairs and are essential to determining the safety and effectiveness of potentially marketable wheelchairs. (ISO, 2003 and ANSI/RESNA, 1998)



### **3 Methods**

The goal behind this project was to develop an innovative wheelchair for hemiplegic individuals that would retain the operative characteristics associated with standard manual wheelchairs. It was clear that manual hemiplegic wheelchairs did not retain these operative characteristics when only one arm was used to operate them. No other limbs or power sources were used to operate these chairs, so the strength that was normally split between two arms in manual wheelchairs had to be taken up by only one functioning arm in hemiplegic individuals.

In order to alleviate this problem, hemiplegic wheelchair designs have incorporated some degree of mechanical advantage to reduce the forces required to propel the wheelchair. This, however, reduced output of the propulsion mechanism, resulting in a trade-off of distance traveled vs. operating force. Other designs tried to reroute propulsion so that one arm and one leg were used to operate the chair, but this option never became popular due to the awkwardness (physically and cognitively) associated with coupling leg and arm motion on one side to propel a wheelchair.

It was concluded that in order to retain manual wheelchair operative characteristics in a hemiplegic wheelchair, some sort of powered device had to be incorporated to reduce the workload placed on the single functioning arm. To begin the design process, a detailed list of task specifications was developed.

### **3.1 Task Specifications**

**1. *Wheelchair must be able to accommodate users up to 250 pounds.***

250 pounds is a common upper limit on user weight for wheelchairs. Users exceeding 250 pounds generally require larger, more durable bariatric wheelchairs.

**2. *Modifications must not increase the wheelchair's overall dimensions***

Exceeding the original size of the wheelchair would reduce its functionality, making it more difficult to navigate obstacles such as doorways and pedestrian traffic.

**3. *Effort exerted by individual extremities must be comparable to that of the individual extremity effort required to operate a standard manual wheelchair.***

By retaining effort levels required in standard manual wheelchair operation, hemiplegic users could operate their modified wheelchair for comparable durations.

**4. *The wheelchair must be foldable.***

Transportability is a main goal of this project, and a foldable option would allow the wheelchair to be stored in the trunk or backseat of a car.

**5. *Wheelchair must have a maximum speed of no less than 5 mph.***

This speed is a common maximum speed for powered wheelchairs. By retaining the maximum speed that wheelchair users are accustomed to, the wheelchair would be better received.

**6. *Wheelchair must be able to travel up an 8 degree slope.***

ADA requires wheelchair ramps to be no more than five degrees

**7. *Wheelchair must be able to travel on cut/loop pile carpet.***

This thicker carpet is a common, yet difficult surface to drive on. Limiting the type of terrain that the chair could drive over would reduce functionality.

**8. *Wheelchair must be able to travel over 1/2-inch obstacles.***

Again, the wheelchair must be capable of traversing typical obstacles

**9. *Wheelchair must be statically stable on 10 degree slopes.***

ADA requires wheelchair ramps to be no more than five degrees.

**10. *Wheelchair must be dynamically stable on 8 degree slopes.***

5 degrees is the maximum incline allowed by ADA, however, wheelchair standards often require dynamic stability at 8 degrees.

***11. Wheelchair must be able to be moved manually without significantly increased effort..***

This is important in situations where the wheelchair needs to be pushed by an assistant, such as when the batteries run out or an unexpected malfunction occurs.

***12. The wheelchair must allow the user to pirouette in space.***

A very common maneuver performed in a manual wheelchair is turning in space. Being able to turn in space allows the user to maneuver around obstacles in a much more effective manner. Power wheelchairs do not generally allow this freedom.

***13. Wheelchair should have a minimum range of 5-8 miles.***

The effectiveness of the wheelchair depends heavily on how long the batteries can maintain wheelchair operation. Five to eight miles is a reasonable range for a primary wheelchair.

***14. Wheelchair wheels should be easily removable.***

The majority of foldable, manual wheelchairs allow the wheels to be easily removed for ease of transportation. The design should not interfere with this feature to maintain functionality of the wheelchair.

***15. Components should be aesthetically pleasing.***

Users will be less likely to use an unattractive product.

***16. Components should weigh no more than 20 pounds***

Manual wheelchairs are lightweight because the user has to propel not only themselves, but the wheelchair as well. Additional weight reduces functionality and makes the wheelchair more difficult to transport.

***17. Steering and propulsion should be decoupled.***

The wheelchair's mechanism for steering should be similar to an automobile in the fact that activating the steering should not initiate motion. By separating propulsion from steering, less aptitude is needed to operate the wheelchair.

***18. It would be beneficial for the steering interface to be adaptable***

Wheelchair users will have different preferences on the type of steering interface used on their wheelchair depending on the type of disability they have, the amount of strength they have in their extremities, and what their personal preference is.

***19. It would be beneficial for the wheelchair components to be universal so that they could easily be attached to any standard wheelchair frame.***

In order for this to become a marketable product, it would have to be adaptable to fit the majority of standard wheelchairs on the market.

## **3.2 Ideation of a Hybrid Manual/Powered Wheelchair**

In order to begin the design process, the three fundamental functions of wheelchair operation had to be split up and analyzed in a logical order. These included propulsion, steering, and braking.

### **3.2.1 Propulsion**

The most important design factor in developing a hemiplegic wheelchair is propulsion. Steering and braking are crucial to the design, however they are dependent on the type of propulsion system used.

It has been determined that power chairs do not fulfill the needs of hemiplegics because they significantly reduce physical activity and are difficult to transport and maneuver because of their size and weight. It has also been determined that manual hemiplegic wheelchairs are ineffective because they either require excessive strength, or move at reduced velocities to compensate for lever arms or gear boxes that utilize mechanical advantage. A design that would allow the user to propel the chair normally with their unaffected arm and simultaneously use powered features to emulate the propulsion of the now affected arm would be a substantial innovation.

By extracting key features found in manual and powered wheelchairs, a hybrid wheelchair could be produced that would allow the user to operate their chair like a standard manual wheelchair without the disadvantages of current manual hemiplegic wheelchairs. Manual wheelchair features would be incorporated into the user's functional side of the wheelchair, while powered features would be incorporated into the user's paralyzed side of the wheelchair.

#### **3.2.1.1 Propulsion Design Concepts**

Research into possible propulsion solutions for this application led to two possible design concepts. Both concepts involved hand-driven propulsion on one side of the wheelchair, and sensors that would transfer propulsion information to the motor-driven side of the wheelchair.

### **3.2.1.1.1 *Torque Responsive Drive***

A torque responsive drive could be directly developed from the concepts that propel current power-assist wheelchairs. This propulsion method is based on a torque sensor mounted in the push rim on the user's functional side of the wheelchair. As the user applied a tangential force to the push rim, a torque would be applied to the axle of the push rim. This torque would be measured by a torque sensor mounted in the push rim axle, and the data would be sent to a microprocessor. The microprocessor would analyze the torque and send a signal to the drive motor on the opposite side of the wheelchair to imitate the applied torque.

After further analysis, it was determined that this method was not feasible because torque was not the correct measurement to read for this application. On flat ground, torque would be an adequate measurement to imitate. However when positioned on inclined ground, facing in a direction other than parallel to the incline, the torque required to keep the wheelchair facing in a specific direction would differ between the wheels. This happens because the center of gravity on a manual wheelchair is in front of the drive wheels. The weight creates a moment about the axle of the wheels, which tends to cause the front of the chair to rotate towards the direction facing downhill since the front casters are free to rotate. If the processor instructed the motor to apply a torque equal to the torque being applied to the push rim, the chair would rotate until the chair was facing perpendicular to the slope. This problem could be alleviated by utilizing accelerometers to determine the position of the chair in relation to the incline, and accounting for the change by calculating the correct torque needed to retain position and/or direction. Implementing gyroscopic accelerometers would be very expensive though, requiring significant programming to create a working product. The accelerometers would have had to been calibrated for every user since weight changes in the user would have affected the wheelchair's behavior on inclines. For this reason, an alternate method needed to be developed.

### ***3.2.1.1.2 Position Responsive Drive***

Another propulsion idea that was developed involved the tracking of wheel position through the use of encoders. Precise angular position of a wheel is a measurement that can be easily read and analyzed using high resolutions encoders. Contrary to torque measurements, mimicking angular position of the wheels would enable maintenance of position on both flat and inclined surfaces. The fact that encoders are relatively inexpensive in comparison to gyroscopic accelerometers was an additional benefit.

Quadrature encoders could be placed on each rear wheel of the wheelchair, and as the user turned the push rim with their mobile arm, the encoder on the hand-driven wheel would signal to the processor how far and in what direction the wheel turned. The processor would then compare this signal to the position and movement of the motor-side encoder based on a predetermined algorithm. This algorithm would produce a signal that would be sent to the motor amplifier. This signal would cause the motor-driven wheel to mimic the hand-driven wheel by delivering power to the motor until the signal from the encoder on the driven-wheel matched the signal from the encoder mounted on the hand-driven wheel.

After analyzing the two propulsion concepts, it was decided that the position responsive drive would be the best choice due to the synchronization ability of encoders and their low cost implementation.

### **3.2.2 Steering**

A method of steering needed to be developed to control direction of travel. A setup involving only direct encoder imitation would only allow forward and reverse driving. In order to control direction, a proportional controller would need to be introduced to the system to control response proportionality of the motorized wheel. This user interface would be activated by the user at a location dependent upon the depth of their disability.

### **3.2.2.1 Steering Design Concepts**

As stated in the design specifications, it was deemed important to decouple steering from propulsion because of the importance of reducing the necessary cognitive skill required to propel the wheelchair. This specification was initially developed because of the difficulty encountered in steering a dual-rim hemiplegic wheelchair. Dual push rim hemiplegic wheelchairs are commercially available and couple steering and propulsion. These tasks proved to be difficult to perform with only one hand. In normal two-handed wheelchair operation, the tasks can be coupled because of the ability of the brain to more easily divide tasks between the left and right hemisphere of the body. The advantage of decoupling can be seen in lever-arm hemiplegic wheelchairs. Propulsion is controlled by the motion of the user's arm in a pumping motion, while steering is controlled by the adduction and abduction of the user's wrist. This decoupled method is much more user-intuitive.

Two design concepts were developed for steering early in the design stage that tested this theory. Both concepts utilized a steering interface consisting of a position sensor. The signal generated by this sensor would be used to alter the signal generated from the hand-driven wheel. By altering this signal, the controller would perceive the speed of the hand-driven wheel to be either faster or slower than it really was. Synchronizing the two wheels based on the altered hand-driven wheel speed would effectively create a turning condition.

#### ***3.2.2.1.1 Additive Steering Concept***

The first steering concept involved adding the signal generated from the steering position sensor to the hand-driven encoder speed. If the steering position sensor was turned in one direction, a negative signal would be added to the hand-driven wheel resulting in a slower speed being read by the controller. If the steering position sensor was turned in the other direction, a positive signal would be added resulting in a faster speed being read by the controller.

While this concept worked conceptually, it had two major downfalls. The first downfall is that motion could be commanded by the steering interface when the hand-



driven wheel was not being operated. This was because adding or subtracting from a zero wheel velocity would create a propulsion condition. Since steering could produce propulsion, this concept violated the specification that the two should not be coupled.

The second downfall was that adding or subtracting to a given signal would not create equal proportion steering at different speeds. The larger the signal that steering was being added to, the less affect the added signal would have on it since the steering signal would be a smaller proportion of the hand-driven signal. While additive steering could effectively steer the wheelchair, the coupled means of initiating propulsion were deemed to be overly difficult to control.

### ***3.2.2.1.2 Multiplicative Steering Concept***

The second considered concept effectively decoupled steering from propulsion. Instead of adding to the hand-driven wheel signal, the signal generated from the position sensor would be multiplied to the hand-driven wheel signal. In this method, propulsion could only be initiated by the user pushing on the push-rim. If the driven wheel was not moving, the multiplication factor would not affect the system since a signal of zero multiplied by any input is still a signal of zero.

This multiplication theory effectively functioned as an amplifier to the hand-driven wheel signal. The steering was proportionally implemented based on the speed of the wheel. If ten tick marks had passed in a given time interval, and a steering factor of two was implemented, then the controller would perceive the hand-driven wheel to have actually moved twenty tick marks.

The multiplication factors issued for a given amount of throw of the steering position sensor would need to be determined during testing of the prototype. When centered, the steering factor would be one to promote straight line driving. The further the position sensor was turned from center, the higher (or lower) the multiplication factor would be (Figure 13). It is noted that this is a non-linear and asymmetric scheme since turning with the motor-side wheel on the inside of the turn allows the motor to be stopped. Turning in the opposite direction cannot be performed with the hand-driven wheel stopped.

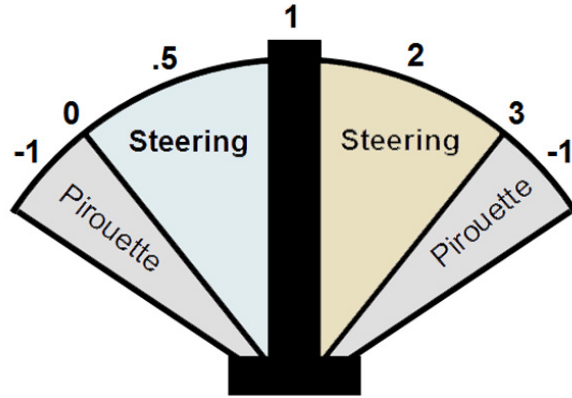


Figure 13 - Multiplicative Steering Concept (Left-side Paralyzed)

### 3.2.2.1.3 Pirouette Steering

A large benefit of having a manual chair over a power chair is that it is easier to turn in place (pirouette). With a manual chair, the axle of the drive wheels passes relatively close to the center of gravity of the person. With the exception of mid-drive power wheelchairs, the drive wheels on a power wheelchair are usually found much further back in the chair's footprint to assist with stability. By being further back, power chairs cannot turn in place effectively. The advantage of being able to turn in place was determined to be a design goal, and was developed with the assistance of the steering position sensor.

Pirouetting in a manual wheelchair is performed by simply turning the drive wheels in opposite directions. To perform this maneuver with the proposed design, the controls system had to perceive that the signal coming from the user-driven wheel was reversed. The reversed signal would cause the wheels to turn in equal and opposite directions. This signal was designed to come from the steering interface when it was turned to the extreme left and right limits of its allowed motion. This pirouette band would simply send a multiplier of negative one to the controller.

Another pirouette concept that was developed was the use of a safety feature built into the controls system that would restrict the user's ability to enter pirouette mode. If the wheelchair was moving at a reasonable speed and the chair entered pirouette mode, the chair could become unstable or cause an undesirable effect due to the motor suddenly reversing direction. To avoid an instantaneous reversal in direction of the motor, a limiter

could be introduced into the controls system that would not allow pirouette mode to be entered unless the velocity of the hand driven wheel was at or near zero.

To further avoid an adverse response, a mechanical buffer was considered that would require an additional force on the steering interface to reach the pirouette bands. The tactile feedback produced by the mechanical buffer would be designed to be a friction or spring loaded mechanism that would signal to the user that they were approaching the pirouette band.

### **3.2.3 Braking**

A benefit of the position responsive design was that braking could easily be performed through a combination of the user's functioning arm and the motor on the opposite wheel. If the user slowed the hand-driven wheel by gripping the push rim, then the motor on the other wheel would respond by slowing down. No additional features had to be incorporated to assist in normal braking because the same controls system used for propulsion could be used for braking.

When the wheelchair was powered off however, the motor-driven wheel would be free to rotate. An emergency-type brake was considered for the prototype that could be manually engaged by the user's functioning arm to provide braking to both wheels at once in case of a sudden power down while driving.

### **3.2.4 Finalized Design Concept**

While normally a decision matrix would be used to determine which design concept would be most advantageous to pursue, in this situation the best design concepts were easily identifiable.

The chosen design concept were the encoder responsive drive system, steered via a steering position sensor using a multiplication technique, with braking controlled naturally by the mimicking nature of the drive system. The following section will delve deeper into design conception by illustrating how the components were initially chosen.

### **3.3 Component Design Conception**

With the potential design concepts identified, the functioning components then needed to be determined. The components needed to adequately meet the requirements listed in the design specifications, as well as meet budgetary requirements in order to produce a proof of concept prototype. Components included a wheelchair frame, motor, motor amplifier, gearbox, controls system, power supply, encoders, steering interface, and manual wheel locks.

#### **3.3.1 Wheelchair Frame**

The wheelchair frame provided the foundation for mounting all other components. In order to make the design modular, all other components had to be designed so they could fit a variety of wheelchair frames. When deciding on the wheelchair frame for the prototype, a few important features had to be considered.

First, the wheelchair frame had to be foldable to meet the requirements for transportability. While a rigid frame would have been acceptable for demonstrating the concept, it would not have represented the geometric and mechanical properties that folding frames exhibit. Under given loads, flexible frames are more compliant.

The frame also had to be a good representation of a common manual wheelchair frame. While it would be beneficial to be able to fit the components to every type of frame available, it would not be realistic. For this reason, choosing a common wheelchair frame as a base for mounting the components would make it easier to visualize how they could be adapted to other frames. Of particular concern was the way in which the wheels mounted to the frame. This issue needed to be addressed when designing the motor to wheel interface.

A few different interface designs can be seen in Figure 14. The first frame attaches the wheel using an axle through a hole in a vertical or horizontal section of the frame. The axle maintains position by clamping a threaded axle mount to the frame. The second frame interface uses a plastic grid or webbing that allows the axle to be mounted in a variety of positions. This allows the wheel to be positioned horizontally and vertically based on center of gravity and elevation. The third frame interface uses a

slotted horizontal cross bar that bolts to two vertical sections of the frame. This interface allows the wheel to mount in a variety of horizontal and vertical positions as well.



**Figure 14 - Assorted Wheel Interfaces**  
(L to R: Vertical, Webbing, Horizontal Slider)

It was determined that the two adjustable frames would have been the easiest frames to mount to because of the additional surfaces that could be used for solidly mounting the motor and gear train. However, because adaptability was important, it was decided that the wheel to frame interface should be designed to fit the most difficult of the three interfaces, the vertical tube orientation. In addition, the vertical tube design is the easiest to manufacture and is the most common wheelchair frame.

### **3.3.2 Motor and Gear Train**

The motor and gear train were critical design choices because their characteristics determined whether or not the prototype could meet a significant number of task specifications. The two main design parameters were torque and speed capabilities. The motor and gear train needs to provide sufficient torque so that the chair could traverse certain terrain and obstacles such as carpet, thresholds, and most importantly, ramps. Adequate speed was needed so that the chair could travel at speeds typical of manual wheelchairs.

The required torque was developed from the maximum user weight and maximum ramp angle specifications. In order for a 250 pound user to travel up an eight degree slope, it was found that the motor and gear train had to produce 26.6 ft-lbs of torque. See calculations in Appendix A).

It was decided that the drive train needed to attain a top speed of at least 5 miles per hour, which was a common top speed for a power wheelchair. In order for the motor and gear train combination to meet these design goals, the first component that had to be decided on was the motor. This is because a gear train is only used to augment the torque and speed outputted by the motor. The output from a gear train depends on the gear reduction and how the gears are meshed and mounted in the gearbox. Neglecting efficiencies, the ratio obtained from a specific gear train increases the torque and decreases the speed outputs of the motor by that exact ratio. Based on a top speed of five miles per hour and wheelchair wheels with a twelve inch radius, the output speed of the drive system had to at least equal 70 rpm. Calculations made for determining the output speed of the drive system can be found in Appendix A.

Other major characteristics had to be considered in addition to gear efficiency, torque, and speed. Size and weight were important to the design. A smaller sized drive train would be beneficial in making the design aesthetically pleasing, as well as making it easier for the wheelchair to compactly fold. It would also allow for more room to fit the other components of the prototype to the frame. Size was also important when designing the interface to the wheel because it could potentially move the wheel out from the frame, making it more difficult to maneuver, and putting more stress on the axle. If the wheel was moved outward, it would also infringe on the allowable dimensions of the chair.

The weight of the drive train would not significantly affect the performance of the occupied wheelchair because it would be such a small percentage of the total weight. However, it would affect the transportability of the chair because it would contribute to a much larger proportion of the unoccupied wheelchair's overall weight. Wheelchair manufacturers try to minimize the weight of the wheelchair frame to make the chair easier to lift. The same principle was employed when designing the prototype's drive train.

### **3.3.3 Motor Amplifier**

The motor amplifier had to be compatible with the chosen motor. In order to be compatible, the amplifier had to convert the signal coming from the controller into a brushless motor signal (three phase alternating output). The signal also had to be pulse

width modulated (PWM) to create smoother motor control. In addition, the amplifier's maximum output voltage and amperage had to meet or exceed the motor's specifications.

### **3.3.4 Controls System**

The controls system was critical to the success of the prototype. The mechanical design of the wheelchair could have been made seamlessly, but without a functioning controls system, the prototype would have been a failure.

In choosing the system, a few important guidelines had to be followed. The generated signal had to be in the required format of the amplifier (either digital or analog). The controller had to have inputs that were compatible with the two wheel-position encoders and the steering position sensor. The system also had to allow for easy programming manipulation. If the program code could easily be altered and analyzed, then optimization of the controls could be obtained more efficiently. A production-ready controls system could be optimally designed later on to reduce the size, weight, and power consumption once the completed program had been finalized.

The packaging and cost for the controls system had more flexibility because as long as the program performed as expected, the packaging and cost could be overlooked. The chosen controls system could always be streamlined for size and cost in a future study because advanced technology already exists for creating production-ready, custom controls systems at low cost in small packages.

### **3.3.5 Power System**

The power system was highly dependent on the power requirements of the controls system and motor chosen for the prototype. The power supply had to provide ample power to prove conceptually that the chair could maneuver and transport for adequate periods of time. Weight and size were also important considerations because of transportability and folding. In addition, the power supply had to be rechargeable, safe, and easily accessible by the user.

### 3.3.6 Encoders

The encoders had to be chosen carefully to ensure that they would be able to read the position changes of the wheel with enough precision so that the controller could adequately respond. Without enough precision, the wheelchair would not be able to smoothly follow the motion of the hand-driven wheel. Precision in an encoder is determined by counts per revolution (CPR). CPR is dependent on the total number of ticks on the encoder wheel. When reading an encoder in quadrature, however, the CPR is effectively multiplied by four because of the two channels reading the tick marks as they pass. The two channels are positioned 90 degrees out of phase, allowing for two separate readings to be made as the tick marks pass below it. Because an optical sensor in a quadrature encoder makes two counts for each tick (once when it first encounters the tick, and again at the end of the tick), the two sensors together actually read four counts per tick.

An estimate of the necessary precision had to be determined before choosing the encoders. The main factor that influenced the precision calculation was the distance the wheel traveled between encoder counts. The estimate also had to take into account that discrete time derivatives and integrations performed by the controller would require up to ten counts to respond properly.

Initial estimates specified that the wheel should travel no more than a quarter inch in the driving plane without the motorized wheel responding. With the assumption that the controller would need, at maximum, ten counts to respond, calculations were performed (Figure 15) to determine the minimum required CPR of the chosen encoders. Ten counts was estimated to account for any lag in the system.



$d := 1\text{ft}$	diameter of wheel
$t_m := 10$	number of tick marks before controller response
$d_r := .25\text{in}$	maximum distance of travel between controlled response
$C := \pi \cdot d$	circumference of wheel
$C = 37.699\text{in}$	
$d_t := \frac{d_r}{t_m}$	maximum distance of travel between individual tick marks
$d_t = 0.025\text{in}$	
$\text{CPR}_{\min} := \frac{C}{d_t}$	minimum counts per revolution of encoder
$\text{CPR}_{\min} = 1507.964$	

**Figure 15 - Encoder Precision - CPR**

While this encoder precision theory accounts for straight line travel, it does not fully apply to steering conditions. When a multiplicative approach is used for steering, a given sample of tick marks read from the hand-driven wheel becomes either coarser or finer. When steering in one direction results in a factor above one, the motorized wheel overcompensates for hand-driven wheel movement making it more difficult to control. When the steering factor is below one, the motorized wheel does not compensate enough for hand-driven wheel movement. By reducing the number of perceived tick marks being read in a given sample time, the controller requires a larger wheel displacement before it can create a motorized response. For this reason, it was understood that a cutoff would have to be made as to how much the steering gain could decrease and increase the hand-driven encoder signals. This cutoff had to be made later in the design process when the control system underwent fine-tuning.

### **3.3.7 Steering Interface**

The steering interface was very important to consider. Possible locations were brainstormed based on the capabilities of potential users. The majority of hemiplegic users would be able to activate a potentiometer-style footplate with their unaffected leg or

foot, however, some users would have the capability to use a hand-operated single-axis joystick on their affected side if limited movement was available in their hand or fingers. Head activated interfaces were not considered because the wheelchair was being designed for active users who could use other extremities. Head interfaces are generally used by quadriplegic power wheelchair users or users with minimal motion in their upper extremities.

### **3.3.7.1 Thigh Interface**

In this format, a single axis joystick would be designed to interact with the user's mobile thigh. The joystick would be mounted to the seat pan of the wheelchair underneath the user's thigh. Two possible designs considered were a U-shaped interface that the thigh would sit in, and an interface consisting of two adjustable posts that would extend upwards along each side of the thigh. To control proportionality, the user would abduct and adduct their thigh to apply pressure to the interfaces. The single-axis joystick would be designed to return to center to support straight line driving.

### **3.3.7.2 Foot Interface**

In this format, ankle adduction and abduction would be targeted. Two possible methods of interfacing with the foot were conceptualized.

The first method consisted of a wheel mounted to the toe end of the footplate that protruded just above the footplate with the axis of rotation located along the length of the foot in the center of the footplate. The user would turn the wheel by adducting and abducting their ankle. The wheel would be attached to a steering sensor to read angular displacement and would have a spring return to assist in straight line driving.

The second method consisted of a rotating plate mounted to the footrest under the heel with the axis of rotation located along the length of the lower leg. The joystick sensor would be fixed to an axle mounted below the plate along the ankle's axis of rotation. The plate would include adjustable sidewalls or a traction-based material to house the user's foot to reduce the chance of the foot slipping on the plate during rotation. The joystick would be self-centering as well to promote straight steering.

### **3.3.7.3 Hand Interface**

Single-axis joystick operation was considered for both affected and unaffected hands. For the case of the unaffected hand, an interface would have had to be designed into the hand rim. Two main concerns became evident. First, since the hand rim would be in motion, it would be very difficult to design an interface to it. Second, since the hand would not be in constant contact with the hand rim during propulsion, this interface concept could not affectively control steering at all times. While these two concerns were not impossible to design around, they were enough to rule out the unaffected hand interface.

For the affected hand interface, a user who retained hand or finger motor control on their affected side would activate the joystick with a simple one-axis knob-type joystick. To mount this interface, the armrest would be modified to include a platform for attachment of the joystick. The platform would be designed to stabilize the user's affected arm and provide a surface for the hand to rest on to promote controlled motion of the joystick.

### **3.3.8 Manual Wheel Locks**

While brainstorming possible ways to control braking, the issue of having accessible manual wheel locks was contemplated. Manual wheelchairs typically use a four-bar style wheel lock to prevent the wheelchair from moving. This is especially useful when performing chair transfers or to help sustain position on inclines when not actively controlling the wheelchair. Due to the inability to use both arms, concern was raised as to whether the chair needed an adapted method of engaging the manual brake on the user's affected side. After careful consideration and simulations, it was determined that reaching across the body to engage the manual wheel lock was acceptable. While it was not as easy to perform this function with only one functioning arm, it was deemed acceptable for the scope of this prototype.

