FINAL DESIGN REPORT: HAND-DRIVE REAR WHEEL DRIVE WHEELCHAIR PROJECT

Joint Effort- California Polytechnic State University, San Luis Obispo and Hochschule München, School of Applied Sciences

January 27, 2009

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Abstract

The project described herein is a senior design project for mechanical engineering students. This report details the design, build, and test process for the development of a wheelchair hand cycle attachment that drives the wheels of the wheelchair, rather than the wheel of the attachment.

The sponsor of the project, Mr. Greg O'Kelly is interested in such a device for his own use as well as having a working prototype as a "proof of concept", should the design be successful enough to manufacture. From the sponsor's perspective, in addition to acquiring a product he can use, this is also an opportunity to offer real world experience to a team of engineering students through the development of a solution to an existing problem.

There are six students working internationally to develop a single final product; three students in the United States attending California Polytechnic State University, and three students in Germany, attending the Hochschule München, School of Applied Sciences. From the student's perspective, this is meant to be a capstone experience- the culmination of their engineering education, and a bridge between the academic world of theory and the professional world of actual product development.

This report covers the background for the project, design development, an in-depth description of the final design, a testing plan, a project management plan, and the conclusion to date.

Chapter 1: Introduction

The following report first details the process we used to generate and evaluate possible solutions for our hand-powered rear wheel drive wheelchair attachment. Since this process resulted in the final design that we are going to build, the main focus of this report is to present an outline for the next phase of development, which is the actual construction and testing of the device.

The project was originated and is sponsored by Greg O'Kelly, a San Luis Obispo local, who is dissatisfied with the current offerings for hand-powered mobility attachments for his own wheelchair. An international collaboration consisting of mechanical engineering students from California Polytechnic University and Hochschule München, School of Applied Sciences was given the opportunity to design and build a working prototype detachable, hand powered, rear wheel drive wheelchair attachment to improve user mobility. The primary intent is to provide Mr. O'Kelly with a fully-functioning mechanism that is a clear improvement over existing hand-powered wheelchair systems. Mass production for a larger market is also a consideration.

We began by translating Mr. O'Kelly's needs as a customer into engineering specifications. From these specifications, we developed subsystems to accomplish the various requirements of the project, by combining extensive research with our collective engineering knowledge. Finally, we have selected an approach to the entire system that we believe will best satisfy the complete list of specifications. This design has been approved by Mr. O'Kelly, and we are ready to build and test the prototype.

Chapter 2: Background

Below is an image of the sponsor's current setup. The shortcomings of this configuration stem primarily from the fact that it is a front wheel drive system. Due to the aft center of gravity on a wheelchair, the front wheel drive system has very little traction on wet surfaces, and cannot climb hills. In addition, the cranks are essentially in the lap of the user, so it is not possible to steer under power- only while coasting.

Figure 1. Greg O'Kelly's Current FWD Hand Cycle Attachment.

The current configuration utilizes an internally-geared, chain-driven 7-speed hub with quick release fixtures at the head tube connection and the connection to the wheelchair, under the user's seat. It brakes by means of a coaster brake, so to stop, you just pedal backwards. The advantages of such a system are:

- increased mobility
- increased efficiency and steering - an unmodified wheelchair steers by braking on wheel, which continually causes the user increased energy expenditure
- exercise for the upper body
- versatility - by being able to detach the steering column from the wheelchair, as opposed to a fixed tricycle for exercise
- carrying capacity of the basket

The initial list of customer requirements was fairly brief- in addition to maintaining the above advantages, the device had to drive the rear wheels of the wheelchair, it had to be lightweight, not too expensive (within the budget of an individual user), detachable, and the modification to the wheelchair had to be minimized. Through continued conversations with Mr. O'Kelly and ideation during the design process, other customer requirements were developed in order to maximize the user's experience with the device. A complete list of requirements can be found in the Quality Function Deployment Table, see Appendix A.

2.1 Additional Background Research

In the lead up to the project proposal, we did extensive research on domestic and international standards for wheelchair construction; the potential market for such a device; and the existing products and patents that were similar to our design. The results are summarized in the sections that follow.

2.1A Applicable Codes and Standards

The internationally accepted standard for wheelchair design is provided by the International Organization for Standardization (ISO). The German national organization for standardization, the Deutsches Institut für Normung e.V. (DIN; in English, the German Institute for Standardization) is the country's ISO member body and has wheelchair designs that are equivalent to the ISO standards. While both codes provide standards for the design of wheelchairs, these standards do not extend to wheelchair attachments and as such there are not governing standards for the design of wheelchair attachments.[i] However, in order to test the strength of our design and guarantee strength and durability, we will design our wheelchair attachment to comply with ISO standards.

ISO 7176/ EISO[ii]

The international standard for evaluating wheelchairs is the International Organization for Standardization (ISO) 7176, International Standard for Wheelchairs. In 1996 Whirwind Wheelchair International, an organization that works to promote safety of wheelchairs in developing countries, where such standards do not exist, developed their own Extended ISO (EISO) standards for testing the strength of wheelchairs. Some of these tests are more rigorous than traditional ISO standards such that they specify static and impact tests for active wheelchairs in a variety of environments, terrains, and loading conditions.

EISO standards cover subjects such as basic seating dimensions, ways of determining tipping stability, static and impact strength requirements, and testing methods to ensure long-term durability. Examples of test methods relevant to our design of a wheelchair attachment are the following:

ISO & EISO Test N = 440N (100lbs)

- Forces on footrest when two helpers lift chair & rider up curb by footrest and push handle
- Each footrest must support ¼ combined weight of chair & rider
- Failure dangerous for rider, so Safety Factor = 1.5

Figure 2. Non-folding Footrest, Upward Support

ISO = 880 ± 26N (200±6lbs)

- Force when two helpers lift chair & rider up steps by both handles
- Each handle supports ½ combined weight
- Safety Factor = 1.5

Figure 3. Push-Handles, Upward Force

EISO Test I = ~280Nm (200lb ft)

- Moment on frame cross members from impact of wheelie off curb
- Static test to simulate dynamic loading during impact
- Estimate values only, not based on actual measurements of forces during impact
- This test was done to provoke failures in the welds and tubes at the base of the backrest. Simulating a hard transfer curb drop impact with the back fabric. Can't repeatedly control forces in the curb drop.

Figure 4. Backrest Tubes Inward Force

EISO Test C = 1.5m/s (3.4mph) impact

- Estimate ~1800N force; not based on measurements of riders' speeds
- Tester pushes chair into curb
- Impact each castor wheel at 90° and 45°
- Motivation = 75kg load collision at 1.5m/s

Figure 5. Caster Wheel Rolling Impact

EISO Test P = 1m (3ft)

- To simulate chair being dropped off back of truck, when loading into car trunk
- Drop onto each wheel (front and back)
- Both opened and folded

Figure 6. Handling Drop Test

2.1B Potential Market for this Product

The intent