## **4 Prototype Design**

A prototype was manufactured to physically prove the viability of the wheelchair design concepts. The prototype in its entirety will be described and justified in the following sections. Significant design changes will also be explained to help illustrate the design process that was utilized to produce the finalized prototype.

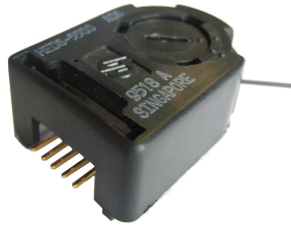
### **4.1 Controls System**

The controls system is made up of a system of PC/104 components that were fine-tuned to interact with three quadrature encoders and a brushless motor amplifier. The controls system's function is to control the motor-driven wheel so that it mimics the movement of the hand-driven wheel while providing a means of steering. In this chapter, each component of the controls system as well as the design of the controls program will be explained and justified.

#### **4.1.1 Hewlett Packard Quadrature Encoders**

Rotary quadrature encoders were chosen as the means of monitoring the prototype's two types of input. These two inputs, steering and wheel position, were the only attributes controlling the operation of wheelchair. For this reason, encoder choice was exceedingly important.

Three HP quadrature (HEDS-5500) encoders were obtained to perform these functions (Figure 16). All three encoders are specified as having 500 counts per revolution (CPR), but since the encoders are being read in quadrature (four pulses are read per cycle), the precision of the encoders is actually 2000 counts per revolution. Two of the encoders are used to track the position of the drive wheels, while the third encoder tracks the position of the foot-activated proportional steering controller.

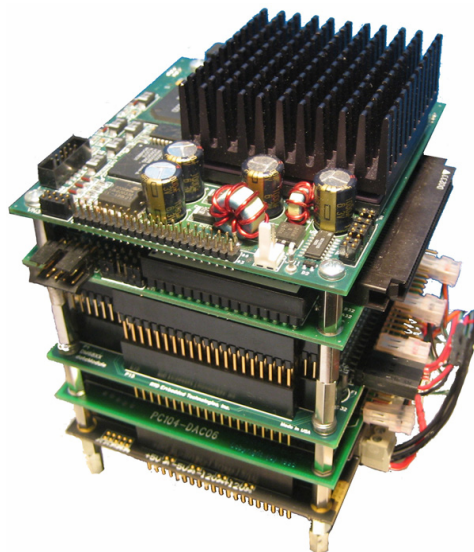


**Figure 16 - HP Quadrature Encoder (HEDS-5500 A14/A06)**

Each encoder is contained within a plastic housing, and uses an optical sensor coupled with multiple photo detectors to track tick marks on a metal disk. The metal disk has a hollow shaft with an inset set screw for mounting an encoder axle. Detailed specifications for the encoders can be found in Appendix B. Methods of mounting the encoders are detailed later in this chapter.

#### **4.1.2 PC/104 Control Hardware**

The control system was designed using a PC/104 stack consisting of five boards (Figure 17). The first two boards hold the Pentium-based PC and a flash drive to read and write drive code and execute the controls program. The third board's function is to read the outputs coming from the encoders so the PC board can decipher them. The fourth board's function is to convert the digital output signal coming from the PC board into an analog signal for the motor amplifier, and the fifth board converts DC voltage from the battery into the four voltages utilized by the stack.



**Figure 17 - PC/104 Stack (EPM-CPU-6/7)**

Each board has similar dimensions. The width and length of every PC/104 board is 90mm x 96mm (3.6" x 3.8"), while the thickness of the boards varies based on their function. The boards are stacked via four mounting holes located on each corner and interface through standard 104-pin connectors. The stack runs off a 5V power line, but, because of the specifications of the DAC board, it also requires +/- 12V inputs.

While the PC/104 stack is oversized and excessive for this application, it allowed for rapid controls prototyping during the design process. A production ready model of the wheelchair could incorporate the completed controls program into a streamlined IC board to reduce the size and cost of the system.

#### 4.1.2.1 Panther PC/104 Processor

The PC board (Panther EPM-CPU-7) was manufactured by VersaLogic, a company specializing in PC/104 systems (Figure 18). This is a versatile system that made programming easy because it allowed the coded program to be efficiently written and rewritten during prototyping. The board uses a flash-based hard drive to store the controls program, and receives and sends data through a variety of interfaces (a null modem and 3.5" floppy drive was used during the design stage).

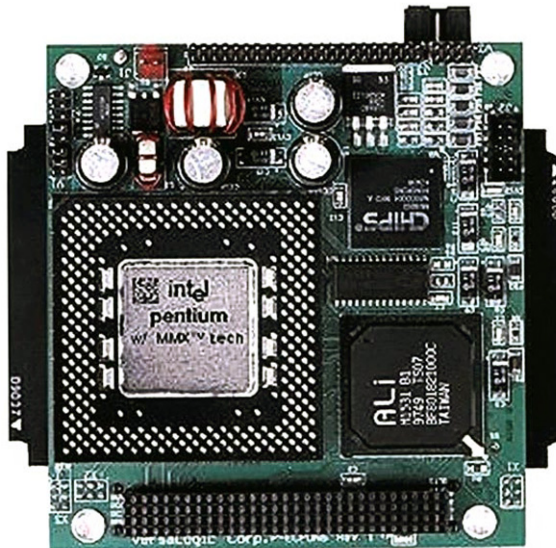


Figure 18 – Panther PC/104 Board (EPM-CPU-6/7)

#### 4.1.2.2 RTD Incremental Encoder PC/104 Board

RTD Embedded Technologies, Inc. was found to be a leader in producing incremental encoder boards for PC/104 systems. For the prototype, a DM6814HR Quadrature Encoder dataModule® with three inputs for monitoring quadrature encoders was purchased and modified (Figure 19). Each of the inputs read three encoder channels: A, B, and index. The index was not useful for this application, so the encoder's index channels were not wired to the encoders. The module's base address was set to channel 300 to identify it from the other boards in the stack.

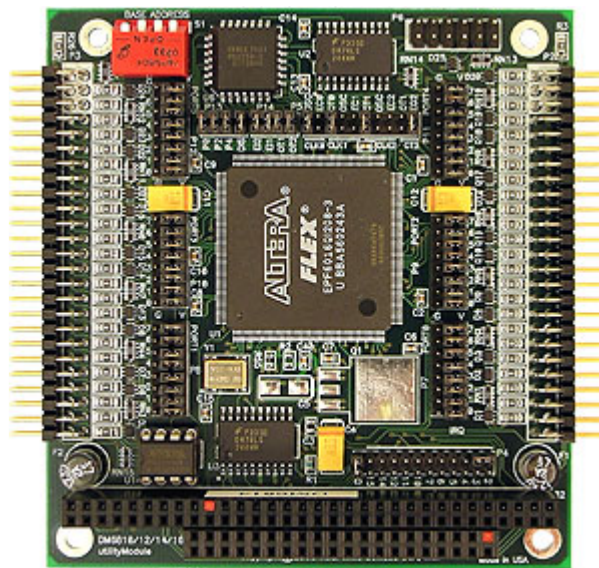


Figure 19 – Incremental Encoder dataModule® (DM6814HR)

Modifications were made to the board to assist in wiring the HP encoders. Each encoder required a main 5V power line. The power line coming from the PC/104 bus was split between the encoder's main voltage lines and the A and B channels. The A and B channels, however, each required a 2.7kΩ resistor to be wired between them and the 5V line (Figure 20). To accomplish this, 2.7kΩ surface-mount resistors were soldered onto the bottom of the board at each required pin location and then wired to the 5V input line.

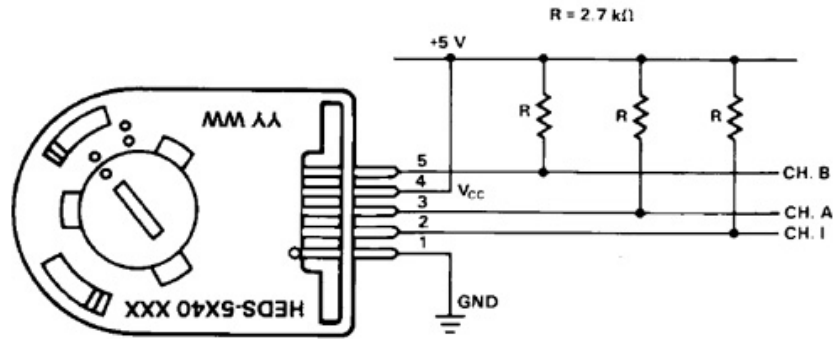


Figure 20 – Encoder Wiring Diagram

#### 4.1.2.3 Measurement Computing DAC Board

Signals generated from the PC/104 stack were created in digital format. Unfortunately, the chosen amplifier for the motor required an analog signal to operate properly. To remedy this, a digital to analog conversion (DAC) board manufactured by Measurement Computing Corporation was obtained. The board, a PC104-DAC06, was placed inline with the stack to convert the digital signals to analog signals (Figure 21). The DAC board was configured to send +/- 10V signals to the amplifier which required the board to be connected to a +/-12V power line. This particular board allows for up to six analog outputs, making it excessive for the prototype since only one output is needed. However, the availability of the board made it an acceptable choice.



Figure 21 - Measurement Computing DAC Board (PC104-DAC06)



#### 4.1.2.4 Tri-M PC/104 DC/DC Power Supply

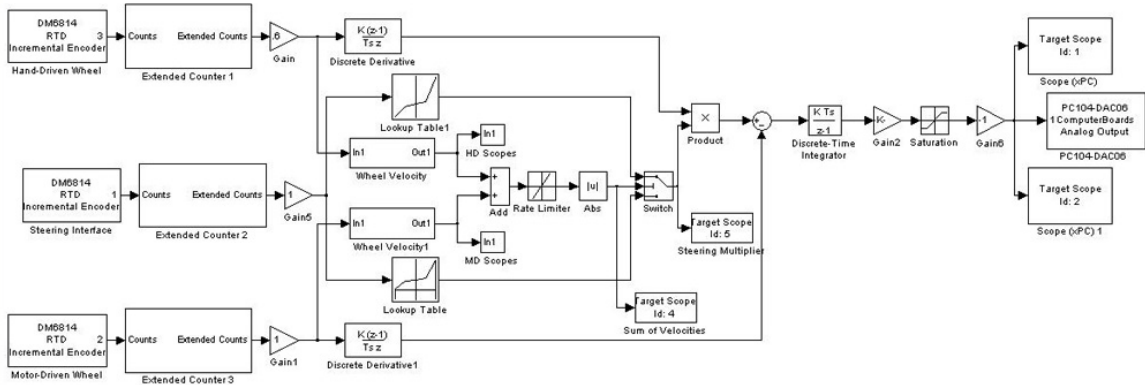
A PC/104 DC/DC power supply board from Diamond Systems Corporation (Tri-M HE104-DX) was used to regulate voltages originating from the battery used to power the chair (Figure 22). The 60W power supply accepts a voltage input ranging from 6 to 40V DC. The board converts the voltage input into four outputs (+5V, -5V, +12V, and -12V) through a series of DC/DC converters. The supply attaches inline with the PC/104 stack and utilizes a connector block to attach the main power line.



Figure 22 - Tri-M Power Supply Board (HE104-DX)

#### 4.1.3 PC/104 Control Software

The control system was designed using Simulink software (Figure 23). Simulink is a program developed by The MathWorks, Incorporated. The program allows intensive computational mathematics to be performed on dynamic systems through an easy to use interface (The MathWorks, 2006). Through a range of Simulink subsets, a complete controls system was designed and tested in real time to optimize the performance of the prototype. Simulink was used to generate block diagrams depicting the setup of the completed controls system. Real Time Workshop was then used to create C++ code of the full functioning controls program. Lastly, xPC Target was used to send that program to the PC/104 stack that allowed the prototype to run the program as a mobile unit.



**Figure 23 - Controls System Block Diagram – Testing Stage**

To begin the design of the controls system, each encoder input was assigned a controls block in Simulink to identify it. This was accomplished by locating the RTD DM6414 block in the Simulink Library Browser and bringing three of these blocks into the Simulink programming window. Each block was assigned a different channel (1, 2, and 3), corresponding to the three individual encoders. The sample time was set to .01ms for each of the encoders to allow for an adequate sampling time of the encoder positions.

The next step taken was to insert a controls block for the DAC board. The first of the six channels was chosen for the output signal in the DAC block. By identifying the start and end of the controls block diagram, direction was given to how the controls system needed to be pieced together. In effect, a blank slate was left in the middle to map out the controls system.

With the three encoder blocks in place, each encoder was tested to ensure they functioned properly. A target scope block was inserted into the block diagram and connected directly to the encoder blocks. The target scope block was useful because when the program was built and downloaded to the target PC, a real time graph was produced on the target PC monitor that showed the encoder data output. The test showed that all three encoders functioned properly but, more importantly, the test identified an issue involving limited encoder counts, which restricted the ability of the wheelchair to drive for extended periods.

### 4.1.3.1 Straight-Line Driving

Straight-line driving was initially accomplished by continuously monitoring encoder position error between the two drive wheels. The control block for the encoders however only allowed for  $2^{16}$  counts to be read (0 to 65536). When it reached either threshold, the count jumped to the opposing limit and continued counting. This jump was a problem since a large jump would destabilize the controls algorithm. When the encoder was started up, it began counting up from zero when turned clockwise; however, if the encoder was turned counterclockwise, it would jump from zero to 65536 and count backwards. When the signal jumped from one limit to the other, it interpreted the change as the wheel rotating over six revolutions. This was calculated by multiplying the encoder CPR of 2000 by the gear train ratio of 5.25 (discussed in the Upper Gearbox Cover section later in this Chapter). The resulting affective CPR of 10500 was then divided into 65536 to obtain a value of approximately 6.24 revolutions. The controls system drastically overcompensated to synchronize the encoder signals when this jump occurred.

Initially, a solution to this problem was made by adding a constant block of 32768 (half of 65536) to the drive-wheel encoder blocks to start counting from 32768. Since the encoder count was limited to counts between zero and 65536, this adjustment started the count in the middle of the available range. After further review, it was promptly deemed unacceptable because the encoders reached the limits in just over three drive wheel revolutions.

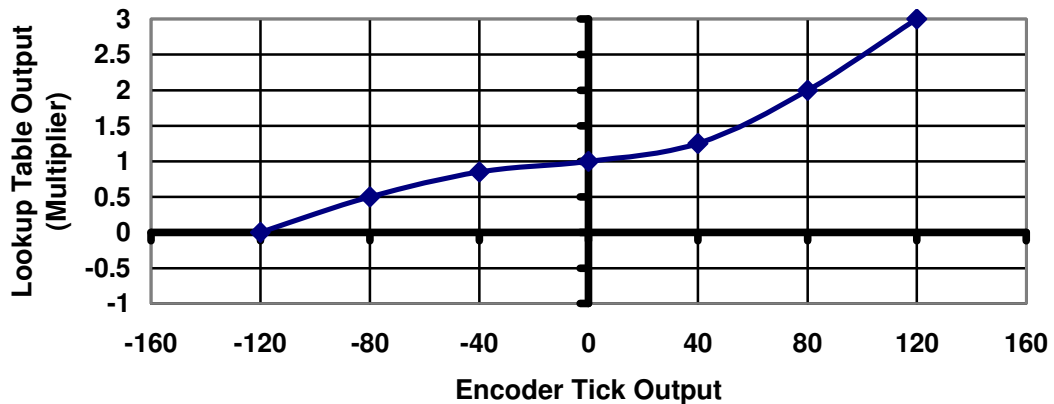
After researching the problem, an extended counter block was found on the MathWorks website for xPC Target. The extended counter works by recognizing a rollover due to a large jump in data, and interprets the jump as a single count. This block allowed the count to begin at zero at startup, and then count in either direction without reaching a limit. The extended counter was placed in line with the encoder blocks.

To create a straight-line driving condition, the two accumulated counts were subtracted from each other to determine how out of phase the encoders were. The resulting difference was then converted into a voltage by implementing a gain and saturation block to convert the signal into a usable voltage range ( $\pm 5V$ ).

### 4.1.3.2 Steering

The next step was to develop controls for steering. Steering was designed to activate by multiplying the signal coming from the hand-driven wheel's encoder by the signal coming from the steering interface's encoder. The mechanical design of the steering interface is further explained in the Methods section. 45 degrees was chosen as an acceptable range for ankle rotation and was integrated into the controls design. The allowable 45 degrees translates to 250 encoder counts ( $\frac{45}{360} = \frac{250}{2000}$ ). The startup count was chosen to be 30000 because it is a rounded number in the middle of the encoder range. A lookup table (Table 1) was developed to create a steering profile between the counts of -120 and 120 (this range is below the 250 count range to allow for the pirouette function to be added in). The lookup table changes the signals produced in this range to a range of zero to three. An inflection point was made at one, which corresponds to the encoder count of 30000. At the inflection point, straight-line driving is retained since the hand-driven encoder signal is multiplied by one. The lookup table moves exponentially to the limits to increase the range of near straight-line driving.

Table 1 - Steering Lookup Table



Problems arose from this direct multiplication method because the accumulated counts were being multiplied instead of the individual encoder tick signals. To address this, the encoder signal was run through a discrete-time derivative loop to obtain wheel velocity instead of position. The discrete-time derivative allows for a controllable range of time to be analyzed instead of calculating instantaneous velocity with a normal

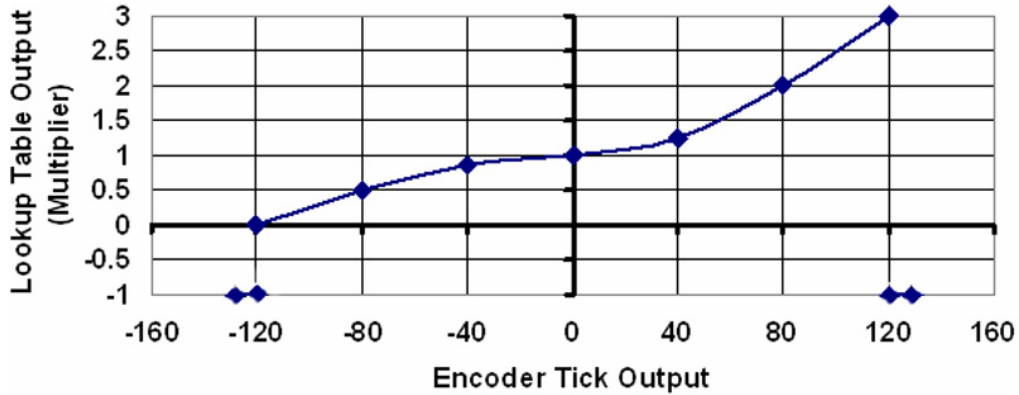
derivative loop at each .01ms time sample. The regular derivative measurement resulted in an unstable system that was non-drivable whereas the discrete-time derivative measures an averaged wheel velocity over a larger sample time which effectively smoothes out the motor response. Once the hand-driven wheel position is sent through the discrete-time derivative loop, it is then multiplied by the steering gain. The signal from the motor-side encoder is also sent through an identical derivative loop and the resulting signals are then subtracted from each other. The velocity difference is then integrated with a discrete-time integration block to obtain the position error between the wheels.

The resulting modified position error is sent through the same gain and saturation blocks that were devised in the straight-line driving section to create a voltage signal that can be delivered to the motor amplifier. The voltage is obtained directly from position error, so the motor voltage increases when the error between the wheels enlarges and decreases as the error diminishes depending on the direction of rotation. This creates a fully functioning closed loop controls system. Since the voltage output by the PC/104 processor is in digital format, it has to be sent to the DAC board to convert it to an analog signal before it can be sent to the amplifier.

#### **4.1.3.3 Pirouette Function**

Turning in place is accomplished by creating a pirouette function. This was done by implementing a controls switch that switches between two steering lookup tables. Both lookup tables were made identical with the exception that the second table (the pirouette table) includes limits that were added to the ends of the steering range (Table 2). The limits were set to negative one so that if the encoder surpasses the steering range, the lookup table can convert the signal to a multiplier of negative one. When multiplied, the motor driven wheel is commanded to turn at an equal and opposite rate, effectively creating a pirouette condition.

Table 2 - Pirouette Function Lookup Table



The ability to enter into pirouette function was restricted so that when the chair moves at a relatively fast pace it cannot switch to pirouette function. This situation could cause an unexpected change in motor rotation, which could result in a safety hazard. To determine when the chair could enter pirouette mode, the wheel velocities were routed into a sum block. The switch directs the steering encoder signal to the pirouette table when the sum of the two wheel velocities is below .75mph and to the original steering table when the velocity is above .75mph. By taking the sum of the wheel velocities, the opposing direction of the wheel velocities cancel each other out when in pirouette function, allowing the switch to remain in the pirouette position even when spinning quickly. In addition to summing the velocities, the resulting signal is sent through a rate limiter to ensure that if a sharp spike in wheel velocity was to occur, it would not affect the switch.

The finalized controls system block diagram was streamlined to remove all scope blocks to reduce computing time. The controls code was written from the block diagram and downloaded onto the Panther CPU board's onboard flash drive. The resulting controls program is initialized at startup by the mobile target PC unit.

#### 4.1.4 Advanced Motion Controls Brushless Servo Amplifier

An Advanced Motion Controls (AMC) amplifier (B30A8) was chosen that produced a PWM signal for a brushless DC motor (Figure 24). The amplifier is rated for DC supply voltages from 20 to 80 volts, with a maximum peak amperage output of +/- 30 amps. Continuous current is rated at 15 amps.



**Figure 24 - AMC Brushless Servo Amplifier (B30A8)**

The amplifier accepts an analog signal for the control of the motor and was well suited for adjusting input output signals for testing purposes. This particular amplifier was also optimal because of the availability and the ability of the amplifier to operate the chosen brushless motor properly (Section 4.2.2.1.1). The size of the amplifier could be greatly reduced if a new amplifier was designed to operate the final chosen motor.

#### **4.1.5 Power System - NiCad Rechargeable Cells**

The wheelchair is powered using a 24V battery pack consisting of twenty 1.2V C-cell Nickel Cadmium (NiCad) rechargeable batteries wired in series. The battery pack supplies 60Ah of power to all of the electrical components of the wheelchair. This battery was deemed sufficient for prototype purposes and testing. More sophisticated batteries such as Lithium-ion batteries could be implemented in future models to reduce the size and weight of the battery pack.

### **4.2 Mechanical Components**

The design of the prototype's mechanical components was performed concurrently with the design of the controls system. To fine-tune the controls system, the controls had to be attached to the working prototype to gauge the effectiveness of the

controls design. In this section, each mechanical component of the prototype will be explained and justified as to why it was chosen or how it was designed.

During the design stage, the entire chair was modeled in Pro/Engineer to ensure proper design choices were being made throughout the development of the wheelchair. Every component, whether acquired or designed, was modeled in Pro/E to ensure alignment, detect interference, and visually assist in the design process. Detailed drawings can be found in Appendix D for further visualization. Manufacturing of all parts was performed at DEKA Research & Developments machine shop in Manchester, NH.

#### **4.2.1 Wheelchair Frame - Invacare Manual Wheelchair**

When choosing an existing wheelchair frame for the prototype, it was important to choose a wheelchair that represented a common foldable manual wheelchair design. As discussed in the Methods chapter, it was decided that the frame should have a vertical, tube-clamp mounting interface for the rear wheels. This type of interface was found to be the most common amongst manual wheelchairs. An older Invacare wheelchair model (Model # L218LA286) donated by the Assistive Technology Resource Center (ATRC) at WPI met these criteria and was readily available (Figure 25).

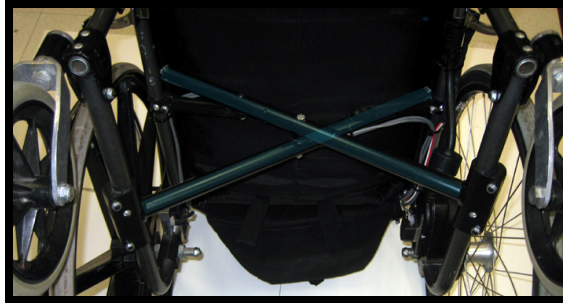
The Invacare has a steel frame and a sling seat and sling back. The wheels are mounted to the chair in a vertical clamping configuration (Figure 14) and are manufactured using a plastic injection molding process. Prior to modifications, the chair weighed 24 pounds.



**Figure 25 – Original Invacare Wheelchair (L218LA286)**



The folding mechanism of the chair consists of two tubular frame members that bolt together in the center for pivoting. When the chair is unfolded, the members are oriented in an 'X' shape (Figure 26), crossing in the center of the chair. When folded, the members are oriented near parallel to each other which brings the wheels into the center of the chair. This type of frame is commonly referred to as an X-frame.



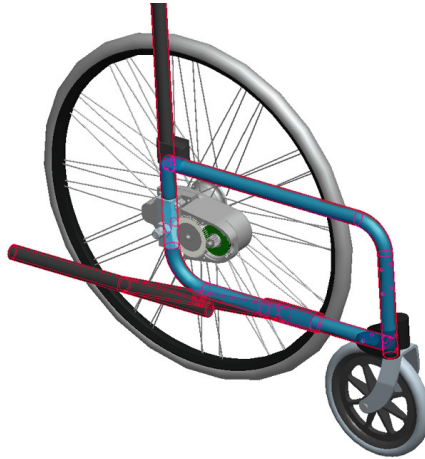
**Figure 26 - X-Frame Folding Mechanism**

The frame has a common interface for attaching leg rests (Figure 27). The acquired chair has removable Everest & Jennings swing-away leg rests that are length adjustable but not angle adjustable. Due to the motion of the swing-away feature and the ability for the leg rests to be removed, careful attention had to be placed on where the wiring for the steering mechanism was located. These constraints will be discussed in the steering section of this chapter. Other features of the wheelchair include detachable armrests with attached clothing guards, eight-inch swivel caster wheels, attendant handles, and four-bar style wheel locks.



**Figure 27 - Leg Rest Interface**

The tubular frame of the wheelchair allowed for plenty of room for attachment of components such as the controls system and battery pack (Figure 28). Components were designed to fit within the wheelchair frame and were checked for interference during folding using Pro/Engineer.



**Figure 28 – Available Frame Space for Attachment of Components**

#### **4.2.2 Hand-Driven Wheel Side Components**

Wheel position of the hand-driven wheel was the only function that needed to be designed into the hand-driven side of the wheelchair. To do this, wheel rotation had to be measured using either an encoder attached directly on the wheel or by using some type of pulley system. Initially, an encoder was going to be placed on the outer side of the hand-driven wheel so that it could be mounted to the wheel hub along its axis. By mounting it to the wheel hub, it would have rotated with the wheel and measured rotation around the stationary wheel axle. This caused obvious problems since wiring would twist as the wheel rotated. Mounting in this position also would have restricted the ability to increase the precision of the encoder through pulleys. Further, by placing the encoder on the outside of the wheel, the dimensions of the wheelchair would have increased, making the encoder vulnerable to bumping into objects. Instead, it was decided to mount the encoder to the inner side of the wheel with pulleys. The design process will be discussed in the following sections.

### 4.2.2.1 Wheel Interface

The wheel interface consisted of two pulleys and a connecting belt to interface between the encoder and the hand-driven wheel (Figure 29). All three parts were acquired from Stock Drive Products / Sterling Instrument, a company specializing in drive components. The pulleys were chosen based on the reduction chosen for the motor-side encoder (1:5.25). This additional gear reduction increases the precision of the encoders to 10500 CPR. The large pulley, consisting of 84 teeth, is made of plastic and has a large enough diameter to provide plenty of surface area to mount to the wheel hub. The pulley has two flanges to restrain the belt. The distance between the flanges is 7.5mm. The pitch of the pulley (which is the same for the small pulley and belt) is 2.5mm (or T2.5). Alignment of the pulley and wheel hub was difficult because the wheel hub did not have many surfaces to align to.

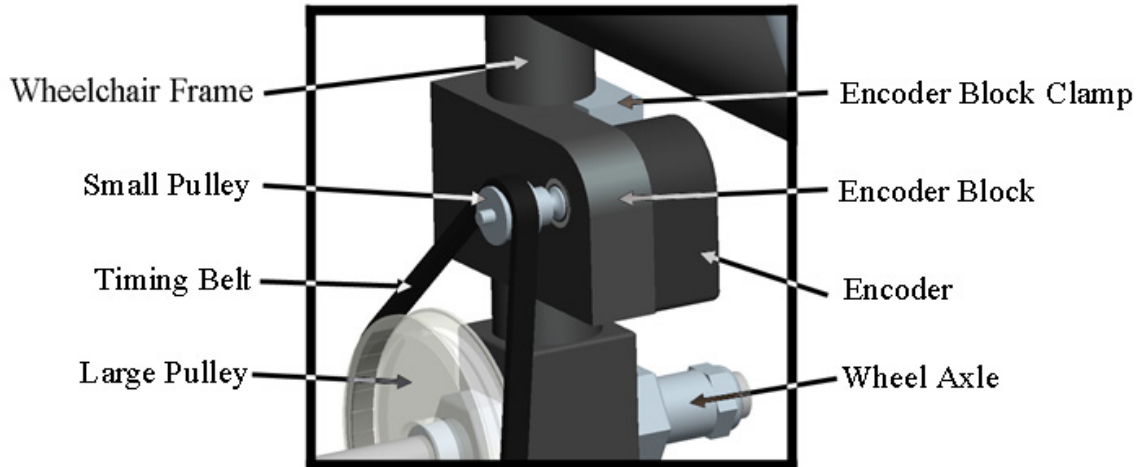


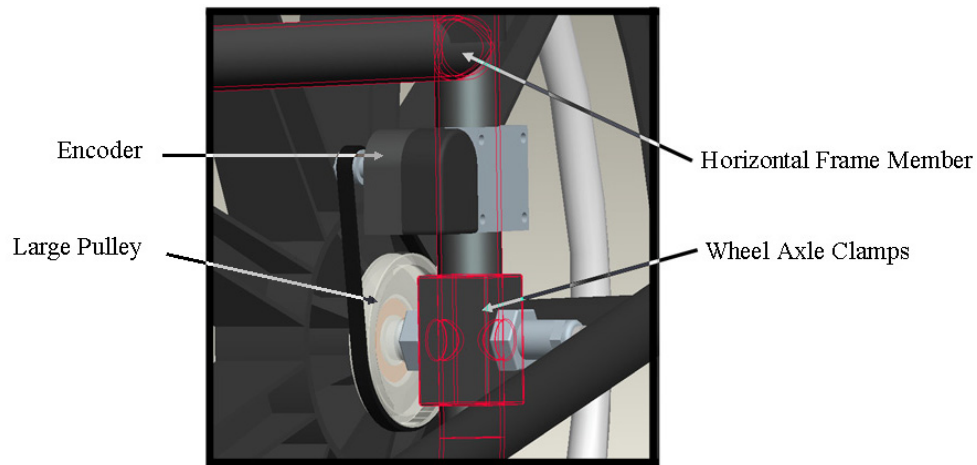
Figure 29 – Hand-Driven Side Encoder Setup

To assist in alignment, an aluminum spacer was machined with protrusions matching the hub of the wheel. The spacer was located on the wheel by using the hub geometry. Thru holes were drilled into the spacer so it could be screwed into the hub of the wheel to maintain its position. Threaded holes were tapped into the surface of the spacer so that the pulley could be screwed onto it.

The smaller pulley has 16 teeth and is also made of plastic. This pulley has two flanges to restrain belt movement that are also located 7.5mm apart. The belt, a 6mm

wide single-sided polyurethane belt consisting of 114 grooves, was chosen based on the center to center distance between the pulleys.

The two pulleys were designed to be placed 75.07mm apart. This spacing was based on two factors: the distance of the encoder from the frame and the available frame space between the wheel clamps and the frame's horizontal cross bar (Figure 30). The horizontal position was limited by the wheel axle clamps and a horizontal member of the frame.

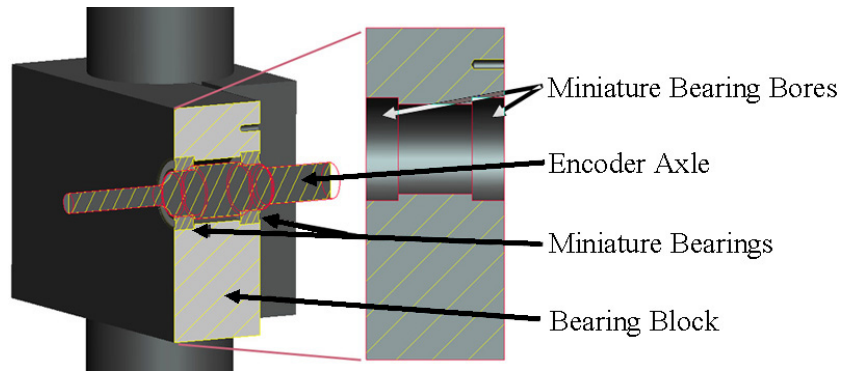


**Figure 30 – Available Frame Space for Encoder Block**

The full calculations used to determine belt properties and center distances can be found in Appendix A.

#### **4.2.2.2 Encoder Mount**

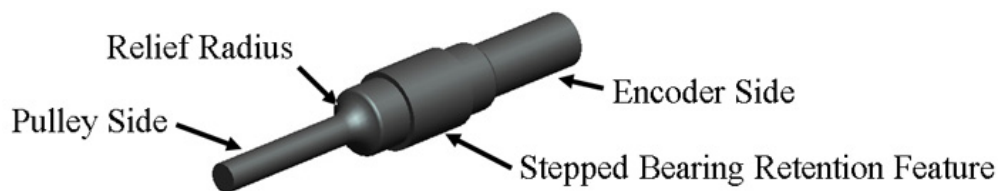
The encoder mount attaches to the wheelchair frame above the wheel axle. The mount was designed to clamp to the frame to allow positioning of the encoder and small pulley. The mounting surface for the encoder positions the encoder close to the frame. Two bearing bores were designed into the mount for press fitting two miniature bearings. The miniature bearings provide support for the encoder axle both in bending and from moving axially. An 11.11mm (7/16”) thru hole was drilled coaxially to allow the encoder axle to pass through with enough clearance while still providing support for the outer races of the miniature bearings (Figure 31).



**Figure 31 - Encoder Mount Cross Section**

### 4.2.2.3 Encoder Axle

The purpose of the encoder axle is to hold the small pulley and interface with the encoder. The axle was designed to fit within the encoder mount and properly interact with the miniature bearings. The axle was machined from hardened steel (Figure 32). The section of the axle that interfaced with the small pulley was designed to be press fit into the pulley to help resist pulley movement both axially and radially. In addition to the press fit, Loctite was used to restrain movement. Additional means of support, such as setscrews, were not used because only small amounts of torque engage the pulley during operation and because the size of the pulley restricts such features from being easily integrated.



**Figure 32 - Encoder Axle**

A large radius was designed into the axle in between the pulley and bearing step to reinforce the axle. Between the bearing surfaces on the axle, another step was designed in to restrain it from moving along its axis (the step contacts the inner races of the miniature bearings).

### 4.2.3 Motor-Driven Wheel Side Components

On the motor-driven side of the design, a motor, gearbox, and encoder to track the motor's position had to be designed to interface with the wheelchair frame and wheel. The motor and gearbox had to provide sufficient power to meet the design specifications while being relatively quiet and small. The encoder had to track the rotation of the wheel with enough precision to supply the controller with sufficient counts. Each of the chosen and designed components met these criteria and will be detailed in the following sections.

#### 4.2.3.1 Gearbox

The gearbox contains a brushless DC motor and a 23:1 gear train. The majority of gearboxes are made to constrain only the gears that make up the gear train. These gearboxes are then mounted externally to a motor that has its own housing. In this configuration, however, the gearbox contains both the gear train and the motor. The components were donated from an existing two arm power-assist wheelchair that provided sufficient power to drive a 250-pound person up an eight-degree slope. The housing was manufactured with an aluminum casting technique and then precision machined to allow for proper alignment.

##### 4.2.3.1.1 *Brushless DC Motor*

The motor contained within the gearbox is a brushless DC motor that is powered by a 24V supply (Figure 33). Motor specifications were not available, so the specifications were deduced through testing. Since the desired characteristics of the motor drive were the output values from the entire gearbox, the gearbox as a whole was tested with the existing power-assist wheel attached. By using this method, inefficiencies found in the gear train and bearings were fully accounted for.

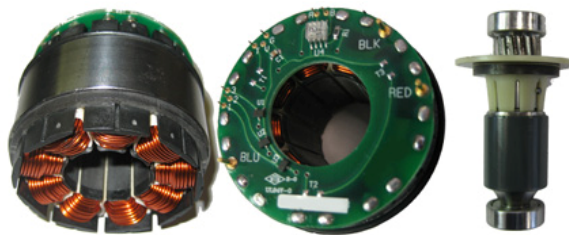


Figure 33 - Brushless Motor

To find the stall torque of the drive system, 15A were delivered to the motor at 24 V. String was attached to the wheel at the furthest extent of the wheel spokes (10 inches from the wheel axis). A force gauge was attached to the string and held stationary at a position perpendicular to the attached wheel spoke. The force measured by the force gauge to resist wheel rotation was found to be 34.25lb. The resulting torque of the drive system was calculated to be 28.5ft-lb (Figure 34). The free running output velocity of the drive system at 24V was found to be 6.2mph as measured by a handheld contact tachometer. The resulting RPM of the motor drive output was calculated to be 86.8RPM (Figure 35). This motor is extremely powerful for its size and capably handles the loads required by the prototype. Since the motor is found within the gearbox, it does not have its own separate housing.

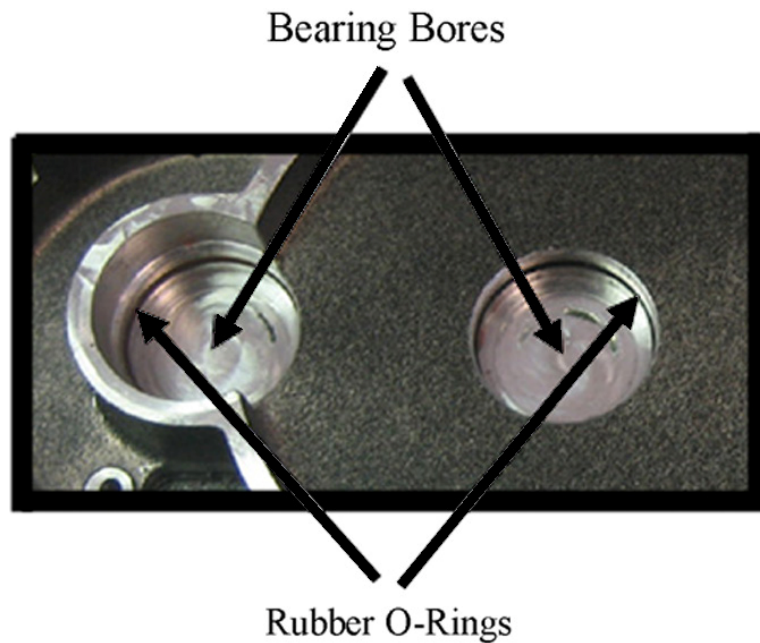
$d_s := 10\text{in}$	Distance of string from wheel axis
$F := 34.25\text{lb}$	Force gauge measurement at stall
$T := F \cdot d_s$	Torque calculation
<b><math>T = 28.5\text{ft}\cdot\text{lb}</math></b>	

**Figure 34 – Drive System Stall Torque Calculation**

$V_w := 6.2\text{mph}$	Calculated wheel velocity at maximum motor speed
$V_w = 545.6 \frac{\text{ft}}{\text{min}}$	
$r_w := 12\text{in}$	Radius of wheel
$C_w := 2 \cdot \pi \cdot r_w$	Circumference of wheel
$C_w = 6.283 \text{ft}$	
$\text{RPM}_w := \frac{545.6}{6.283}$	RPM of drive system
<b><math>\text{RPM}_w = 86.8</math></b>	

**Figure 35 - Drive System RPM Calculation**

The brushless configuration of the motor consists of three phases with three Hall Effect sensors to track the rotor's position. Hall Effect sensors respond to changes in magnetic fields and adjust their output voltage accordingly. Since the rotor contains a magnet, as it spins, the Hall sensors track the rotor's magnetic poles. The rotor floats within the motor coils but is restrained from moving coaxially by two bearings press fitted at each end of the rotor. The bearings are constrained within the gearbox by slip fit bearing bores with inset rubber o-rings to inhibit vibration (Figure 36).



**Figure 36 - Bearing Bores with Inset O-rings**

#### ***4.2.3.1.2 Gear Train***

The motor came packaged in a gearbox with a gear train ratio that met the needs of the project. The reduction of 23:1 is made with a combination of plastic and metal helical gears. The helical gears are advantageous because they produce less noise than spur gears and provide continuous gear meshing during operation.

The gear train was originally setup with four stages consisting of seven gears (Figure 37a). This gear train had additional gears built into it to assist with torque-responsive power-assist driving. Since torque response was not required for this

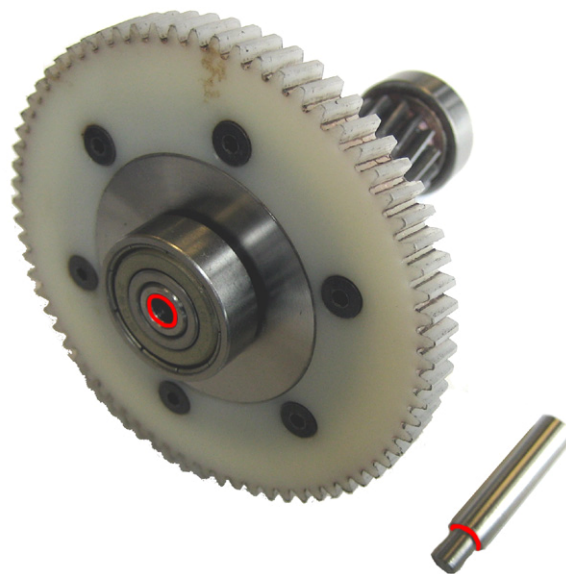


application, the extra gears were removed for the prototype. In order to drive the power-assisted wheel, only two stages and four gears were actually needed (Figure 37b).



**Figure 37 - Original Gear Train (Left) vs. Modified Gear Train (Right)**

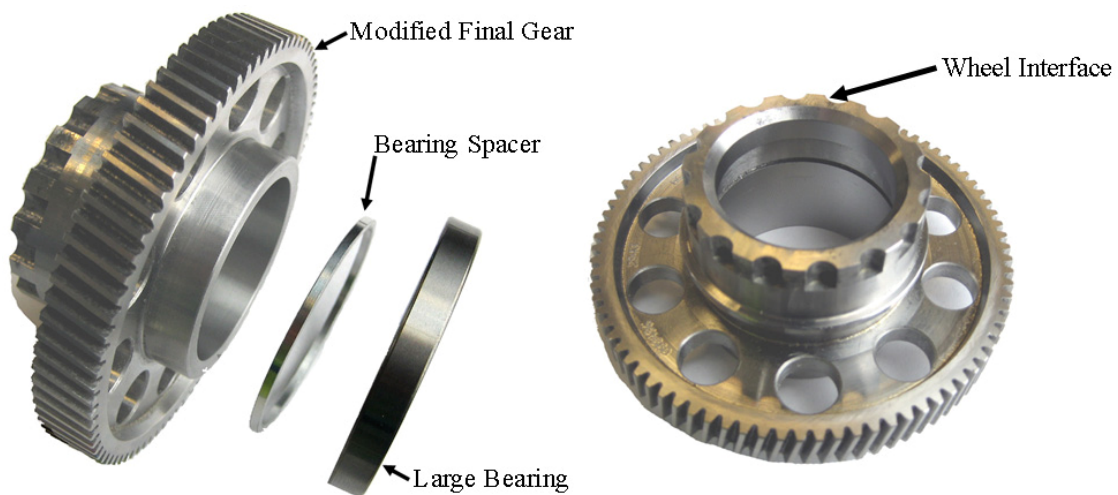
The first stage of the gear train consists of one steel and one plastic helical gear. The steel helical gear consists of 16 teeth and is machined directly into the rotor of the motor. No modifications were performed on this rotor gear. The plastic helical gear consists of 70 teeth. This gear meshes with the metal gear on the rotor creating a 4.38:1 gear ratio. The plastic gear is affixed to a steel shaft that holds another sixteen tooth steel helical gear that makes up the first half of the second stage of the gear train. The shaft was modified at the plastic gear end to allow an encoder axle to be press fit into the end of the shaft (Figure 38).



**Figure 38 - Modified Gear Shaft and Encoder Axle**

The second stage of the gear train consists of two metal helical gears that mesh together. The first gear is the 16 tooth metal gear previously discussed that is affixed to the shaft with the plastic gear (Figure 38). The second gear is a large steel helical gear consisting of 84 teeth (Figure 39). The two gears create a 5.25:1 gear ratio. Together, the two stages of the gear train create a total 22.97:1 gear ratio.

The large gear is not only the final gear in the gear train, but it is also the interface between the gearbox and the wheel. This gear protrudes out of the gearbox and has a machined profile that allows it to interface with a complimentary profile machined into the hub of the existing power-assist wheel.



**Figure 39 - Modified Final Gear and Wheel Interface**

In the original gear train, the final axle involved not only the final gear, but a second metal gear (one of the three removed gears) on the same axis that rotated independently (Figure 37, Left). This second gear supported the axle of the wheel. The axle entered into the gearbox through the hollow center of the final gear and then inserted into the second gear through a keyed profile. The wheel was fully supported by the second gear, making the gearbox the main support structure for the wheel.

Since the goal of the prototype was to attach the gearbox to the existing setup of a manual wheelchair, the gearbox was redesigned to attach to the wheel without acting as a support structure for its axle. By removing the second gear and creating a hole in the gearbox cover, the axle could pass freely through the hollow final gear and into the existing support structure on the wheelchair frame.

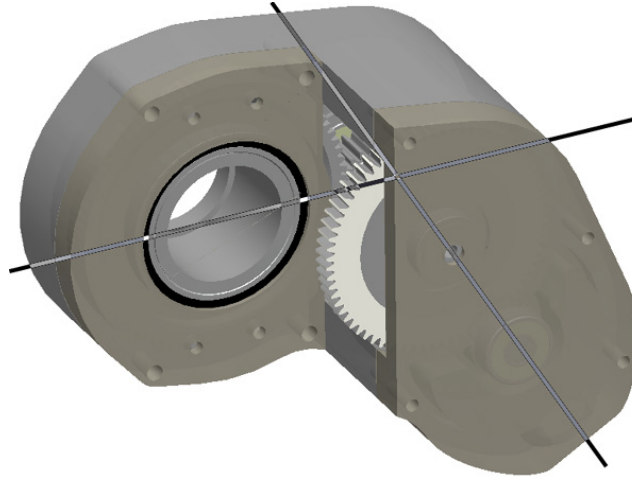
To minimize the distance between the wheel and the wheelchair frame, the width of the final gear was reduced. This was done because the further the wheel is from the frame, the longer the distance is between the wheel axle supports (the wheelchair frame and the wheel hub). The greater the distance, the larger the deflections become under applied loads. With the reduced width of the gear, the wheel could be placed at the same distance from the frame as it was on the original manual wheelchair.

The final gear was restrained in the gearbox base by a large, thin bearing. To interface with the lower cover, an identical bearing was placed on the cover-side of the final gear hub, and offset from the gear by inserting a bearing spacer.

#### ***4.2.3.1.3 Gearbox Modifications***

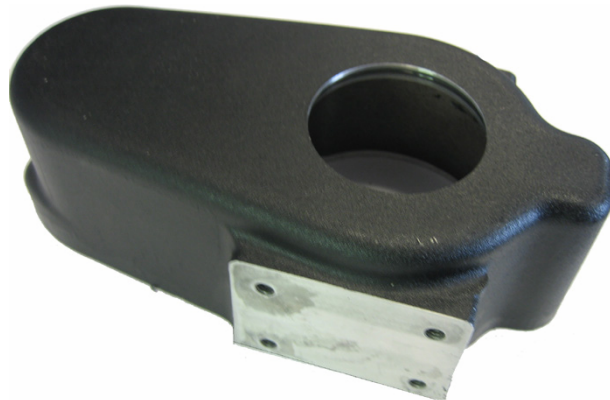
As previously noted, the original gear train had three additional gears that were not necessary for the functions of the prototype. The original gearbox was designed to hold these gears as well, but because of their location, if the gearbox was placed between the wheel and the frame with the existing housing, the wheel would have been pushed out another four inches from the frame. This would have been unacceptable because it would have increased the overall size of the wheelchair.

The first design originally involved an entirely new gearbox design that optimized the size and shape of the gearbox (Figure 40). The motor's location was rotated so that it was no longer inline with the middle and final gear. By rotating the motor, the gearbox housing had to be angled to accommodate the new position. The angle was made to bring the end of the gearbox closer to the wheelchair frame so that a second frame mounting feature could be included. This move would also have created more room for the controls and power system to be mounted inside the frame. Particular attention was paid to the location of the bearing bores because they effectively aligned the gears. A CMM (Coordinate Measuring Machine) was used to find the precise distances between the bores on the original gearbox as well as depths of the bores from the adjoining surfaces of the base and cover. Unfortunately, after fully designing the new gearbox and preparing it for manufacturing, it was found that the machining costs would have been too high for the scope of the project, and this design was put aside for possible future work.



**Figure 40 - Initial Gearbox Redesign**

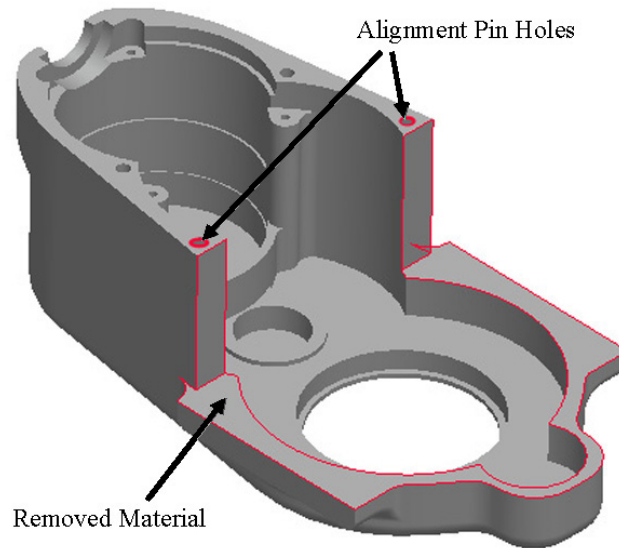
To remedy this situation, the existing gearbox (Figure 41) was instead modified to fit the new gear train setup. The first step of modifying the gearbox was to map out the new configuration of the gear train and determine how the gears would best be seated within the existing gearbox. It was important to ensure that the gears would still be properly aligned after any modifications. The CMM measurements were used to model the gearbox in Pro/E so that during machining, proper alignment features could be dialed into the CNC (Computer Numerically Controlled) machines.



**Figure 41 - Original Gearbox Base**

The gearbox base was first analyzed to determine where modifications could be made to remove the void created by removing the three unneeded gears. With only the single 84-tooth gear acting at the end of the gear train, the gearbox housing only had to accommodate the length of this gear. To accomplish this, the walls of the gearbox base were shortened around the final gear (Figure 42). By lowering a portion of the gearbox

walls, the need was created for two separate gearbox covers as opposed to one. These covers will be referred to as the upper and lower covers in the following sections.

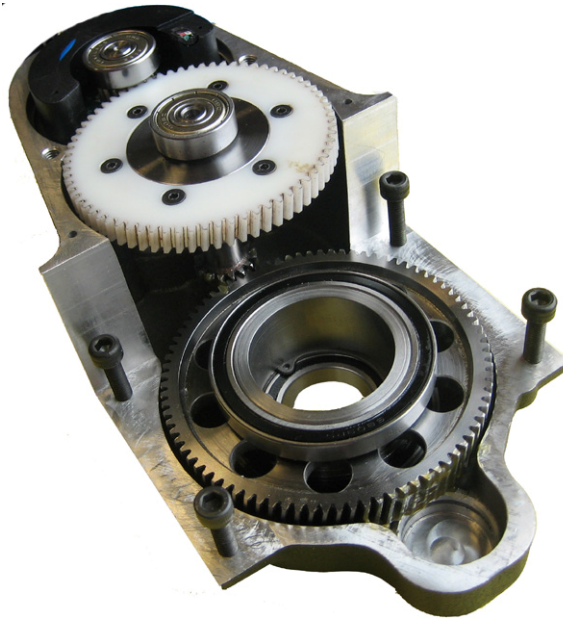


**Figure 42 - Final Modified Gearbox**

The location of the cut in the gearbox base was carefully made because of three different factors. The first factor was the location of the plastic/metal gear axle's bearing bore on the upper cover. Enough material had to remain after the cut to properly support the upper cover. The second factor was the lower gearbox cover. The lower portion of the gearbox base had to retain a specific geometry to ensure the final gear's bearing bore would be properly supported. Since the lower gearbox cover was inset in the gearbox base, the base had to be machined down to where the cover was positioned, which removed a portion of the supporting surface for the upper cover. The third factor was the location of the alignment pin holes. The most favorable location for the pins was as far distal from the existing alignment feature. Due to the gearbox base geometry, the location of the pin holes was also limited due to the wall thickness. The wall tapered out between the plastic/metal gear axis and the final gear axis on both sides, creating an optimal location for the pins.

Originally, the vertical cut was modeled to allow for excessive room for the lower gearbox (closer to the middle gear axle than the final gear). The purpose of this was to allow the lower cover to be designed oversized to provide ample space for creating alignment features. However, it was discovered when modeling in the alignment holes for

the upper cover that allowing this extra room removed the tapered section of the wall where the pins needed to be placed. The cut in the base was rethought and eventually designed in an optimal position so that the alignment holes could be drilled in the tapered section and so that adequate room was reserved for the lower gearbox cover.



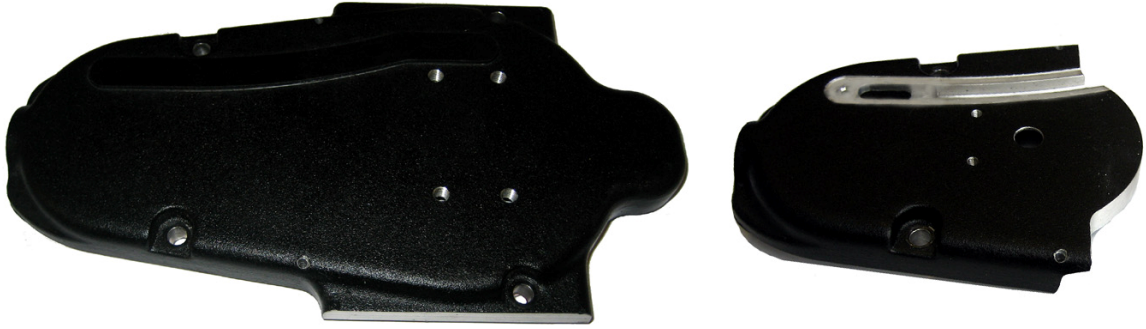
**Figure 43 - Final Gearbox Base**

#### **4.2.3.1.3.1 Upper Gearbox Cover**

The upper gearbox cover has two primary functions. The first function is to hold and align the rotor and the plastic/metal axles. The second function is to secure and align the encoder that tracks the wheel position.

To properly fit the cover to the gearbox base, the cover had to be cut to align with the modified housing walls. After evaluating the effect of cutting off a portion of the cover, it was determined that an additional method of alignment needed to be incorporated into the cover. The cover's original alignment was accomplished via two different alignment protrusions that tightly fit into the gearbox base when pressed together. Both protrusions were round, which was effective since there were two of them, leaving only one degree of freedom. By bolting the cover down, the cover was reduced to zero degrees of freedom. However, when the cover was cut between the protrusions, only one alignment feature was left, allowing the cover to rotate creating two degrees of freedom. To remedy this situation, two alignment pin holes were drilled into the cover

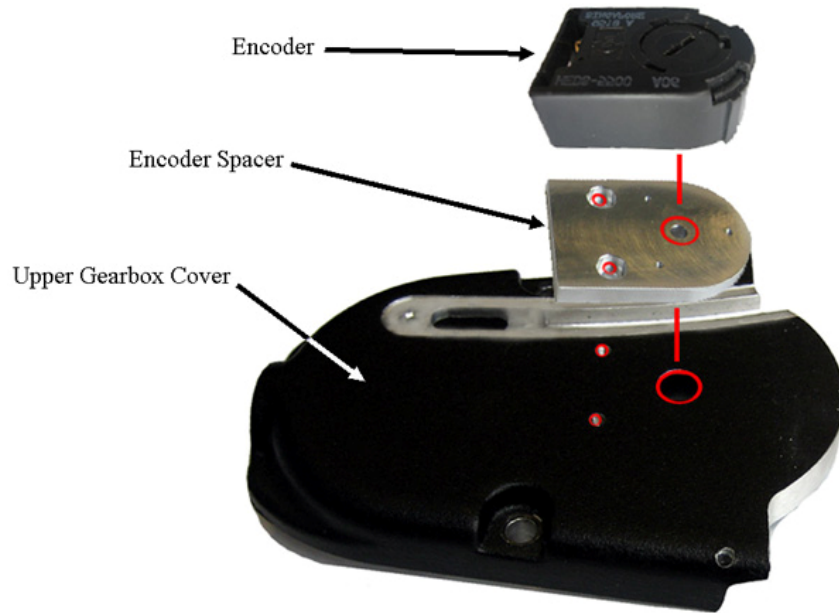
and base prior to modifications to ensure alignment. The holes were drilled as far distal from the existing alignment feature to reduce the stress on the pins. The cover was then cut between the plastic/metal and final gear bearing bores to match the base profile (Figure 44b).



**Figure 44 - Upper Gearbox Cover**  
([a] before and [b] after modifications)

The second function of the upper gearbox cover is to provide a mounting and alignment feature for the motor-side encoder. The encoder mount was designed to interface with the middle gear axle (plastic/metal) Mounting the encoder to the middle gear axle effectively increased the precision of the encoder. In addition, the gearbox provided an excellent interface for the encoder since the gear axles were already properly constrained. The gear ratio of the final gear to the middle gear axle of 1:5.25 provided additional precision to the encoder. As discussed in Section 4.1.1, the chosen encoders have a precision specification of 2000 CPR. With a 1:5.25 ratio, the precision was increased to 10500 CPR, which far exceeded the required precision calculated in the Methods section.

To attach the encoder, an encoder spacer was designed to space the encoder away from the cover while maintaining its position coaxially. The spacer was made so that the encoder's alignment screws would not encroach on the cover's bearing bore. A hole was drilled into the cover for the encoder axle to pass through. A second hole was drilled into the plastic/metal gear axle to provide a press fit attachment point for the encoder axle.



**Figure 45 - Gearbox Encoder Mount**

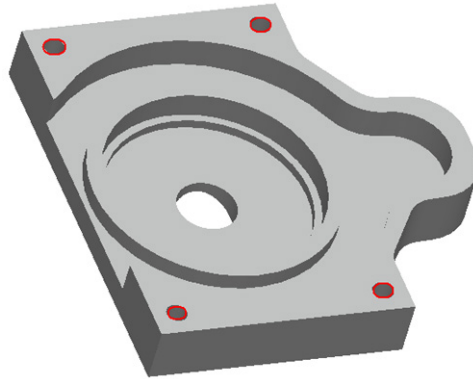
#### **4.2.3.1.3.2 Lower Gearbox Cover**

A new lower gearbox cover was designed to accomplish two main functions. The first function is gear alignment; however, in this case only one gear axle required alignment as opposed to the two in the upper cover. The second function is to provide a method of mounting to the wheelchair frame.

Alignment of the gear was a little more difficult because after machining the gearbox base, the existing alignment feature was removed. Instead, alignment pins had to replace this feature. The problem was that the alignment holes could not be drilled prior to taking apart the gearbox, as was the case for the upper cover. The housing was cast, so only precision machined features could be used for alignment. While the pin holes could have been machined during housing modifications, obtaining the desired precision in the x-y axes of the machined surface would have been difficult since the only alignment features remaining after modifications were the bearing axes. Instead, for prototype purposes it was decided to drill the alignment pins after assembling the final gear into the gearbox (with no other gears). By using this method, the final gear could be spun freely, allowing the cover to align naturally, and then bolted down to allow the pin holes to be



drilled simultaneously in the base and lower cover. The bolt holes in the cover were slightly oversized to allow for proper positioning.



**Figure 46 - Lower Gearbox Cover Alignment Holes**

Mounting the gearbox to the frame was a more difficult task. The gearbox had to fit as close to the frame as possible to allow the motor-driven wheel to remain close to the frame. With the modifications made to the base, final gear, and the cover, the gearbox could be successfully placed within the space between the wheel and the frame; however, the method of mounting to the frame had yet to be designed.

#### ***4.2.3.1.4 Gearbox Mount***

The gearbox was mounted using newly designed clamps that were longer than the existing clamps, which effectively spread the clamping forces further over the surface area of the frame. The clamping piece on the motor side of the frame was designed directly into the lower gearbox cover, creating a solid mounting piece that also helped to align the wheel axle with the gearbox. The clamping piece that interfaced with the cover was manufactured as a standalone piece.

The clamps were designed to mount to the frame the same way the original clamps were by inserting the threaded axle holder through both clamps and clamping the pieces together with two nuts. To provide an even more robust hold, four additional clamping bolt features were designed into the corners of the clamps.

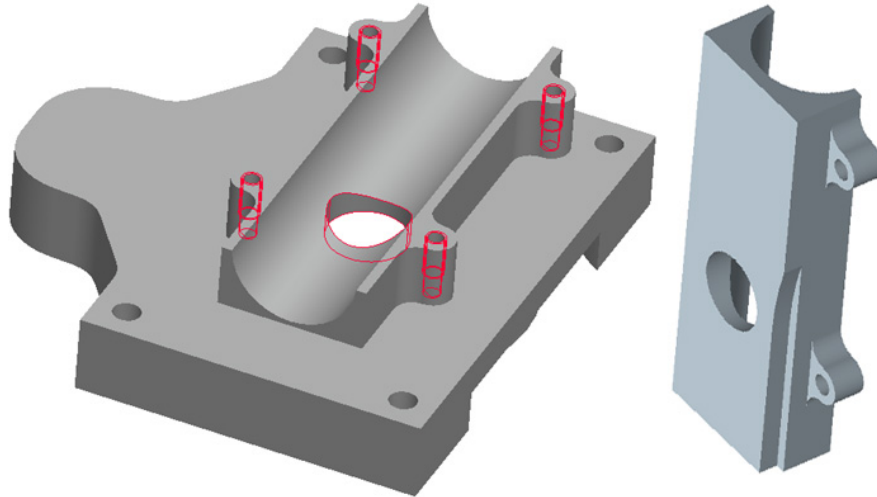


Figure 47 - Redesigned Clamping Feature

### 4.2.3.2 Wheel and Axle Interface

The interface between the gearbox and the wheel was carefully designed to ensure that the passive method of mounting the wheel to the wheelchair frame did not affect the alignment between them (Figure 48). In the original gearbox, alignment was not of concern since the gearbox supported the wheel. If the wheel moved, so did the gearbox. To properly constrain the wheel and the gearbox, the following design features were incorporated into the chair.

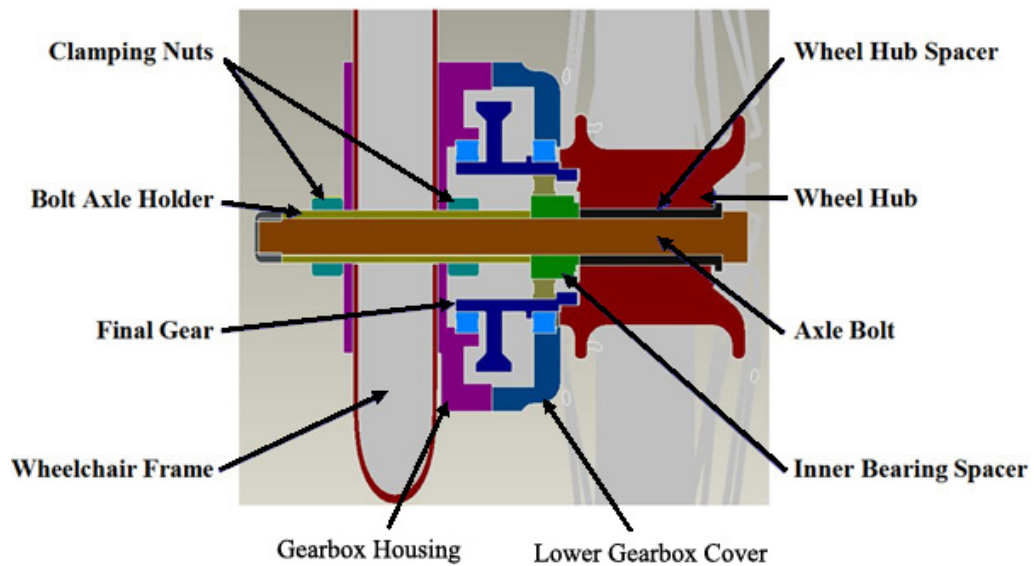
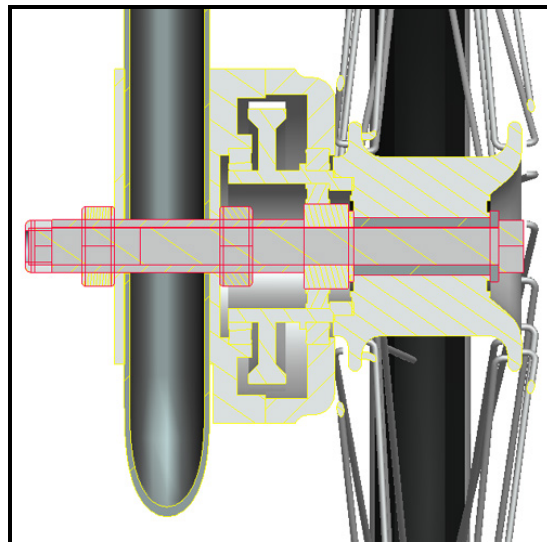


Figure 48 - Cross Section of Motor-Side Wheel Interface

The existing power-assist wheel had two inset ball bearings placed in the hub to permit rotation about an axle. The inner races of the bearings however were larger than the bearings found in the manual wheelchair wheels. The power-assist wheel axles were oversized (17mm) because they were made to rotate with the push rim and thus needed to handle cyclical loads. The majority of manual wheelchair wheels use a statically placed bolt to act as the wheel axle that most commonly has a diameter less than half an inch (12.7mm). The larger bearings were actually used as an advantage because it meant that most manual wheelchairs could use the power-assist wheels without having to use a modified shaft. Instead, a spacer could be used to accommodate the diameter differences based on the size of the axle. This was an important feature that helped make the design modular.

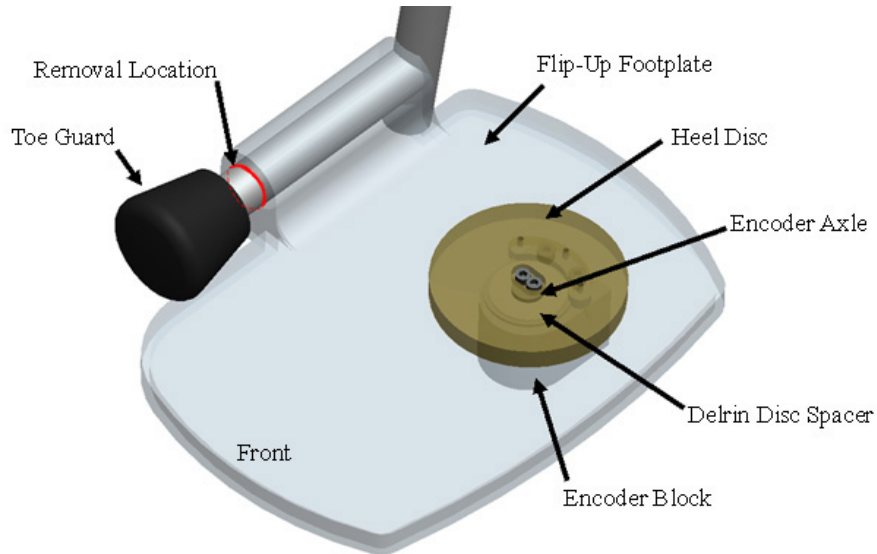
For the prototype, the spacer was designed to fit around the existing 11mm bolt. To help maintain the alignment of the wheel axle and the final gear, an additional ball bearing was placed in the inner bore of the final gear. A second spacer was designed to insert into the bearing that the wheel axle slides through. The length of the spacer was designed so that it would fit between the axle bolt holder and the wheel hub spacer. With the two spacers in place, the bolt could be tightened to press the spacers and the axle bolt holder together restraining any axial movement (Figure 49). The wheel hub was allowed to float slightly in the axial direction between the spacers to permit unconstrained wheel rotation.



**Figure 49 - Wheel Spacer Cross Sections**

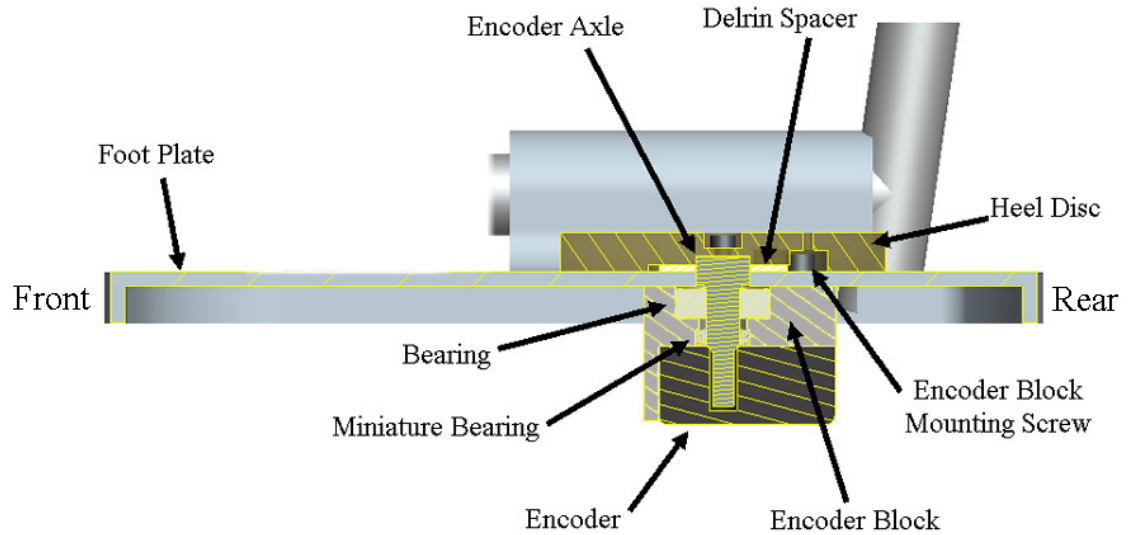
#### 4.2.4 Steering Interface

The steering interface was designed to interact the user's foot and attaches to the Everest & Jennings leg rest (Figure 50). A heel disc tracks angular position through a third HP encoder. As the user abducts and adducts their foot, the friction between their heel and the disc causes the interface to rotate. Attached to the disc is an encoder axle that passes through the footplate and into an encoder block consisting of two bearings.



**Figure 50 - Steering Interface Assembly**

The flip-up footplates on the leg rests had toe guards to limit ankle rotation that restricted where the steering interface's axis of rotation could be placed. To compensate, the toe guard was removed and the interface axis was slightly offset from the center of the footplate. While it was not desirable to move the intended foot position, for prototype purposes this was acceptable. An encoder block was designed to attach to the bottom of the footplate (Figure 51).

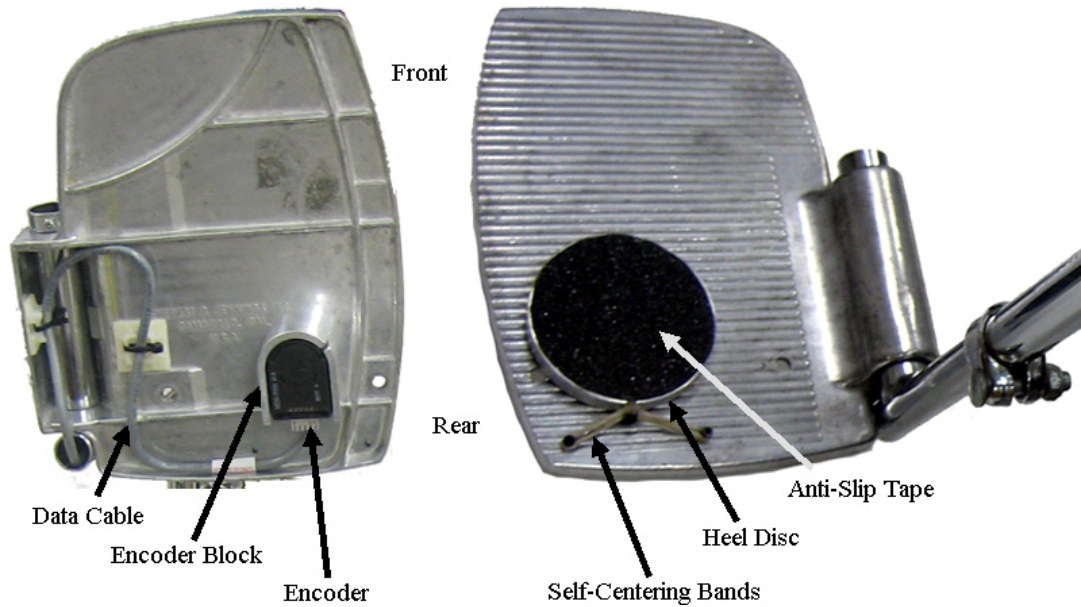


**Figure 51 - Steering Interface Cross Section**

The disc is attached to the encoder axle through two socket head cap screws and is supported by both bearings in the encoder block. Between the disc and the footplate is a thin piece of Delrin to allow the disc to rotate easily. Anti-slip tape was attached to the heel contact surface to prevent slipping. The heel interface is effective because it also allows the front of the foot to remain in contact with the footplate to help maintain steering position. A slot was machined into the underside of the disc to fit the mounting screws for the encoder block. This slot was cut to double as a mechanical stop. As the disc rotates, the ends of the slot contact the bearing block screws and prohibit further rotation. Self-centering is accomplished through two pre-loaded elastic bands mounted rear of the disc (Figure 52).

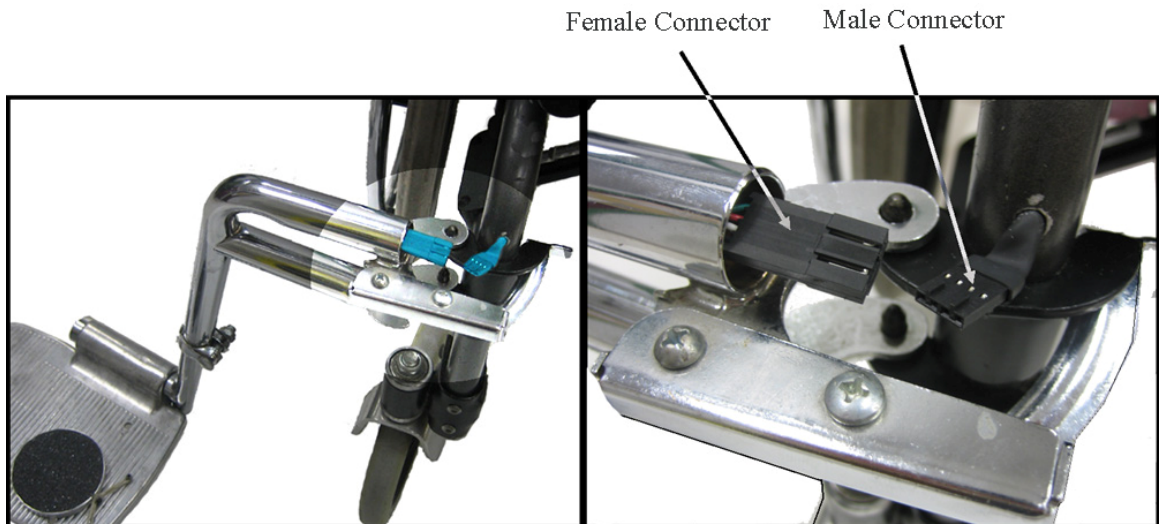
### Underside of Steering Interface

### Top of Steering Interface



**Figure 52 - Steering Interface Views**

The steering interface wiring was routed through the leg rest and into the frame to the controls system. A connector was placed between the leg rest and the frame of the chair to allow the wiring to be disconnected for removal of the leg rest (Figure 53). The swing away feature was utilized to hide the wiring when locked in place.



**Figure 53 - Legrest Wiring Connection**

## 4.2.5 Controls Component Mounting and Wiring

Mounting the controls system to the wheelchair frame was not feasible due to the size of the components. While the shape and size of the individual amplifier and battery pack made them well-suited for attachment to the wheelchair frame, the PC/104 stack was not sized well for mounting to the frame due to its boxy shape.

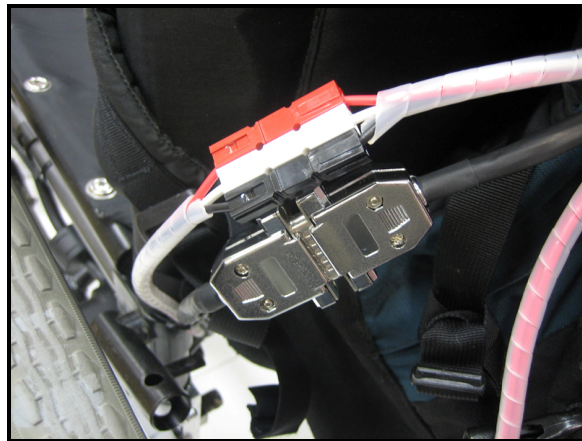
For prototype purposes, it was decided to mount the controls system in a detachable backpack that drapes over the back of the wheelchair (Figure 54). Using the backpack allows the oversized components to be removed during wheelchair transport to offset the additional weight. In a production-ready model, optimized controls would be significantly smaller, lighter, and better suited to be attached permanently to the wheelchair frame.



**Figure 54 - Controls Backpack Mount**

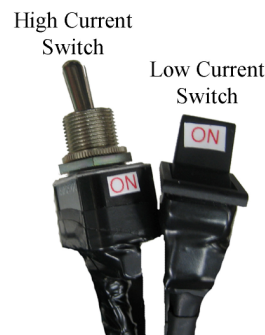
With all components in place, the wiring had to then be routed in a manner appropriate to its functionality. Of particular concern was the chair's ability to fold. With components located on both sides of the wheelchair, the wiring had to account for the changing gap depth between the drive wheels. To circumvent this, the wiring was routed along the folding joints in the x-frame so that the wiring path remained the same length during folding. Between the three encoders and the motor wiring, eleven data wires, eight

low voltage, and three high voltage wires had to be routed to the removable control pack. To accomplish this, the data and low voltage wires were routed into a 26-pin connector and the three high voltage wires were constrained in three side-by-side single interlocking Anderson connectors. These two main connectors were restrained along the wheelchair frame and connected to complimentary connectors emerging from the controls backpack (Figure 55).



**Figure 55 - Wiring Connectors**

Power was controlled by two on/off switches protruding through the controls backpack (Figure 56). Two power switches were required because of the startup properties of the PC/104 stack. When power is delivered to the stack, approximately twenty seconds is required to load up the controls program. During this time, a constant voltage leaks into the digital to analog converter which signals the amplifier to operate the motor. The two power switches allow the amplifier (high current switch) to be powered on separately from the PC/104 stack (low current switch) to allow enough time for the program to load.



**Figure 56 - Power Switches**



## **5 Testing and Analysis**

Testing was conducted on the finalized prototype to ensure the design integrity. Integrity was determined by how well the wheelchair met the design specifications. The tests performed were based on ISO 7176 and ANSI/RESNA WC standard testing sections that applied to power-assist wheelchairs. Controls testing was also conducted to assess the usability of the product based on driving performance characteristics.

Testing was performed with either a 250lb (113kg) ISO test dummy or a human occupant depending on the type of test. Weights were added to the occupant to reach the required 250lb weight to simulate a worst-case test scenario in all test scenarios. Prior to testing, the motor-side wheel was inflated to the recommended 90psi. Testing was performed at both DEKA Research & Development's ISO-approved testing laboratory in Manchester, NH, and WPI's Assistive Technology Research Center.

### ***5.1 Standards-Based Testing (ISO and ANSI/RESNA)***

Testing was performed based on the testing requirements mandated by ISO 7176 and ANSI/RESNA WC standards. While a prototype does not need to meet the majority of these requirements, it is advantageous to perform these tests to help prove design concept validity. Efficiency of further design iterations to obtain a production-ready model can be increased by determining possible deficiencies in the prototype early in the design iteration process. (ISO, 2003 and ANSI/RESNA, 1998)

#### **5.1.1 Determination of Static Stability (ISO 7176-1, ANSI/RESNA WC-1)**

To begin testing, the wheelchair was loaded with the 113kg ISO dummy to perform static stability testing. Stability testing was performed to ensure that the wheelchair could be proficiently operated in ADA-approved environments (ADA, 1994). An adjustable ramp was used to test the wheelchair's performance at different angles. Stability was considered compromised when any of the wheels lifted from the test plane.

While this testing is normally performed with the brakes on, manual wheel locks were not available at the time of testing. To simulate the brakes, a stop block was used to

stop the wheelchair from translating. When facing uphill, the stop block allowed the chair frame to rotate about the rear wheel axis with brakes on, the chair would tip at a somewhat smaller angle since the entire chair would rotate about the point of contact with the test plane instead of the rear wheel axis. Stability tests facing downhill and sideways were performed exactly as per ISO standards. As predetermined in the task specifications, the minimum stability angle was 10°. This angle was arbitrarily chosen based on prior wheelchair testing knowledge.

The chair was positioned in three different orientations (Figure 57). The first orientation was facing uphill with the casters trailing downhill. The ramp was raised until wheel lift was detected. In this orientation, the chair remained stable up to 14.1°,



**Figure 57 - Static Stability Test Setups**

The second orientation was facing downhill with the casters trailing uphill. No wheel lift was detected up to 15° and testing was stopped for safety purposes. At 15°, the wheelchair far exceeded the 10° requirement.

The final orientation was facing sideways on the slope with the wheels trailing downhill. The ramp was also raised to 15° without wheel lift detection and testing was stopped. The testing results are displayed in Table 3.

**Table 3 - Static Stability Test Results**

<b>ORIENTATION</b>	<b>TASK SPECIFICATION</b>	<b>ACTUAL ANGLE</b>	<b>PASS/FAIL</b>
Facing Uphill	$\geq 10^\circ$	14.1°	Pass
Facing Downhill		$> 15.0^\circ$	Pass
Facing Sideways		$> 15.0^\circ$	Pass

### 5.1.2 Determination of the Effectiveness of Brakes (ISO 7176-3, A/R WC-3)

Brake testing was performed to ensure that the wheelchair could hold position on an incline. Brake distance testing was not performed because braking depended on the strength of the individual user. Even if the motor was not strong enough to brake within an acceptable distance, if the hand-driven wheel was stopped by the user, the chair would simply rotate about the stopped wheel. If the user was not strong enough to stop the hand-driven wheel, then the rotation of the hand-driven wheel would cause the motor-driven wheel to continue rotating to maintain synchronicity between the wheels.

Holding position was however determined to ensure that the wheelchair could maintain position on a slope when stopped. To perform this test, the wheelchair and 250lb test dummy were placed on an adjustable ramp (Figure 58). The hand-driven wheel was restrained to simulate the user holding the wheel in place. The ramp was then raised until the motor-wheel could no longer maintain position. The wheelchair had to hold position for at least five seconds. Since the motor amplifier allows peak current to the motor to be applied for a two-second period before the amplifier drops the maximum amperage output to 50%, the minimum five seconds of holding time was necessary to accurately portray holding capabilities.



Figure 58 - Brake Holding Test Setup

The wheelchair was tested both facing uphill and downhill. The test was run twice, once immediately after power-on, and once after five minutes of driving to heat up the motor (Table 4).

**Table 4 - Brake Holding Test Results**

<b>ORIENTATION</b>	<b>MOTOR TEMP.</b>	<b>TASK SPECIFICATION</b>	<b>ACTUAL ANGLE</b>	<b>PASS/FAIL</b>
Facing Uphill	Cool	$\geq 8^\circ$	10.5°	Pass
	Hot		10.5°	Pass
Facing Downhill	Cool		10.2°	Pass
	Hot		9.9°	Pass

### **5.1.3 Determination of Dynamic Stability (ISO 7176-2, A/R WC-2)**

Dynamic stability testing was performed to ensure that the wheelchair could travel safely on flat and inclined ground. Due to the mimicking nature of the motor, straight line stability testing was not performed. Wheelchair users can effectively accelerate the chair fast enough to raise the front casters to balance themselves on the two rear wheels. Since the motor applies a responsive torque, the acceleration is limited by the user’s input. Instead, the wheelchair was tested on slopes while turning to ensure stability in the lateral directions.

The test setup involved positioning the wheelchair at the top of a 15 meter adjustable test ramp facing downhill. A human occupant was used because of the user interaction required to maneuver the wheelchair. The wheelchair was then propelled forward and a turn was executed at as close to maximum speed as the occupant could attain. Maximum speed was rated at 6.2mph as determined by the drive system specification analysis performed in the Methods Section. The test was performed using both left and right turns on incrementally increasing ramp angles (Table 5). To be considered stable, three of the four wheelchair wheels had to remain on the plane.

**Table 5 - Dynamic Stability Test Results**

<b>RAMP ANGLE</b>	<b>TURN DIRECTION</b>	<b>EXPECTED RESULTS</b>	<b>ACTUAL RESULTS MATCH EXPECTED RESULTS? (Y/N)</b>	<b>PASS/FAIL</b>
0°	Left	At least 3 wheels remained on test plane	Yes	Pass
	Right		Yes	
3°	Left		Yes	Pass
	Right		Yes	
5°	Left		Yes	Pass
	Right		Yes	
8°	Left		Yes	Pass
	Right		Yes	

**5.1.4 Determination of Obstacle-Climbing Ability (ISO 7176-10, A/R WC-10)**

Obstacle traversal testing was performed to ensure that the wheelchair could travel over environmental obstacles that would commonly be encountered while driving. Examples of such obstacles are door thresholds and weathered outdoor surfaces. Testing was dependent on the user’s strength, because the hand-driven wheel requires user propulsion for that wheel. If the user could not propel a single wheel over a given obstacle, then the obstacle would not be traversable anyway. For the testing, the chair was tested until either the occupant could not propel the hand-driven wheel over an obstacle or the motor could not propel the motor-side wheel over an obstacle.

The test setup involved a human occupant loaded into the wheelchair on a level test plane. Wooden sheets with minimal edge radii were placed successively on the test plane to simulate increasing obstacle heights and the chair was then commanded to drive over the obstacle. This test required a small level of technique to propel the casters over large obstacle heights. The technique involves a quick acceleration just prior to reaching the obstacle to assist in raising the casters off the ground to clear the obstacle (two-handed wheelchair users normally use this technique when maneuvering over obstacles as well). Once the caster wheels were positioned on top of the obstacle, two methods of testing were performed. The first method allowed no run up to traverse the obstacle. The rear drive wheels were positioned flush with the obstacle, and the occupant attempted to climb the obstacle. The second method involved using run up for traversal and was only

used if the wheelchair could not climb a given obstacle height with no run up. In this method, once the casters were on top of the obstacle, the occupant accelerated prior to the rear wheels reaching the obstacle to allow momentum to assist in climbing the obstacle.

The minimum obstacle height that was required of the chair was a half inch. The obstacle heights were increased in increments of 0.25in (63.5mm) until the test was completed. Testing showed that the wheelchair could successfully traverse the required obstacle height and was continued until the maximum obstacle height was reached. Final results indicate that the wheelchair is able to traverse obstacles up to 0.75in with no run up, and 2.00in (50.8mm) with run up. The wheelchair was not able to traverse obstacles greater than these maximum heights due to the inability of the motor to propel the motor-side wheel over the obstacle after the hand-driven wheel had already traversed the obstacle (Table 6).

**Table 6 - Obstacle Traversal Test Results**

<b>OBSTACLE HEIGHT (IN)</b>	<b>TRAVERSAL DIRECTION</b>	<b>EXPECTED RESULTS</b>	<b>ACTUAL MATCH EXPECTED (Y/N)</b>	<b>PASS/FAIL</b>
0.25	Forwad (No Run Up)	Able to Traverse	Yes	Pass
	Backward (No Run Up)		Yes	Pass
0.50	Forwad (No Run Up)		Yes	Pass
	Backward (No Run Up)		Yes	Pass

<b>OBSTACLE HEIGHT</b>	<b>TRAVERSAL DIRECTION</b>	<b>EXPECTED RESULTS</b>	<b>OBSTACLE HEIGHT (in)</b>	<b>PASS/FAIL</b>
Maximum Height	Forward (No Run Up)	N/A	0.75	N/A
	Forward (Run Up)		2.00	

The wheelchair was also tested on various types of surfaces to ensure it could operate on commonly encountered terrains. Terrain types included high pile carpet, brick, concrete, tile, and dirt. The wheelchair was effectively able to traverse these surfaces. Testing of the wheelchair on extreme terrains, such as ice, mud, and loose gravel was not conducted due to the intended scope of the prototype. However, this testing would have to be performed on a production-ready model.

### **5.1.5 Dimensions, Mass, & Turning Space (ISO 7176-5, A/R WC-05)**

The dimensions, weight, and required turning space were analyzed to determine how the additional components affected the wheelchair prior to modifications. Dimensional analysis was performed only in areas where the components were added. These include the motor/wheel setup on the motor-driven side of the wheelchair, the pulley/encoder setup on the hand-driven side of the wheelchair, and the steering interface setup on the hand-driven side footplate.

The overall height of the wheelchair was not affected since the new wheel on the motor-side was exactly the same circumference as the existing wheel. Height was however changed locally at the footplate. The addition of the encoder block decreased ground clearance by 0.75in based on the fixed location of the existing footrest. This measurement was calculated by taking the difference between the minimum distance from the ground to the footplate (3.25in) and the minimum distance from the ground to the encoder block (2.50in).

The overall length of the chair also was not altered by the modifications. While the backpack would not be utilized in a production-ready model, it still remained within the footprint of the wheelchair since the driven wheels protruded behind the backpack. With the leg rests attached, the total length of the wheelchair remained at 46in from the rear of the back wheels to the tip of the front footplate.

The distance between the rear wheels was increased since the motor-side wheel is located 0.6in further away from the wheelchair frame than the original wheel; however, since the push rim was removed from the motor-side wheel, the overall width of the wheelchair remained the same (23.5in). Maneuverability was not effected by this change; however, additional stability was acquired since the ground contact area of the wheels was spread further apart.

Folding interference was also tested to ensure that components would not restrict the wheelchair from properly folding. While interference was analyzed in Pro/Engineer prior to manufacturing, careful visual inspection confirmed that the components did not restrict folding in any way.

The components of the chair were weighed to determine how the modifications affected the overall chair weight. Prior to modifications, the wheelchair weighed twenty-

four pounds. With the addition of the mechanical components, six pounds was added to raise the wheelchair weight to thirty pounds. The controls system backpack added another eighteen pounds to the chair (motor amplifier, battery pack, and PC/104 stack), raising the total weight to 48 pounds. The additional weight of twenty four pounds exceeded the maximum component weight specification of twenty pounds. The additional weight can be justified however because four pounds can easily be removed from the PC/104 stack and amplifier by designing an optimized controls system. In addition, the gearbox can be reduced in weight as well by streamlining its design (possibly by pursuing the original gearbox design proposed in the Methods Section). Since the gearbox is no longer intended to provide wheel axle support, it potentially could be redesigned to lower its weight.

Turning space was determined by setting up adjustable parallel walls along a horizontal test plane (Figure 59). The object of the test was to determine the minimum width that the wheelchair could successfully turn 180 degrees without contacting the walls. The wheelchair was tested by an occupant both prior to and after modifications. The minimum turning space remained the same after wheelchair modifications (50 inches with the leg rests attached). The time required to perform this maneuver was increased, but the prototype was still able to match the two-handed maneuverability through the turning space.



**Figure 59 - Turning Space Test Setup**



The prototype does not allow turning the motor-driven wheel to turn while the hand-driven wheel is stationary. However the modified wheelchair can roughly perform the same maneuvers as a two-handed wheelchair since the prototype has the ability to pirouette. The pirouette feature also allowed the prototype to retain the same turning radius as the wheelchair prior to modifications.

### ***5.1.6 Other Testing***

Other standard wheelchair testing was not performed since the wheelchair is only a proof of concept model. Testing such as environmental testing (humidity, altitude, water ingress, etc.), electrical protection (electric shock discharge, over-voltage, reverse polarity, etc.), and range testing would however have to be performed on a production-ready model in order to pass FDA requirements.

## ***5.2 Controls System Testing***

Controls system testing was performed to ascertain a user perception of the driving performance of the prototype. This approach was necessary to determine the effectiveness of the controls program and any improvements that could be made in the future. It should be noted that for every test, the occupant performing the test had at least thirty minutes of driving experience. This driving experience was necessary to overcome the initial awkwardness commonly seen in first-time users due to the unfamiliarity with the prototype's performance.

### ***5.2.1 Straight-Line Driving Test***

The first of the tests involved driving the prototype along a straight-line. A thirty foot path was chosen on a horizontal test plane (a line between floor tiles), and a dry-erase marker was attached between the footplates along the centerline of the chair to record deviation of the wheelchair from the straight-line path. The marker was attached to a piece of metal that hung from a cross bar attached between the footplates. The dry-erase marker was attached to the hanging metal piece so that it extended down beyond the

ground. The metal piece was forced to rotate to accommodate the extra length of the marker, which in turn exerted a force on the marker to ensure a constant application on the floor during the test (Figure 60).



**Figure 60 - Straight-Line Marker Mount Test Fixture**

Three passes were made along the path and the maximum deviation was recorded. Each pass required that the wheelchair traveled at 3.5mph minimum (average estimated walking speed) to simulate the speed a user would be traveling in trafficked areas. To ascertain this speed, the time to traverse the path was recorded. The wheelchair had to complete this path within 5.84 seconds at as close to a constant rate as the occupant could control. The maximum deviation recorded in the three passes was 5.5in from the centerline.

### **5.2.2 Figure-Eight Obstacle Maneuvering Test**

The ability to maneuver around obstacles is a critical ability that wheelchairs require to be effective. A figure-eight test track was setup with two obstacles spread 30in apart. The obstacles were low enough to the floor so that the footrests could pass over them. However, all of the wheelchair wheels were required to pass through the obstacles. The goal of the obstacle course was to travel between the obstacles in a figure-eight pattern without contacting them but remaining as close to them as possible. The figure-eight path was traversed five times with four different wheelchairs: the prototype, a standard manual wheelchair, a dual-rim hemiplegic wheelchair, and a lever-arm hemiplegic wheelchair. At least thirty minutes of driving experience was required for

each wheelchair before the test was performed. The five times were recorded and then averaged to determine the amount of time each wheelchair took to complete the course.

**Table 7 - Figure-Eight Test Results**

<b>Wheelchair</b>	<b>Test Run #</b>	<b>Time(sec)</b>	<b>Average(sec)</b>
Hemiplegic Prototype	1	17	16.7
	2	20	
	3	16	
	4	14.5	
	5	16	
Two-Handed Manual	1	13	10.5
	2	10	
	3	9.5	
	4	9	
	5	11	
Dual-Rim Hemiplegic	1	35	33.8
	2	40.5	
	3	28.5	
	4	35	
	5	30	
Lever Arm Hemiplegic	1	48	46.9
	2	55	
	3	37.5	
	4	44	
	5	50	

The two-handed manual wheelchair clearly was the fastest maneuvering wheelchair; however, the hemiplegic prototype was a close second, undoubtedly performing better than the existing hemiplegic manual wheelchairs.

## 6 Discussion

The expectation of this project was that a prototype would be produced that would conceptually prove that an effective one arm power-assist wheelchair could be designed that exceeded the performance of current hemiplegic wheelchairs. These expectations were far exceeded as the finalized prototype performed exceedingly well in all aspects of the design specifications. Careful design and selection of controls and mechanical components combined to create a prototype that could meet the majority of wheelchair testing standards required for power-assisted add-on wheelchair systems.

The wheelchair prototype successfully allows a user to propel themselves with the same amount of exertion (or less) in their functioning arm as would be required by a two-hand operated manual wheelchair. The power-assist motor completely replaces the function of the affected arm and with the aid of the steering interface allows sufficient maneuverability. An added benefit is that the propulsion provided by the motor actually decreases the amount of strength needed to propel the wheelchair. As the motor-driven wheel propels the motor-side of the wheelchair, the tendency of the chair to drive in a straight line allows the user to use less exertion to continue driving in a straight path. This tendency is a result of the friction of the wheels on the ground. Turning on any two wheels that are oriented parallel to each other requires a level of “scrub steering” which refers to the scrubbing of the wheels across the contacting surface as they rotate along the normal axis to the ground.

Performance was the most important aspect of the prototype in proving the effectiveness of this design. Weight and dimension properties were also very important to the success of the prototype to show that it could easily be transported and maneuvered in tight spaces. Other tests normally performed on production-ready wheelchairs were not as important to the success of the prototype. These tests include electrical compliance and environmental testing.

The controls system was the most important feature of the prototype. Without a properly functioning controls system, all other components on the wheelchair would have been superfluous. The controls were the limiting factor in the overall design and thus had to be carefully generated. Using the PC/104 stack as the centralized control system was

extremely beneficial. The MATLAB software provided a means to conveniently design the controls structure. Real-time monitoring vastly reduced the development time and subsequently aided in optimization. The system provided an ideal setup for a prototype. However, for a production-ready model, the controls would have to be streamlined into a more compact and lower power consuming system.

Acquiring the power-assist gearbox was a critical turning point to the success of the prototype. The existing motor and gear train was already proven effective for wheelchair propulsion and with appropriate modifications was able to be redesigned for this application. Modifying the gearbox to fit between the wheel and the wheelchair frame allowed the dimensions of the wheelchair to remain unaltered. All components added to the wheelchair frame were designed to fit within the existing wheelchair footprint, which not only helped with dimension testing, but also with stability testing. The components added to the wheelchair to create the hemiplegic prototype were not only incorporated within the wheelchair's footprint, but they were also located in areas that were clear from interference during wheelchair folding.

The existing gearbox and wheelchair frame were rated for 250-pound users; however, testing had to be performed on the prototype because of all the modifications. Propulsion capabilities were tested on different inclines and successfully proved that the wheelchair could meet the desired specifications. Since the gearbox was originally designed to not only propel a wheelchair wheel, but also support it, the expected life span of the gearbox was increased by removing its function as the primary wheel support. Additional means of support, such as the bearing placed inside the final gear, only helped to sustain alignment between the wheel and the gearbox.

The original gearbox was designed to allow free rolling so that the power-assist function could be turned off for normal manual wheelchair operation. This feature was retained in the redesigned gearbox. Because of this, the wheelchair meets the requirement of being able to be pushed by an assistant when powered down. Manual wheel locks can be used to hold the chair's position on inclines when the chair is powered off and to assist in chair transfers.

Ease of wheel removal was an important design specification since transportation was of top concern. The ability to remove the wheels assists in stowing the wheelchair in

the trunk or backseat of a car. Creating a passive method of wheel mounting that allowed the motor-driven wheel axle to pass freely through the gearbox allowed the wheelchair frame to retain its existing method of wheel removal. The method of mounting the pulleys on the hand-driven side also suitably met this need.

The passive mounting features were also advantageous because the add-on components are more adaptable to different manual wheelchairs. Assembly on the motor-side involved fitting the gearbox over existing wheel shafts, which was a quick and easy procedure to perform. It is noted however, that to fit wheelchairs with different wheel mounting features (i.e. webbing or horizontal slider (Figure 14)), the gearbox would need to be modified with additional mounting interfaces to attach to these different frame styles.

While the goal of making the wheelchair modular required components to be attached to the chair with minimal wheelchair modifications, certain components did require some modifications to be made to the existing wheelchair. The steering interface required mounting holes to be drilled into the footplate. In addition, the wiring had to be routed up through the frame of the wheelchair to avoid possibilities of ensnarement and poor aesthetics. This internal wiring required additional effort to accomplish. Utilizing a wireless steering interface could resolve this issue, but could create additional problems. The issues of power management would become a safety concern since the interface would require a separate power supply. If the steering mechanism lost power during wheelchair operation, an adverse wheelchair response could result. Another modification was performed on the hand-driven side of the wheelchair. The encoder interface required accurate alignment with the wheel hub. To accomplish this, mounting holes were drilled into the wheel hub to attach the large pulley. While this was acceptable, multiple interfaces would have to be made available to fit different wheelchair models.

There is a significant learning curve required to operate the prototype effectively, however after becoming familiar with the controls concepts, ease of maneuverability is quickly increased. For example, the pirouette function of the wheelchair requires previous knowledge to understand how to utilize it correctly. The wheelchair user has to be driving at a very slow speed for the pirouette-based lookup table to be activated. Turning in the direction of the hand-driven wheel also requires practice and familiarity

with the controls program. When turning toward the hand-driven side, the hand-driven wheel signal is amplified by increasing the steering multiplier. The motor-side wheel correspondingly speeds up. If the hand-driven wheel is not actively controlled (slowed) during this turning maneuver, the acceleration of the motor-side wheel results in an increase of the hand-driven wheel speed as well, due to the tendency of the wheelchair to drive straight. If the motor-side wheel velocity is too great during turning, the wheelchair can continue to turn even after the hand-driven wheel and steering control is stopped. This potential problem for an individual client could be addressed by modifying the controls system functions.

Formal testing of the wheelchair helped prove the effectiveness of the prototype design. Stability testing adequately showed that the wheelchair exceeded the task specifications related to inclines. Five-degree ADA inclines are easily traversed by the prototype while safely maintaining stability and braking capabilities.

The prototype successfully demonstrated that it could maneuver through the same obstacles that two-handed manual wheelchairs can. The time to complete intricate maneuvers was over 50% slower than the two-hand operated wheelchair; however, in comparison to the other hemiplegic manual wheelchairs, the prototype performed the maneuvers in under half the time. With further iterations to the controls program, it is believed that this percentage could be significantly lowered. During straight-line driving and normal turning, the prototype can maneuver efficiently at speeds up to 6.2mph, which far exceeds the average walking speed (3.5mph). While 5.5in is a small amount of deviation, a more stable controls system could also improve the results of the straight-line driving test.

Overall, the compact size of the components coupled with low audible levels and smoothness of operation helps detract attention from its presence. When a wheelchair is less noticeable it blends into society better by reducing unwanted attention. To the majority of wheelchair users, these features will add to its appeal.

Final costs of building the prototype were calculated based on the actual cost of the components despite the fact that the majority of the components and machine time was donated by DEKA Research & Development. The controls system contributed to the

majority of the costs because of its extensive, advanced capabilities. A breakdown of the costs can be viewed in Appendix C.



## 7 Conclusions

A hemiplegic power-assist wheelchair prototype that effectively meets the various transportation needs of individuals with hemiplegia has been designed, manufactured, and tested. Intricate design detail and execution resulted in a visually simplistic design that promotes low cost and low maintenance. The modular aspect of the components allows the system to be retrofit to most manual wheelchairs with only minimal modifications.

The main goal of replacing power lost by a user's affected arm while maintaining maneuverability and transportability was successfully achieved. The prototype retains the folding capabilities and overall dimensions of the existing wheelchair and therefore maintains its ability to be transported in the trunk or backseat of a full sized car. An unexpected result of motorizing one side of the wheelchair was that the effort required by the non-affected arm to provide propulsion was favorably reduced.

Formal and subjective testing was performed on the completed prototype to determine design validity. Testing methods were developed from ISO and ANSI/RESNA standard testing procedures to determine static and dynamic stability, effectiveness of brakes, obstacle climbing ability, mass and dimensions, and required turning space. Additional qualitative tests were conducted to subjectively test the controls system performance. Testing results met and exceeded the task specifications and proved to perform better than the leading types of existing hemiplegic wheelchairs.

Identified possible deficiencies of the prototype include the need for significant training to master propulsion techniques as well the use of a somewhat rudimentary controls theory. Both of these potential issues can be successfully overcome by implementing a more advanced controls structure. Focus would be put on smoothing out the response of the motor-driven wheel to reduce motor lag, overcompensation, and windup.

In comparison with the existing dual-rim and lever-arm hemiplegic wheelchairs, the prototype clearly excels in maneuverability and lowers required arm strength. Based on the extensive population of individuals with varying forms of hemiplegia, the potential for this product to deliver increased freedom to a significant consumer base is prominent.

There are no mobility devices currently available for individuals with hemiplegia that approach the level of usability that this prototype successfully demonstrates.

## 8 Future Recommendations

Additional improvements to the current prototype were identified for future research and development. These steps would have to be taken to continue the progression of the prototype to a final product.

The controls system needs to be optimized. A strong controls base was developed during the development of this prototype, but a significant improvements would need to be made to increase the efficiency, safety, and overall performance of the controls system. Once the controls system was optimized, it could be easily integrated into a smaller and more efficient microprocessor, thus removing the excessively large and powerful PC/104 processor. The individual multi-input I/O boards could also be removed and replaced with a single I/O board that was designed to handle only the required inputs and outputs. An ideal amplifier should also be built into this controls board. Together, these changes would not only reduce the size and weight of the controls system, but also ultimately reduce the costs once the initial research and development costs were recouped.

The gearbox used on the prototype is over designed for this application since it was designed to fully support the wheel axle. Therefore, the gearbox could be redesigned to reduce the size, weight, and costs. The gearbox interface with the wheelchair frame would also have to be further researched to develop the necessary interface options for mounting to different wheelchair frames.

Improvement to the hand-driven components could proceed in one of two ways. The first option would be to design a shroud for the pulleys and belt to isolate them from the environment. The second option would be to redesign the interface with the wheel to circumvent the need for the pulley system. Perhaps an optical sensor or axle mounted encoder that could be attached more easily to the wheel hub would achieve this.

The steering interface could benefit from the usage of a smaller encoder, or another form of position sensor (potentiometer, strain gauge, etc.) to both reduce the space occupied by the sensor and to optimize the overall steering performance. Additional designs should also be developed for locating the steering interface in different positions as described in the Methods Section.

In a production prototype, the wiring of the system would also need to be redesigned to minimize cost and material. It is important to note that the electronics would need to be designed to meet the extensive safety requirements mandated by ISO and ANSI/RESNA Testing Standards.

Lastly, the finalized production prototype would need to undergo extensive additional testing to successfully pass the wide-ranging power-assist wheelchair requirements. Testing would need to be performed with all ISO or ANSI/RESNA approved test equipment/fixtures and meticulously documented to provide sufficient proof that the wheelchair met all requirements.

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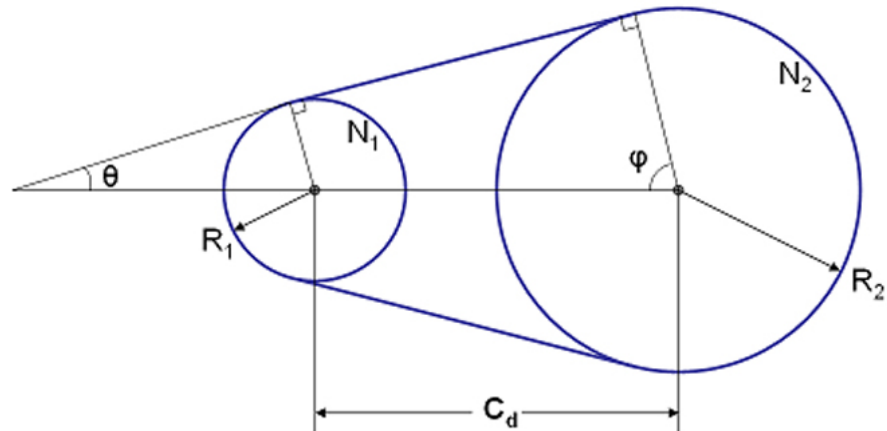
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## Appendix A – Calculations

### Center Distance and Belt Length



#### Belt and Pulley Specifications

$p := 2.5\text{mm}$	Pitch
$N_1 := 16$	Number of grooves (first pulley)
$N_2 := 84$	Number of grooves (second pulley)
$C_d := 75\text{mm}$	Desired center distance between pulleys (based on the available frame space)

#### Initial Calculations

$R_1 := N_1 \cdot \left( \frac{p}{2\pi} \right)$	Radius of first pulley
$R_1 = 6.366\text{ mm}$	
$R_2 := N_2 \cdot \left( \frac{p}{2\pi} \right)$	Radius of second pulley
$R_2 = 33.423\text{ mm}$	
$\phi := \arccos\left( \frac{R_1 - R_2}{C_d} \right)$	Angle between center line and radial line tangent to belt
$\phi = 1.94 \text{ (radians)}$	
$\theta := \frac{\pi}{2} - \phi$	Angle between belt and center line
$\theta = -0.369 \text{ (radians)}$	

Number of Teeth on Belt Calculation

$$NB := \left[ \frac{(N_1 + N_2)}{2} \right] + \left[ \frac{(N_1 - N_2)}{\pi} \right] \cdot \text{asin} \left[ \frac{(N_1 - N_2) \cdot p}{2 \cdot \pi \cdot C_d} \right] + \sqrt{\left( \frac{2 \cdot C_d}{p} \right)^2 - \left( \frac{N_1 - N_2}{\pi} \right)^2}$$

$$NB = 113.948$$

$$NB_a := 114 \quad \text{Actual Belt Length (based on availability)}$$

$$L := p \cdot NB_a \quad \text{Length of belt}$$

$$L = 285 \text{ mm}$$

Actual Center Distance Calculation

$$AC_d := \frac{[L - \pi \cdot (R_1 + R_2) - (\pi - 2 \cdot \phi) \cdot (R_1 - R_2)]}{2 \cdot \sin(\phi)}$$

$$AC_d = 75.069 \text{ mm} \quad \text{Actual center distance to place pulleys apart}$$

Number of Teeth on First Pulley Meshing with Belt

$$N_{tm} := N_1 \cdot \left[ 5 - \frac{[2 \cdot (R_2 - R_1)]}{2 \cdot \pi \cdot AC_d} \right]$$

$$N_{tm} = 6.164 \quad \text{6 teeth in mesh (the minimum recommended for a pulley system)}$$



## Motor Torque Requirement

Determining the theoretical max load torque needed to maintain position on an 8 degree slope

$$w_u := 250\text{ lbf} \quad w_u = 1.112 \times 10^3 \text{ N} \quad \text{Weight of max user}$$

$$w_w := 40\text{ lbf} \quad w_w = 177.929 \text{ N} \quad \text{Weight of manual wheelchair}$$

$$w_t := w_u + w_w \quad \text{Total weight of user and wheelchair}$$

$$w_t = 1.29 \times 10^3 \text{ N}$$

$$\theta := 8\text{ deg} \quad \text{Angle of max slope}$$

$$\mu := .1 \quad \text{Friction coefficient (estimated bearing friction in wheels)}$$

$$F_f := \mu \cdot w_t \cdot \sin(\theta)$$

$$F_f = 17.953 \text{ N} \quad F_f = 4.036\text{ lbf} \quad \text{Force due to friction}$$

$$F := w_t \cdot \sin(\theta) + F_f \quad \text{Force needed to hold position on slope}$$

$$F = 197.484 \text{ N} \quad F = 44.396\text{ lbf}$$

$$F_{pr} := \frac{F}{2} \quad \text{Force per pushrim}$$

$$F_{pr} = 98.742 \text{ N} \quad F_{pr} = 22.198\text{ lbf}$$

Tangential force required to hold a 250lb wheelchair user's position on an 8 deg slope is approximately 22 lbs.

$$d := 1\text{ ft} \quad d = 0.305 \text{ m} \quad \text{Radial distance from axle to pushrim (ft)}$$

$$T_{pr} := F_{pr} \cdot d \quad \text{Torque required for individual drive wheels}$$

$$T_{pr} = 30.097 \text{ N}\cdot\text{m} \quad T_{pr} = 22.198\text{ ft}\cdot\text{lbf}$$

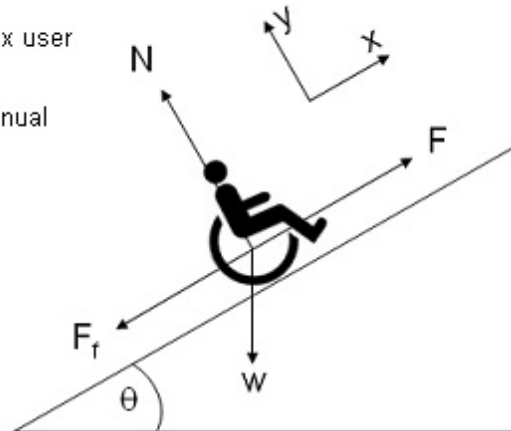
$$F_s := 1.2 \quad \text{Factor of Safety}$$

$$T_{motor} := F_s \cdot T_{pr}$$

$$T_{motor} = 36.116 \text{ N}\cdot\text{m}$$

$$T_{motor} = 26.638 \text{ ft}\cdot\text{lbf}$$

Load torque required by motor



## Drive Wheel RPM Requirement

$d := 24\text{in}$  standard wheelchair wheel diameter

$C := \pi \cdot d$

$C = 1.915\text{m}$  circumference

$\text{speed} := 5 \frac{\text{mi}}{\text{hr}}$  maximum thesis wheelchair speed

$$\text{speed} = 2.235 \frac{\text{m}}{\text{s}}$$

$$\text{speed} = 134.112 \frac{\text{m}}{\text{min}}$$

$\text{RPM} := \frac{134.112\text{m}}{C}$  required rpm of the motor and gearbox under load

$$\text{RPM} = 70.028$$

## Gear Train Ratio

$N_1 := 16$  Number of Teeth on Small Metal Gear

$N_2 := 70$  Number of Teeth on Large Plastic Gear

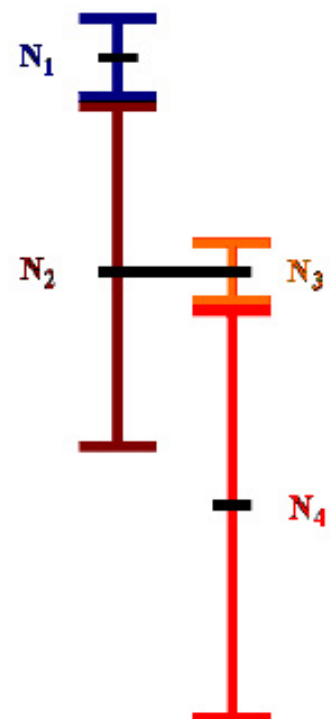
$N_3 := 16$  Number of Teeth on Small Metal Gear

$N_4 := 84$  Number of Teeth on Large Metal Gear

$$m_v := \left( \frac{-N_1}{N_2} \right) \cdot \left( \frac{-N_3}{N_4} \right)$$

$m_v = 0.044$  Train Ratio

$\text{ratio} := \frac{1}{m_v}$  ratio = 22.969



# Appendix B – Component Specifications

## HP Quadrature Encoders (HEDS-5500 A06/A14)



### Quick Assembly Two and Three Channel Optical Encoders

#### Technical Data

##### Features

- Two Channel Quadrature Output with Optional Index Pulse
- Quick and Easy Assembly
- No Signal Adjustment Required
- External Mounting Ears Available
- Low Cost
- Resolutions Up to 1024 Counts Per Revolution
- Small Size
- -40°C to 100°C Operating Temperature
- TTL Compatible
- Single 5 V Supply

##### Description

The HEDS-5500/5540, HEDS-5600/5640, and HEDM-5500/5600 are high performance, low cost, two and three channel optical incremental encoders. These encoders emphasize high reliability, high resolution, and easy assembly.

Each encoder contains a lensed LED source, an integrated circuit

with detectors and output circuitry, and a codewheel which rotates between the emitter and detector IC. The outputs of the HEDS-5500/5600 and HEDM-5500/5600 are two square waves in quadrature. The HEDS-5540 and 5640 also have a third channel index output in addition to the two channel quadrature. This index output is a 90 electrical degree, high true index pulse which is generated once for each full rotation of the codewheel.

The HEDS series utilizes metal codewheels, while the HEDM series utilizes a film codewheel allowing for resolutions to 1024 CPR. The HEDM series is not available with a third channel index.

These encoders may be quickly and easily mounted to a motor. For larger diameter motors, the HEDM-5600, and HEDS-5600/5640 feature external mounting ears.

The quadrature signals and the index pulse are accessed through

HEDM-550X/560X  
HEDS-550X/554X  
HEDS-560X/564X



five 0.025 inch square pins located on 0.1 inch centers.

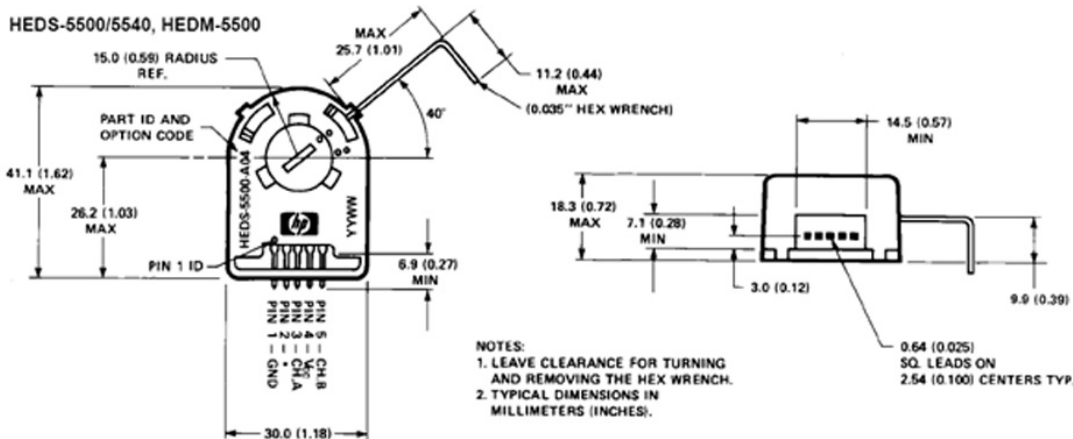
Standard resolutions between 96 and 1024 counts per revolution are presently available. Consult local Hewlett-Packard sales representatives for other resolutions.

##### Applications

The HEDS-5500, 5540, 5600, 5640, and the HEDM-5500, 5600 provide motion detection at a low cost, making them ideal for high volume applications. Typical applications include printers, plotters, tape drives, positioning tables, and automatic handlers.

#### Package Dimensions

HEDS-5500/5540, HEDM-5500



## Versallogic Panther PC/104 Processor (EPM-CPU-6/7)

### Technical Specifications

*Specifications are typical at 25°C with 5.0V supply unless otherwise noted.*

**Board Size:**

3.55" x 3.775" (PC/104 standard). Two board set.

**Storage Temperature:**

-40° C to 85° C

**Free Air Operating Temperature:**

0° C to +60° C (free air, CPU fan with heatsink attached and operating)

**Power Requirements:** (with 32 MB SDRAM, keyboard, mouse, running Win95 with Ethernet)

EPM-CPU-6/7bj	266 MHz K6-2 CPU	5V ±5% @ 3.30 A (16.5 W) typ.
EPM-CPU-6c	233 MHz Pentium CPU	5V ±5% @ 3.50 A (17.5 W) typ.
EPM-CPU-6/7g	400 MHz K6-2 CPU	5V ±5% @ 4.25 A (21.3 W) typ.
EPM-CPU-6/7h	266 MHz K6-2E CPU	5V ±5% @ 2.55 A (12.8 W) typ.
EPM-CPU-7s	266 MHz Tillamook	5V ±5% @ 1.95 A (9.7 W) typ.
EPM-CPU-7t	266 MHz Tillamook	5V ±5% @ 2.05 A (10.3 W) typ.

+3.3V or ±12V may be required by some expansion modules

**System Reset:**

V<sub>CC</sub> sensing, resets below 4.37V typ. Watchdog timeout

**DRAM Interface:**

One 144-pin SODIMM socket, 8 to 256 MB, EDO (60 ns) or SDRAM (66 MHz or PC-100 compatible, runs at 66 MHz).

**Flash / BBSRAM Interface:**

One 32-pin JEDEC DIP socket.  
Accepts one 8 to 96 MB DiskOnChip device or 512 KB battery-backed static RAM chip. Height limit of 0.0330"

**Video Interface:**

EPM-CPU-6: Based on Intel/C&T 69000 chip. 2 MB VRAM. Resolutions to 1600 x 1200.  
EPM-CPU-7: Based on Intel/C&T 69030 chip. 4 MB VRAM. Resolutions to 1600 x 1200  
44-pin flat panel display interface compatible with common panels.

**IDE Interface:**

One PCI-based IDE channel, 40-pin interface, compatible with enhanced IDE mode 4 and Ultra DMA only.  
Supports up to two IDE devices (hard drives, CD-ROM, etc.)

**Floppy Disk Interface:**

Supports two floppy drives

**Ethernet Interface:**

Autodetect 10BaseT/100BaseTX based on AMD 79C973. 12K transmit/receive buffer.

**COM1 Interface:**

RS-232, 16C550 compatible, 115K baud max.

**COM2 Interface:**

RS-232/422/485, 16C550 compatible, 460K baud max.

**LPT Interface:**

Bi-directional/EPP/ECP compatible

**Connectors:**

I/O: Two high-density 80-pin (break out to standard .1" IDC and PC connectors).  
Video: 10-pin 2mm SVGA connector, 44-pin 2mm FPD connector  
Power: 10-pin .1"

**BIOS:** General Software embedded BIOS with OEM enhancements

Field upgradable with Flash BIOS Upgrade Utility

**Bus Speed:**

CPU External: 66 MHz  
PCI, PC/104-Plus: 33 MHz  
PC/104: 8 MHz

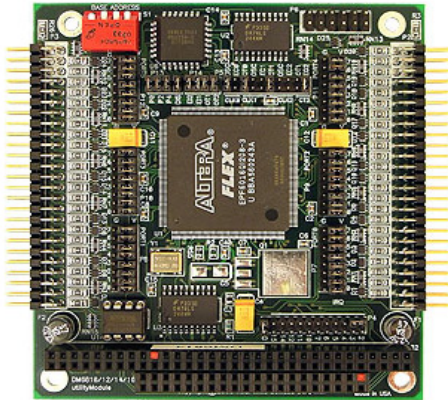
**Compatibility:**

PC/104 – Full compliance  
Embedded-PCI (PC/104-Plus) – Full compliance, 3.3V or 5V modules

Specifications are subject to change without notice.



## RTD DM6814 Quadrature Encoder Input PC/104 dataModule



### DM6814/DM5814 Characteristics Typical @ 25° C

#### Interface

Switch-selectable base address, I/O mapped  
Jumper-selectable interrupts

#### Incremental Encoder Interface

Number of channels..... 3  
Counter size..... 16-bits  
Input rate..... 1 MHz  
Input type..... TTL  
Input level..... 0 - +5 volts

#### Digital I/O

Number of lines..... 6 bit programmable  
I/O type..... TTL  
Input/Output levels..... 0 - +5 volts  
I<sub>source</sub>..... -12 mA  
I<sub>sink</sub>..... 24 mA

#### Digital Inputs

Number of lines..... 18  
Input levels..... 0 - +5 volts

#### Timer/Counters..... CMOS 82C54

Three 16-bit down counters  
6 programmable operating modes  
Counter input source..... External clock (8 MHz, max) or  
on-board 8-MHz clock  
Counter outputs..... Available externally; used as PC interrupts  
Counter gate source..... External gate or always enabled

#### Miscellaneous Inputs/Outputs (PC bus-sourced)

+5 volts, ground

#### Power Requirements

+5V @ 238 mA = 1.18W typical

#### Connectors

P2 and P3: 50-pin right angle header  
P6: 12-pin box header

#### Environmental

Operating temperature..... 0 to +70°C  
Storage temperature..... -40 to +85°C  
Humidity..... 0 to 90% non-condensing

#### Size

3.55"L x 3.775"W x 0.6"H (90mm x 96mm x 15mm)

## Measurement Computing PC104-DAC06 Analog Output Board

### Power Consumption

I <sub>cc</sub> : +5V quiescent	130 mA typical, 180 mA maximum
I <sub>cc</sub> : +12V quiescent	50 mA typical, 75 mA maximum
I <sub>cc</sub> : -12V quiescent	30 mA typical, 45 mA maximum

### Analog Output section

D/A converter type	AD7237
Resolution	12 bits
Number of channels	6
Ranges	±10V, ±5V, 0 to 10V, 0 to 5V; each channel individually jumper-selectable
D/A pacing	Software
Data transfer	Software-pollled
Throughput	125 kHz typical (PC-dependent)
Offset error	Adjustable to zero
Gain error	Adjustable to zero
Integral non-linearity	±0.5 LSB
Differential non-linearity	±0.5 LSB
Monotonicity	Guaranteed over temperature range
Gain drift	160 ppm/°C
Zero drift	150 ppm/°C
Current Drive	±5 mA minimum
Short circuit current	±40 mA
Output resistance	0.1 ohms
Slew rate	1.7V/μs
Miscellaneous	Double buffered input latches Update DACs individually or simultaneously (jumper-selectable by DAC pairs) DAC output state on power-up and reset undefined

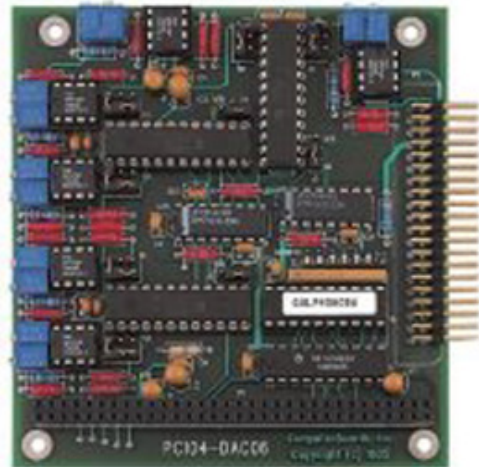
### Environmental

Operating temperature range	0 to 70°C
Storage temperature range	-40 to 100°C
Humidity	0 to 95% non-condensing

Measurement Computing Corporation  
16 Commerce Boulevard,  
Middleboro, Massachusetts 02346

Tel: (508) 946-5100  
Fax: (508) 946-9500

E-mail: [info@measurementcomputing.com](mailto:info@measurementcomputing.com)



## Tri-M HE104-DX Power Supply

# HE104-DX

60 Watt PC/104 Power Supply



### features

- 60 Watt power supply
- +5V, +12V, -5V and -12V DC output
- 6V to 40V DC input range
- High efficiency up to 95%
- PC/104 compliant
- Extended temperature: -40° to +85°C

### specifications

#### Electrical Specifications

- 5V output\* 10.0A
- 12V output 2.0A
- -5V output 0.4A
- -12V output 0.5A

#### Input Voltage 6 to 40VDC

#### Mechanical/Environmental

- Size (W x L x H)\*\*\*\* 3.55" x 3.75" x 0.55"
- Weight 6.08 oz/172.37 grams
- Temperature Range -40 to +85°C

#### Performance Characteristics

- Peak to Peak ripple\* <20mV
- Load Regulation\*\* <80mV
- Line Regulation\*\* 40mV
- Output Temp. Drift\*\* <40mV
- Output Ripple\*\* 20mV
- Quiescent Current\*\*\* 2mA
- Efficiency up to 95%

\* Current rating includes current supplied to 12V and -12V regulators

\*\* Measured on the 5V output

\*\*\* LEDs disabled and power supply is in shutdown mode

\*\*\*\* Not including pass through pins

# Advanced Motion Controls B30A8 Brushless Servo Amplifier

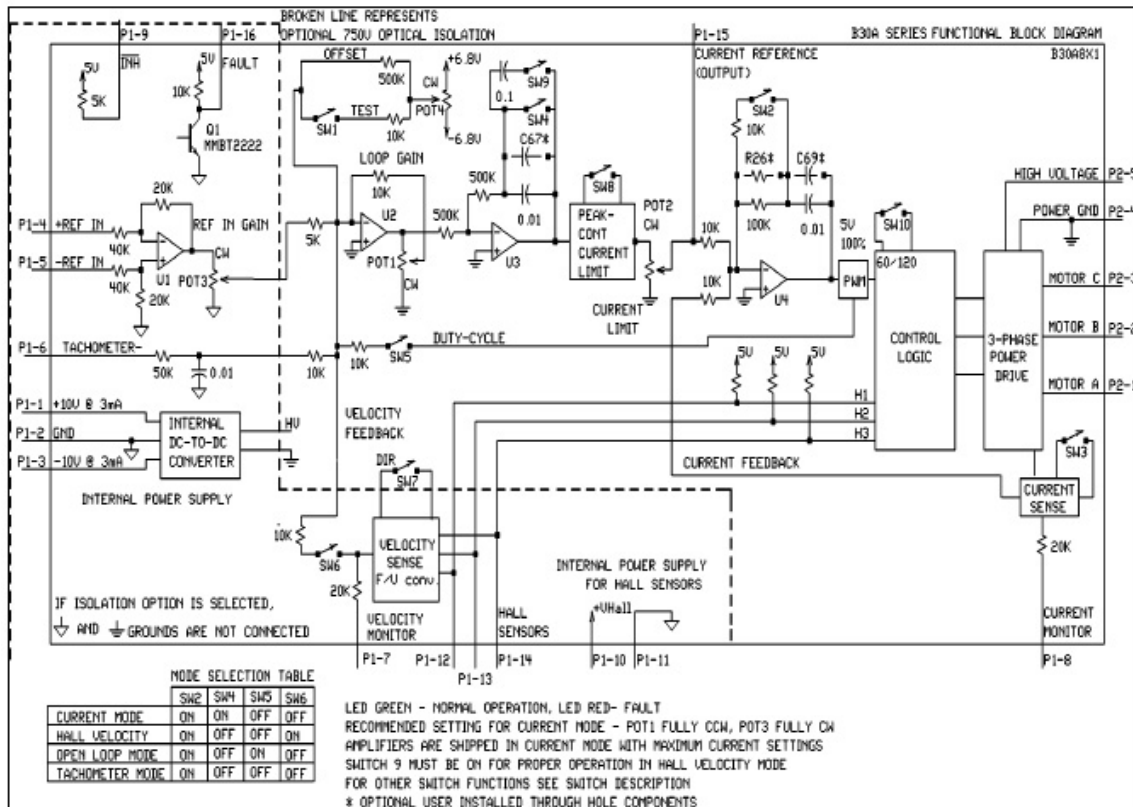
## B30A SERIES BRUSHLESS SERVO AMPLIFIERS Models: B30A8, B25A20, B40A8, B40A20

### FEATURES:

- Surface-mount technology
- Small size, low cost, ease of use
- Optional input signal isolation
- DIP switch selectable modes:  
current, open loop, tachometer,  
or HALL velocity
- Four quadrant regenerative operation
- Agency Approvals:



### BLOCK DIAGRAM:





## Appendix C - Cost Analysis

Estimated total costs if all components purchased separately. The majority of the components were either lent or donated. Purchased items are marked with an asterisk.

COMPONENT CATEGORY	DESCRIPTION	MODEL	SUPPLIER	COST	QTY.	TOTAL COST	
Wheelchair Frame	Manual Lightweight Wheelchair	L218LA286	Invacare	≈\$630.00	1	\$630.00	
Controls System	PC/104 CPU	Panther EPM/CPU-6	Versallogic	\$1002.00	1	\$1002.00	
	Quadrature Encoder Input Board	DM6814HR	RTD	\$298.00	1	*\$298.00	
	Digital to Analog Output Board	PC104-DAC06	Measurement Computing	\$399.00	1	\$399.00	
	60 Watt Power Supply	HE104-DX	Tri-M Engineering and Systems	\$255.00	1	\$255.00	
	Quadrature Encoder	HEDS-5500 A06/A14	HP	\$42.67	3	\$128.01	
	Motor Amplifier	B30A8	Advanced Motion Controls	\$435.00	1	\$435.00	
Power Supply	24V 60Ah C-Cell Battery Pack	Unknown	Unknown	≈\$100.00	1	\$100.00	
Gearbox	Motor	Unknown	Unknown	≈\$500.00	1	\$500.00	
	Gear Train	Unknown	Unknown	≈\$400.00	1	\$400.00	
	Gearbox	Unknown	Unknown	≈\$100.00	1	\$100.00	
Machine Shop Time	N/A	N/A	DEKA R&D	\$62.50/hr.	≈80	\$5000.00	
Materials	Various	N/A	N/A	≈\$450.00	1	*\$450.00	
						<b>Estimated Overall Cost</b>	<b>\$9697.01</b>
						<b>Actual Total Cost</b>	<b>≈\$750.00</b>

\*Purchased Items

## Appendix D – Part Drawings and Assembly

All parts were manufactured at:  
DEKA Research & Development (Manchester, NH)

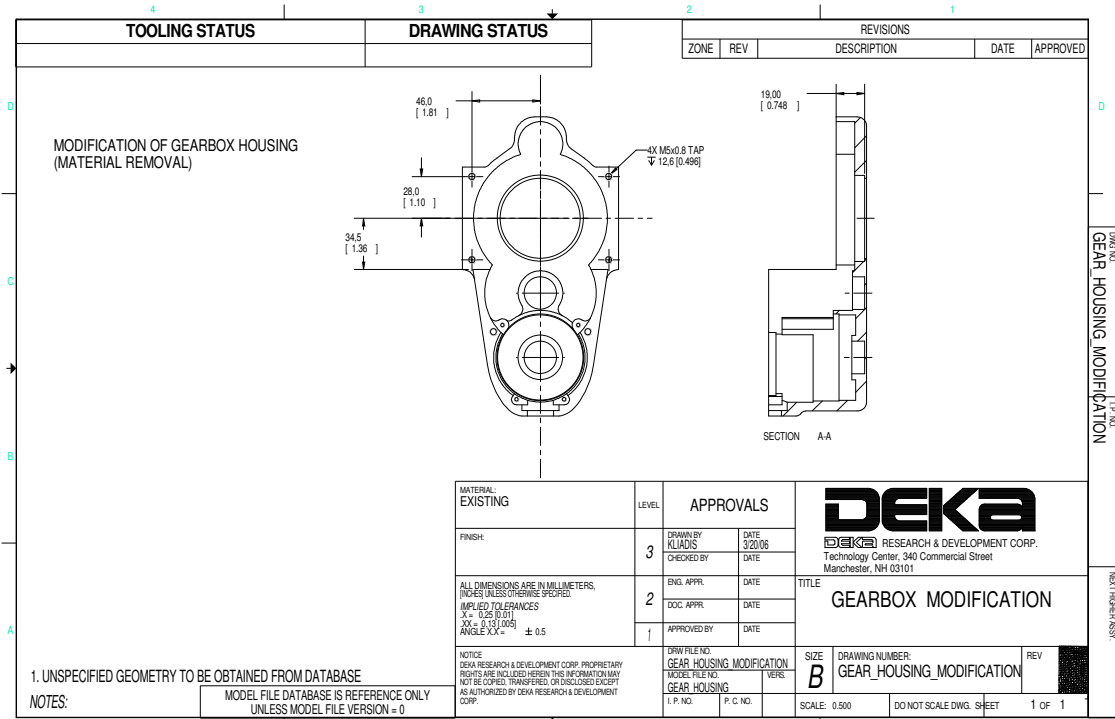
### *Overall Assembly*



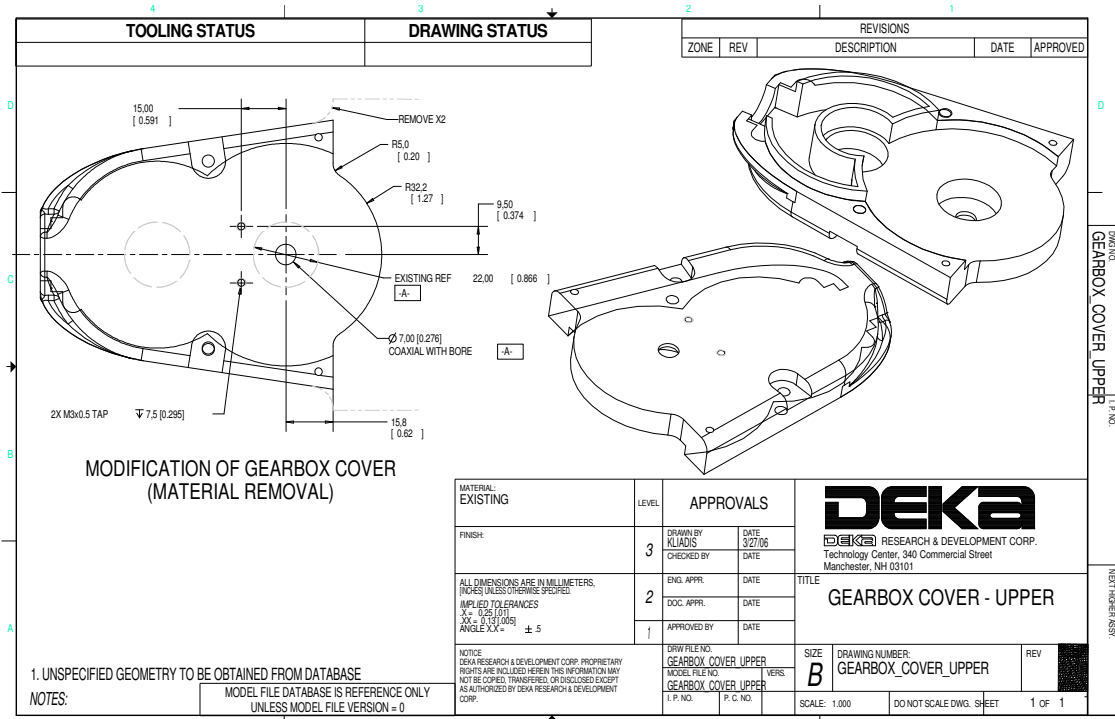
***Motor-Driven Side Components***



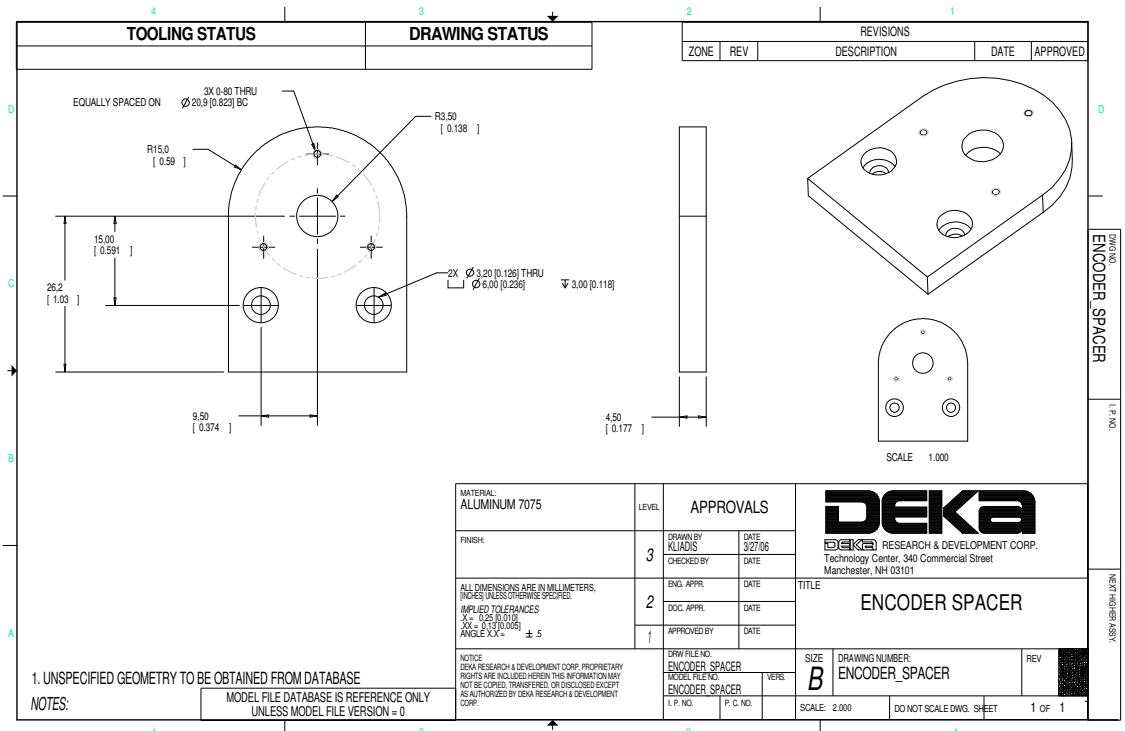
# Gearbox Housing – Modified



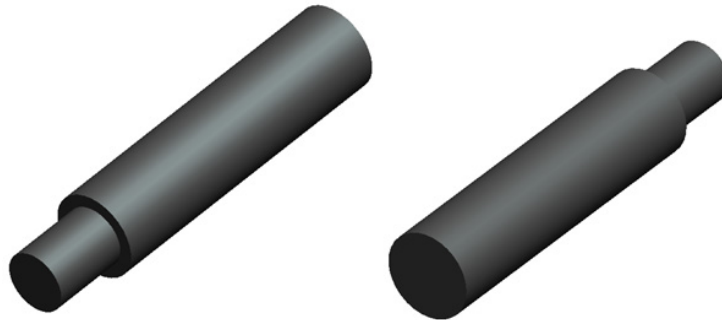
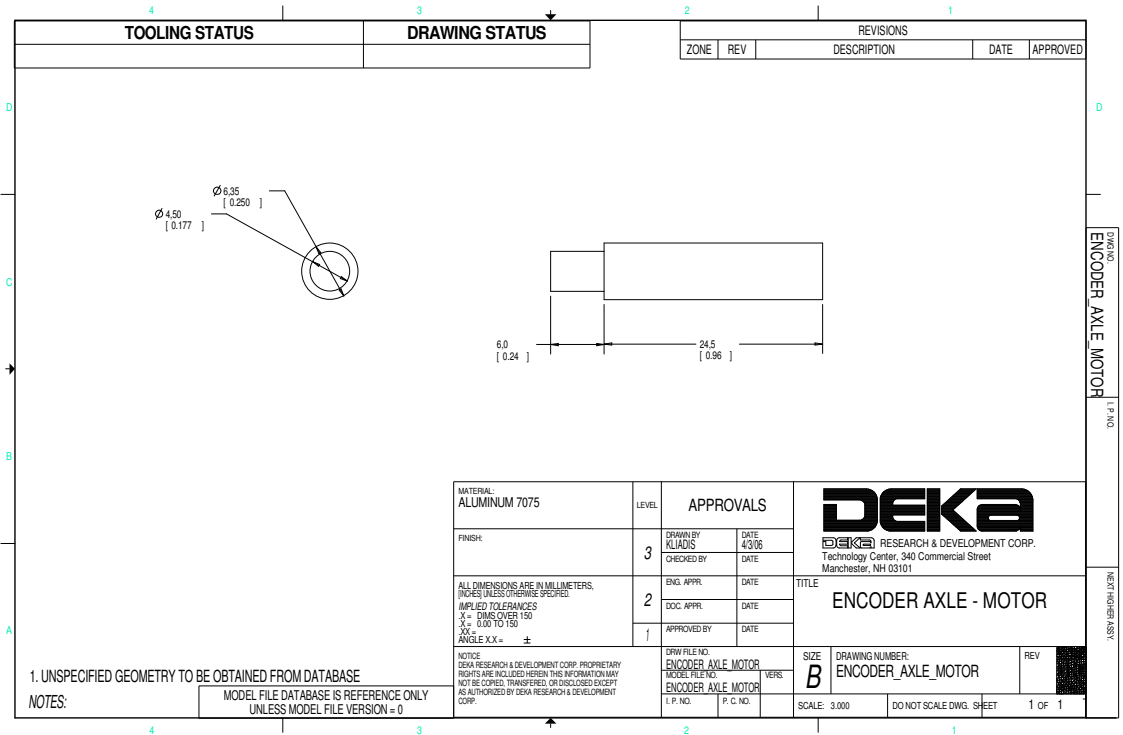
# Upper Gearbox Cover – Modified



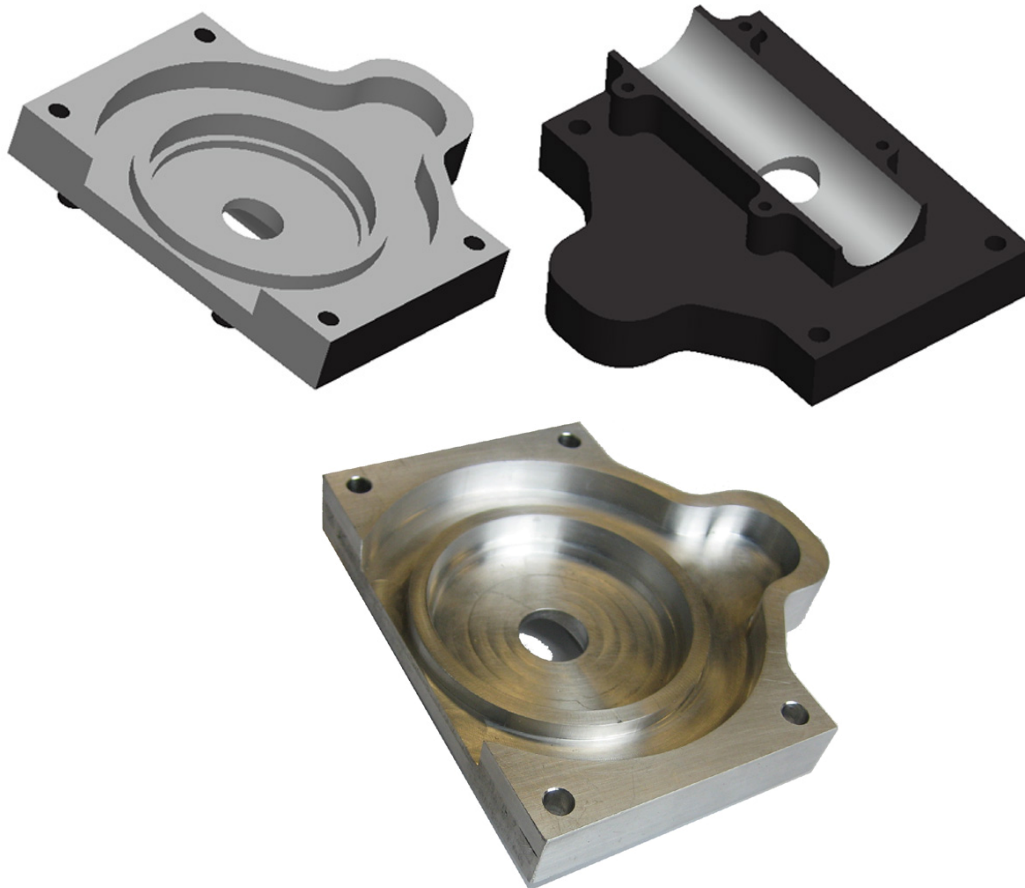
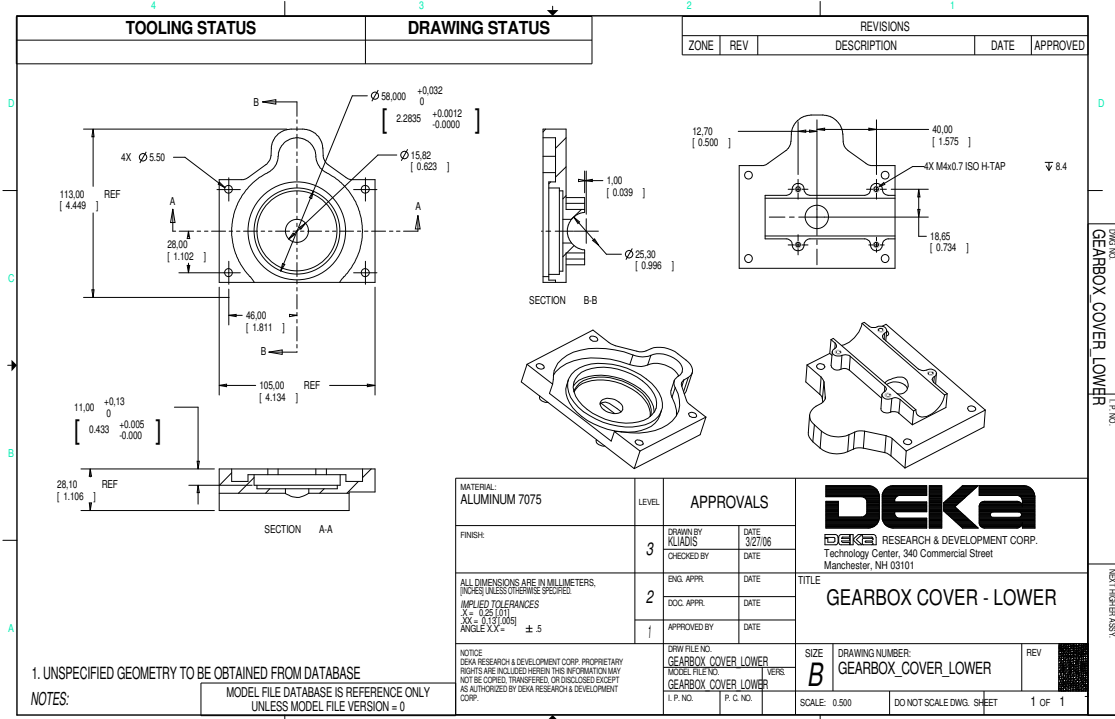
# Encoder Spacer – Motor-Side



# Encoder Axle – Motor-Side

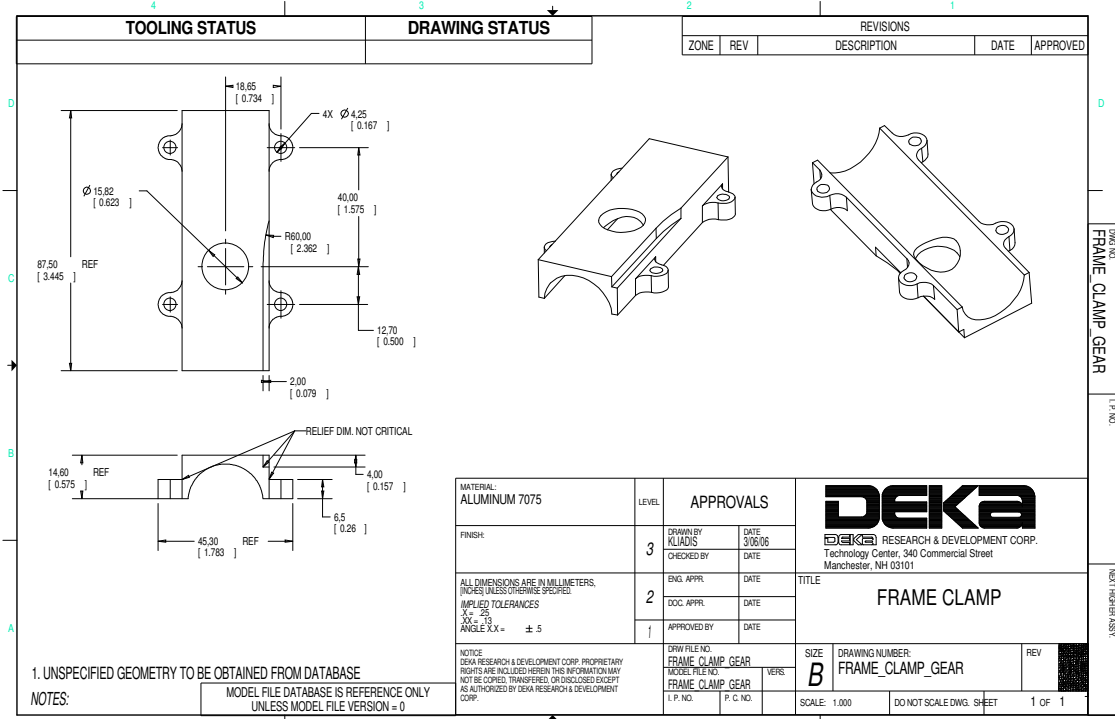


# Lower Gearbox Cover

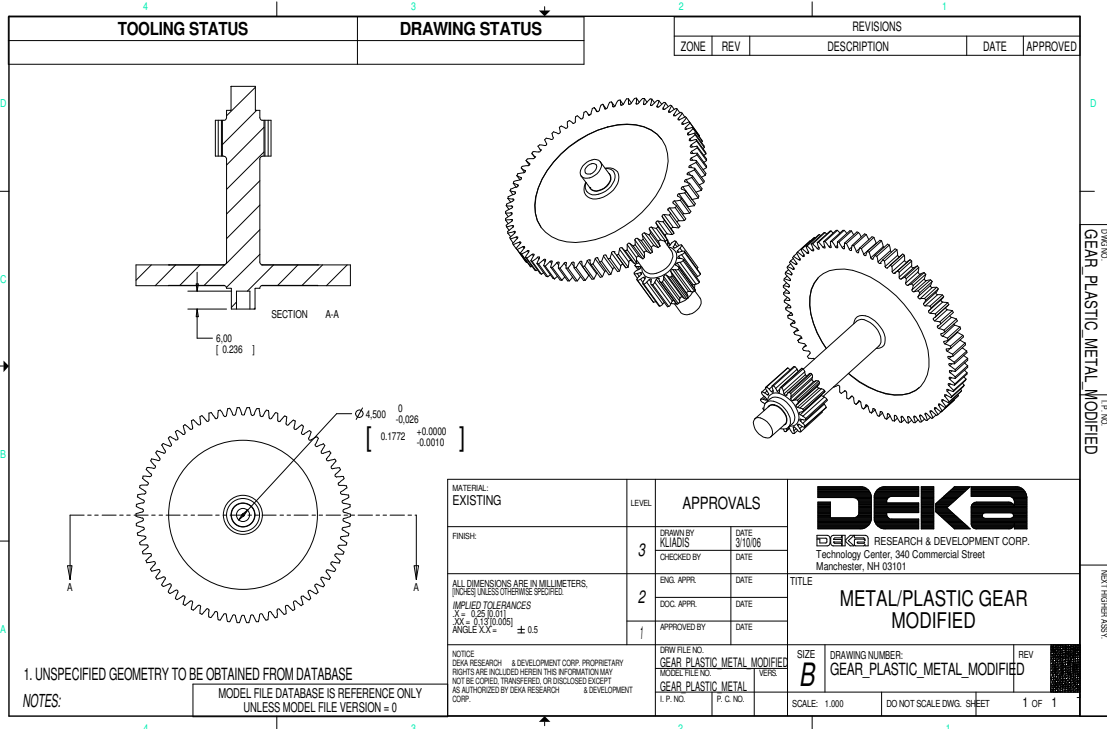




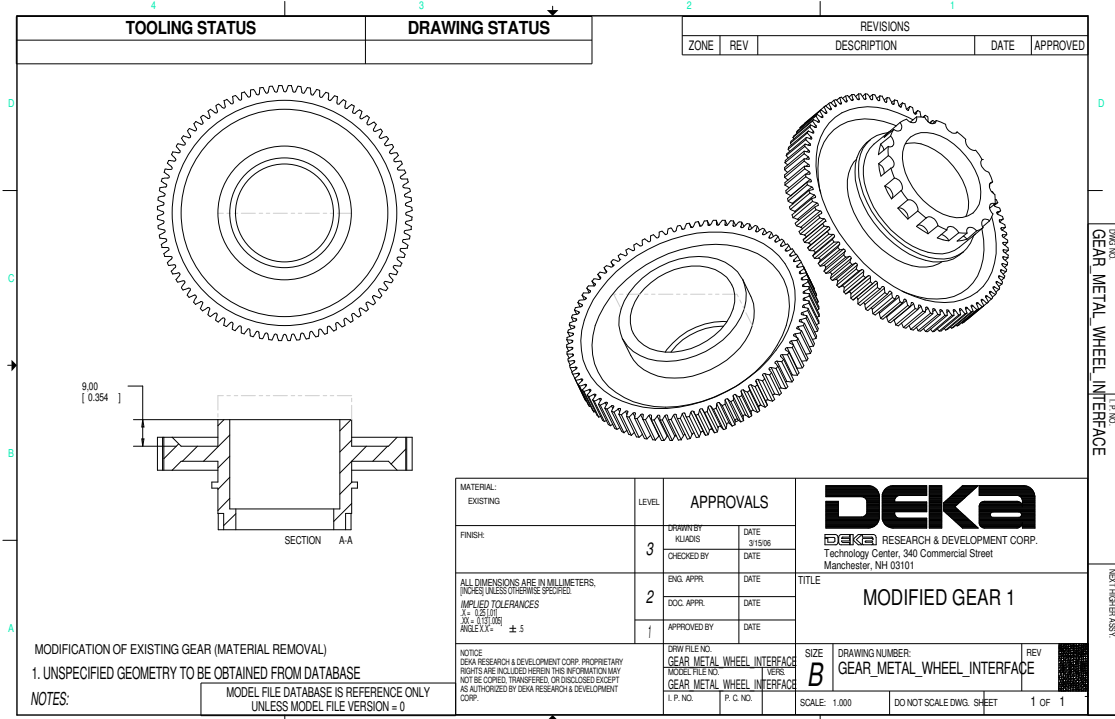
# Frame Clamp – Lower Gearbox Cover



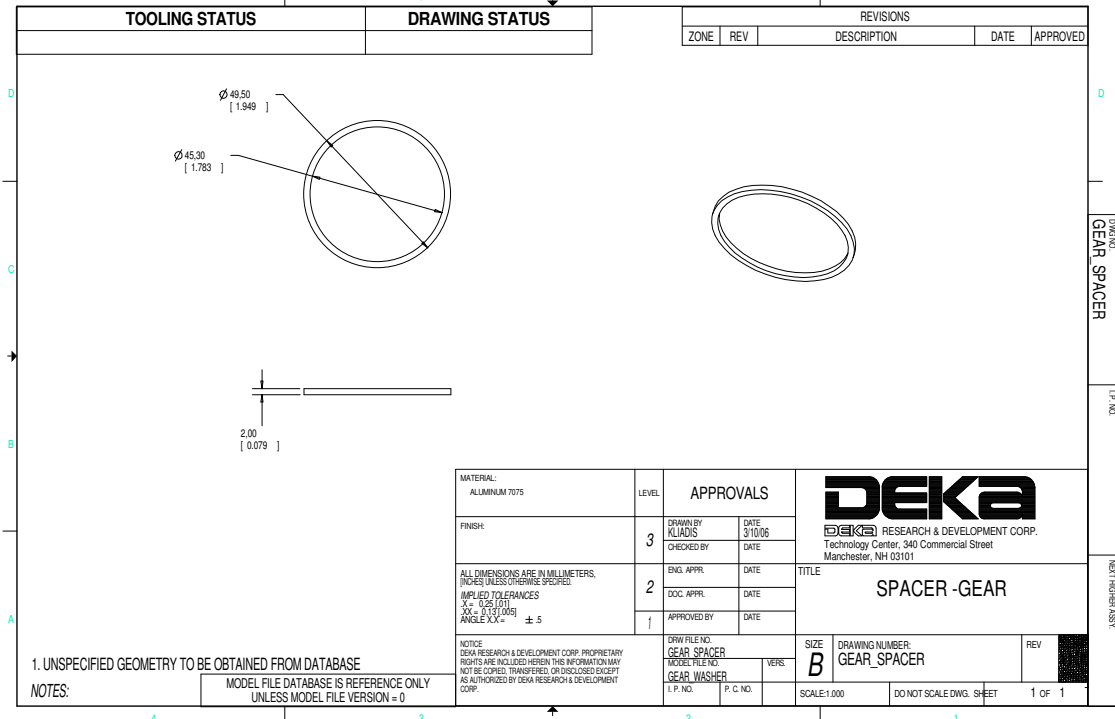
# Modified Gear – Plastic/Metal



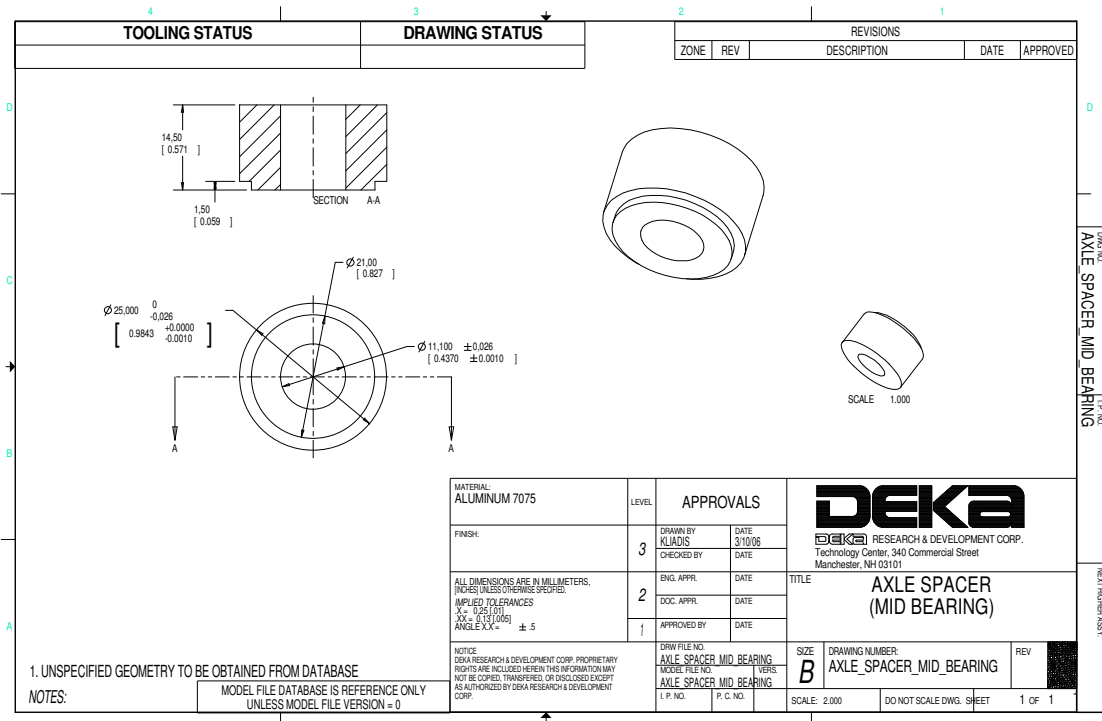
# Modified Gear – Metal Wheel Interface



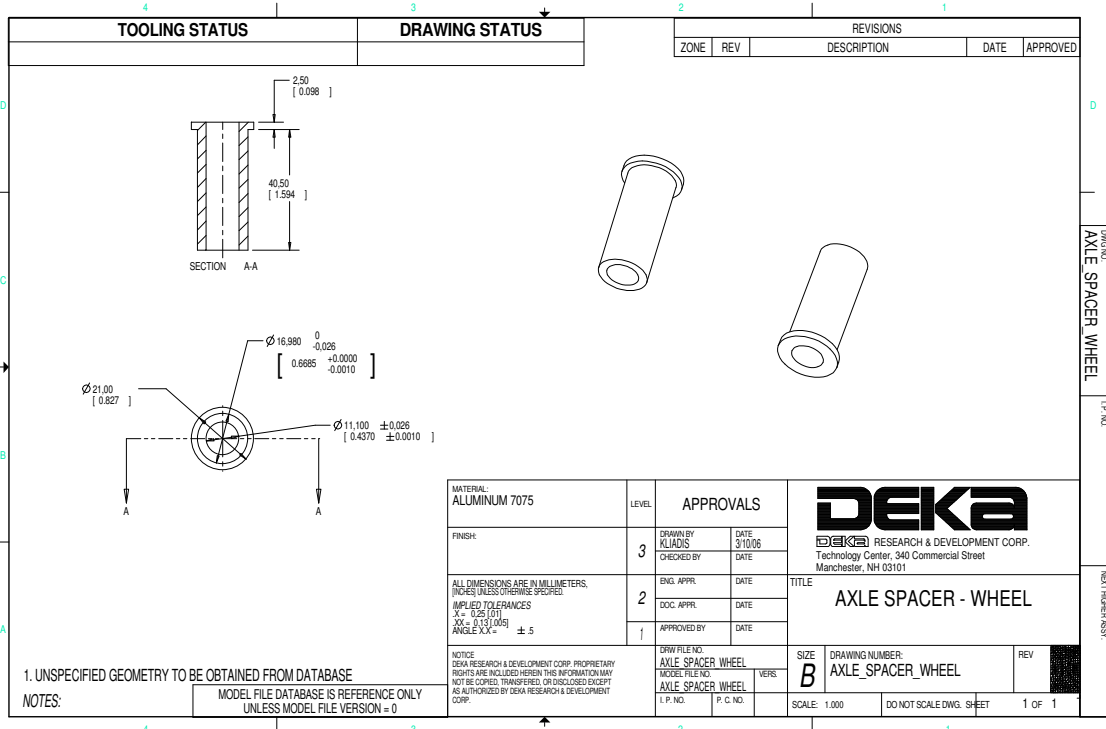
# Bearing Spacer – Metal Wheel Interface



# Wheel Axle Spacer – Metal Wheel Interface



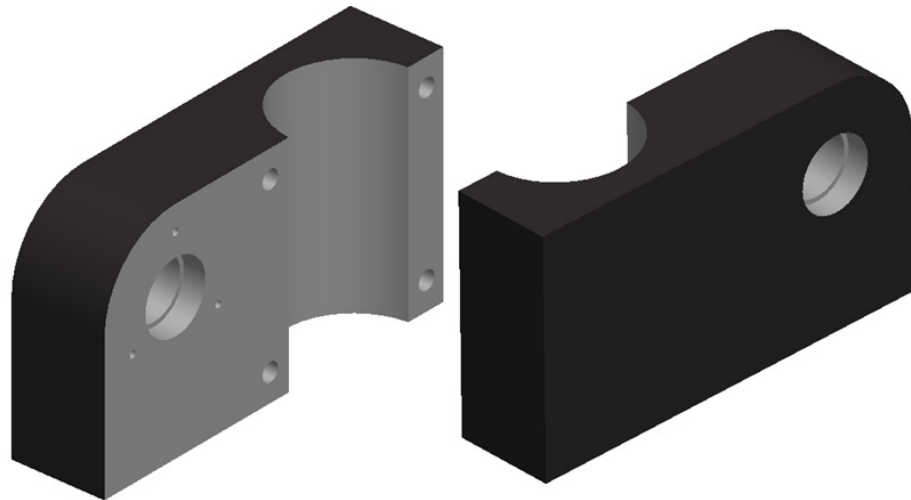
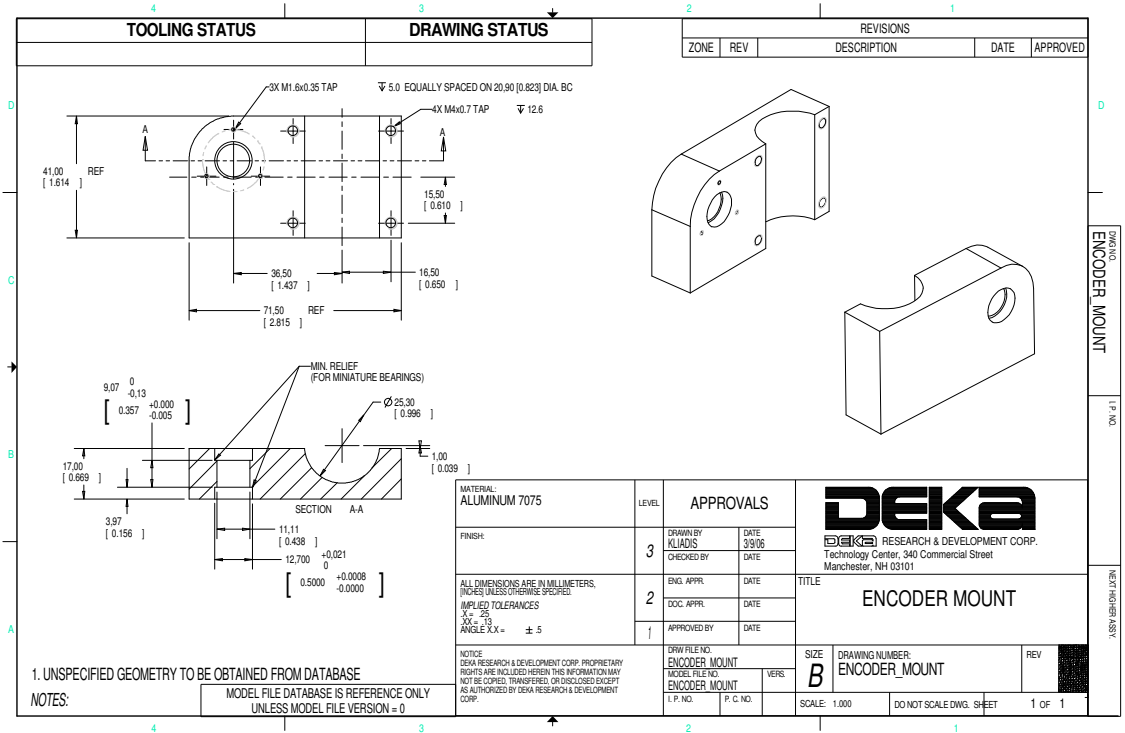
# Wheel Axle Spacer – Wheel Hub



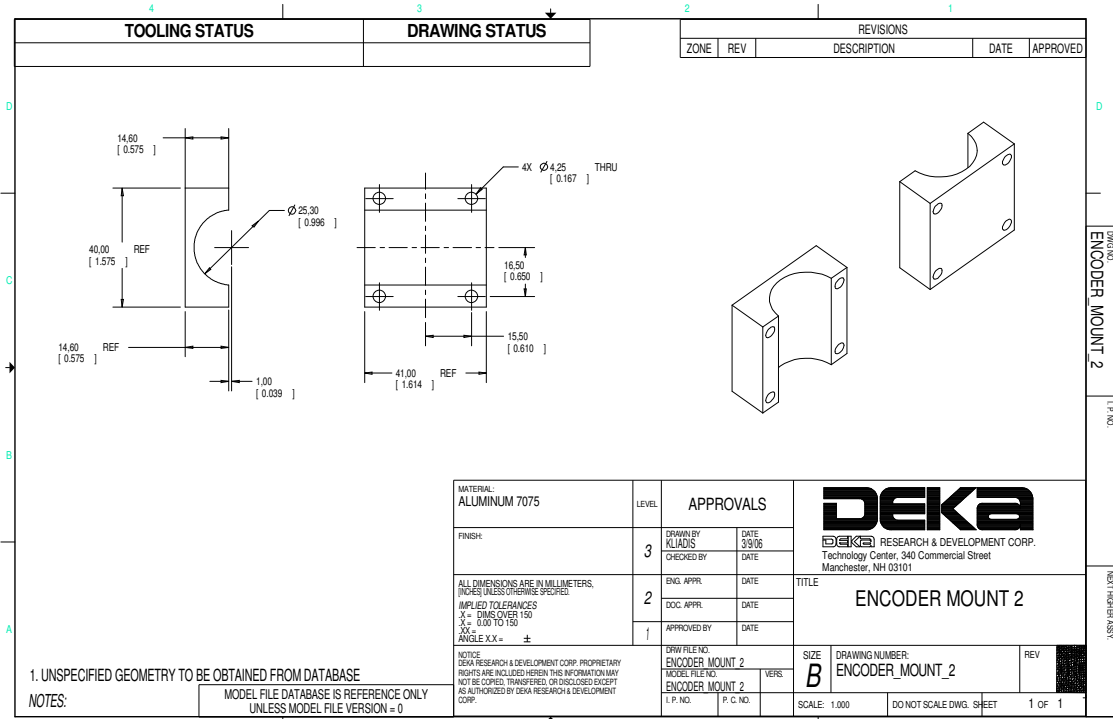
***Hand-Driven Side Components***



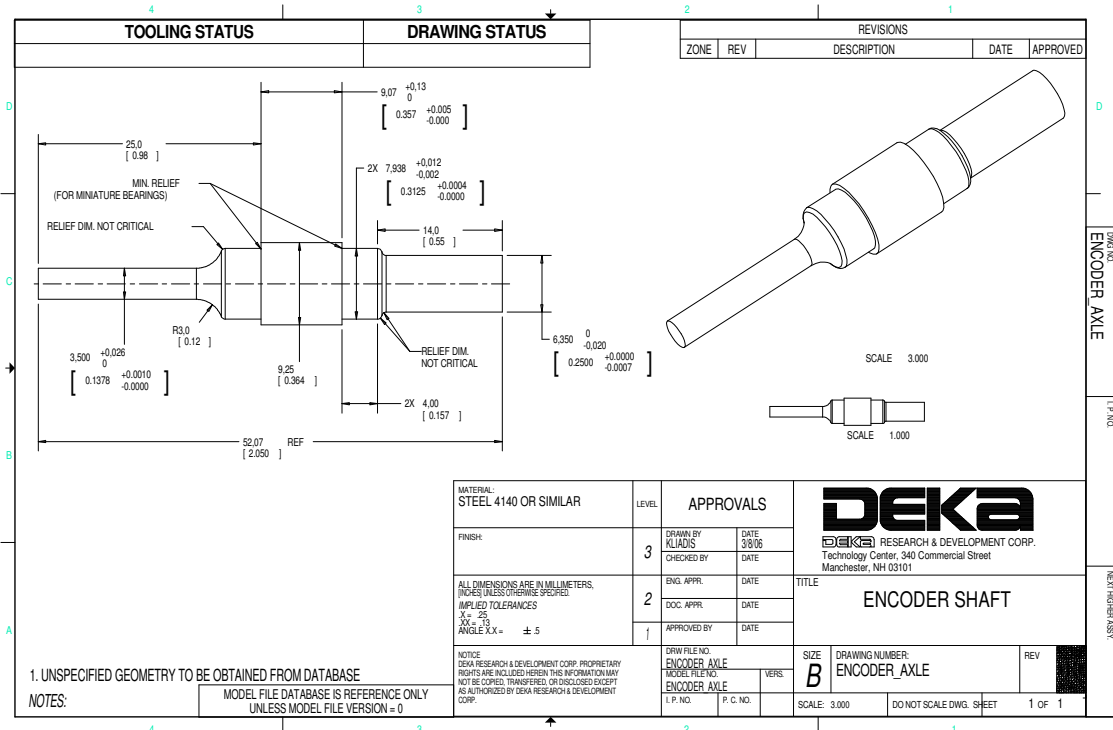
# Encoder Block – Hand-Driven Side



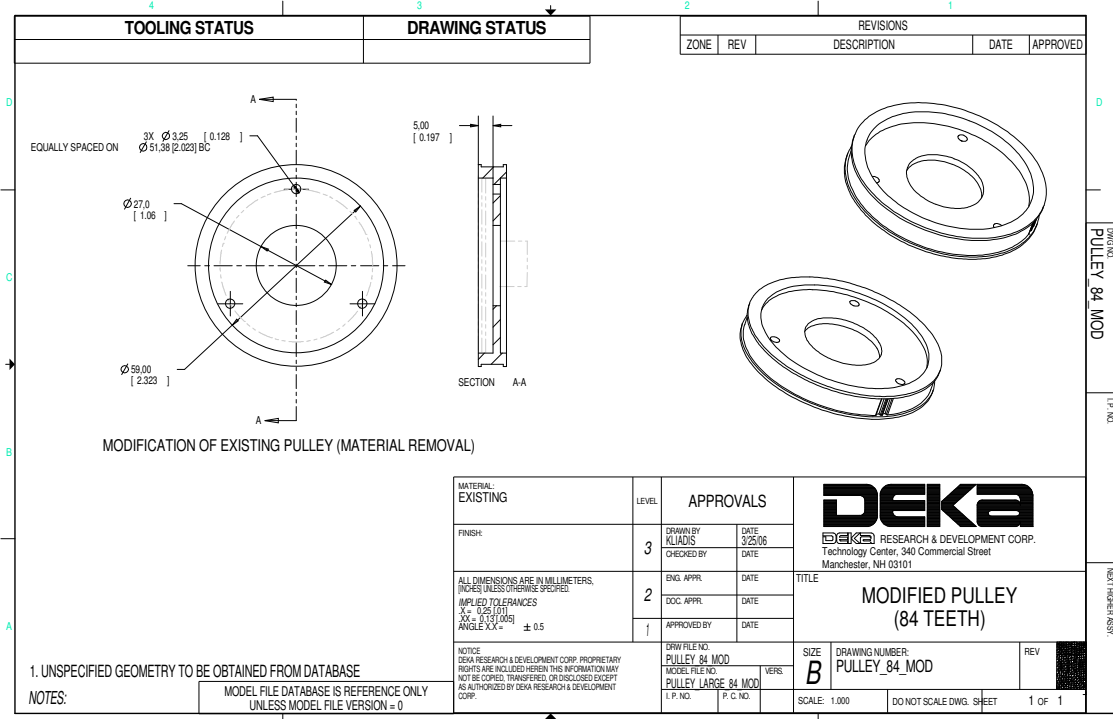
# Encoder Block Clamp



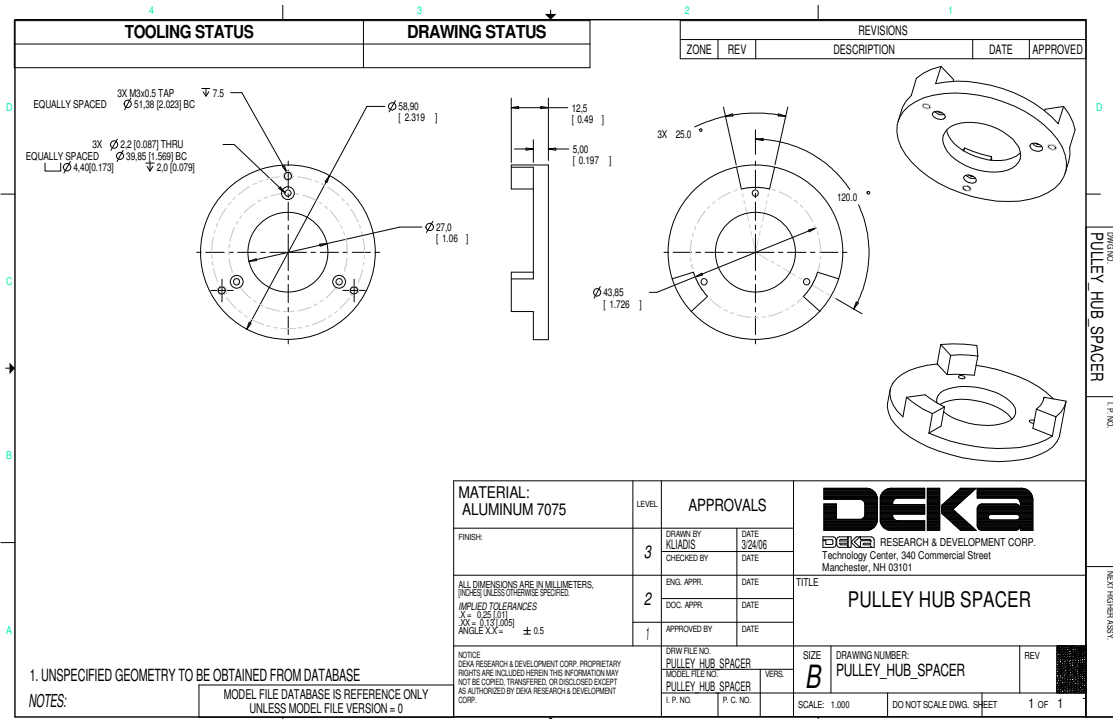
# Encoder Axle – Hand-Driven Side



# Large Pulley – Modified



# Large Pulley Mount

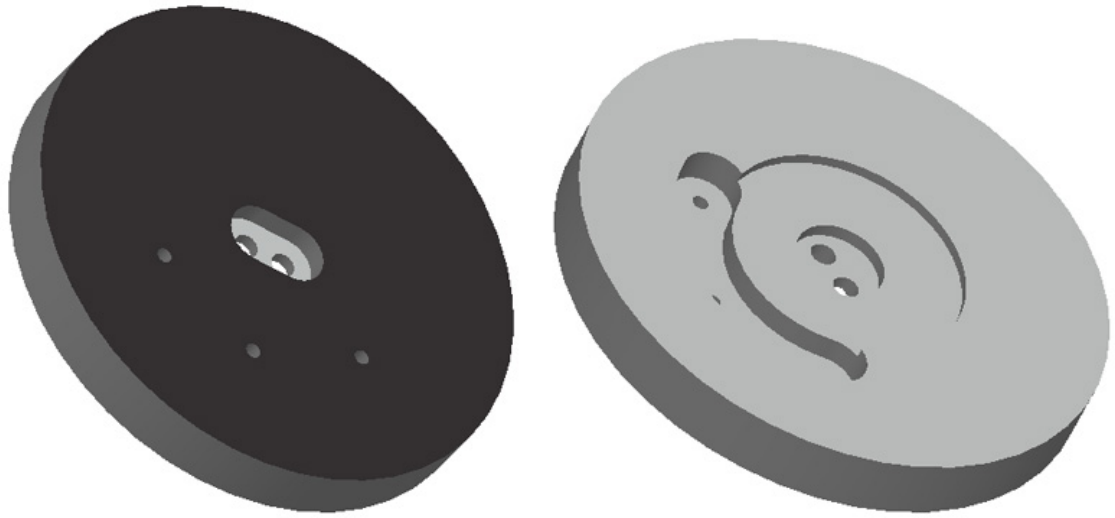
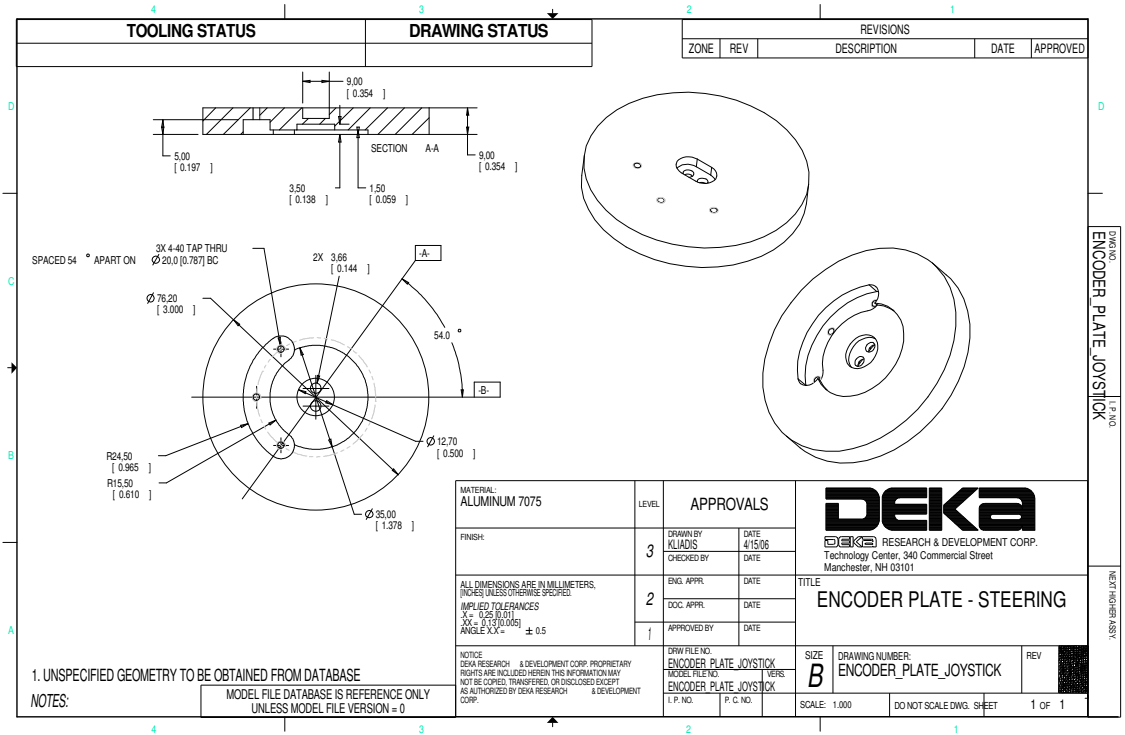


## ***Steering Interface Components***

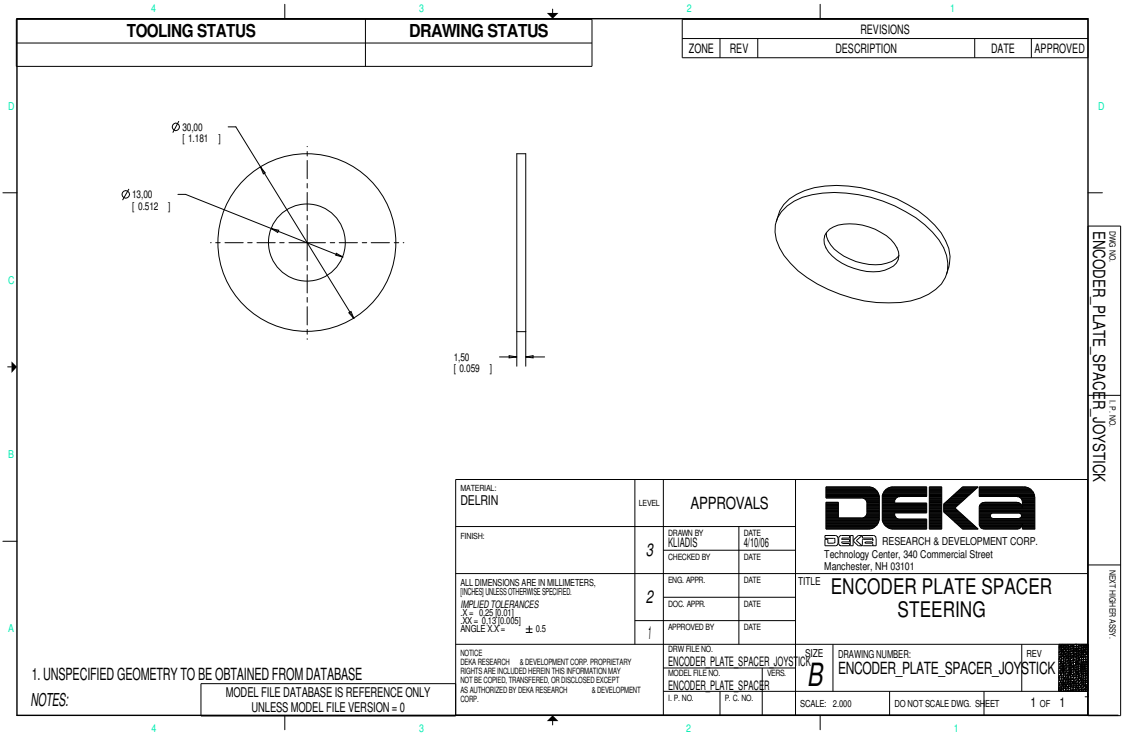




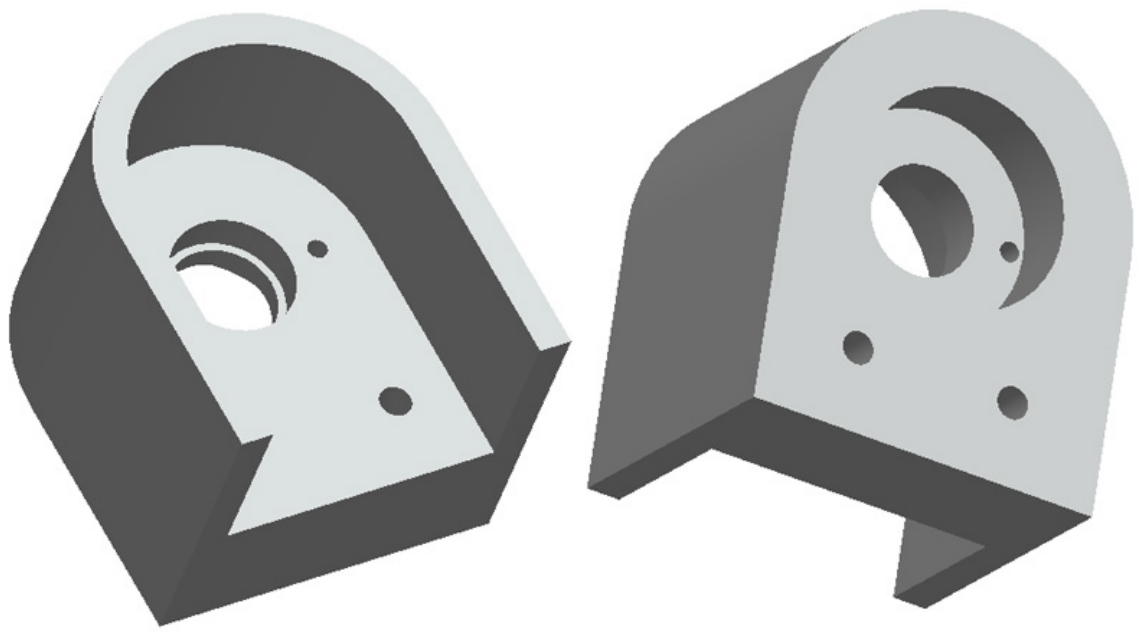
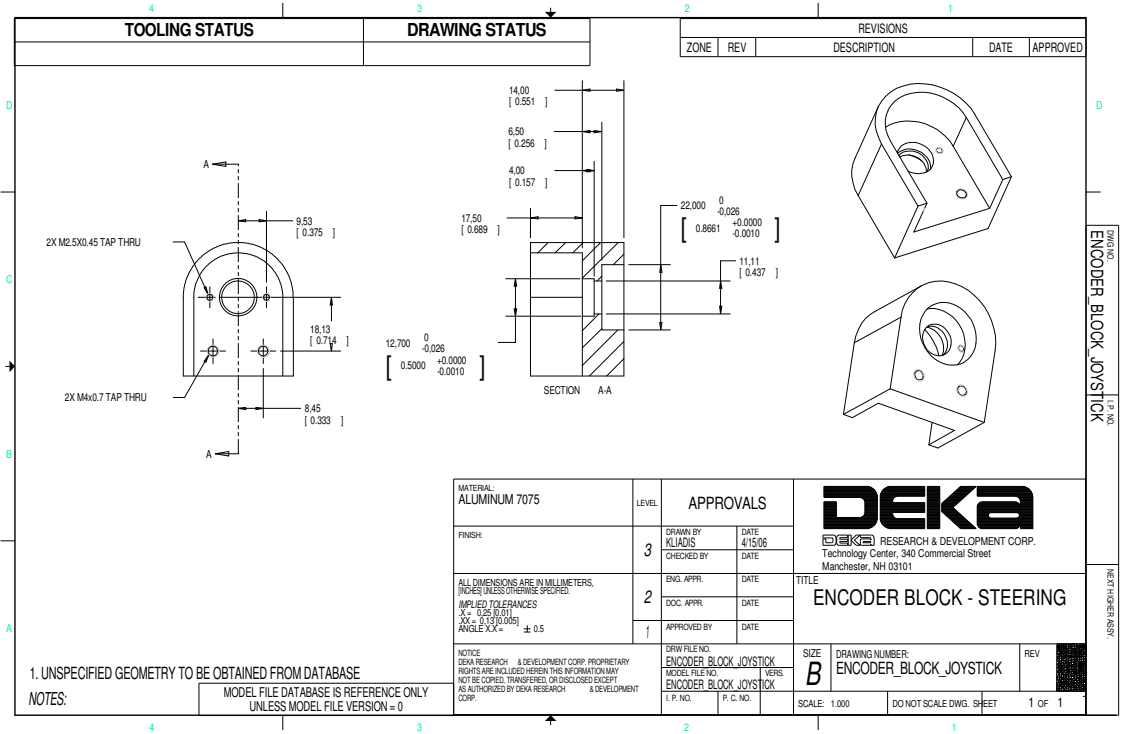
# Heel Disc



# Heel Disc Spacer



# Encoder Block – Steering Interface



# Encoder Axle – Steering Interface

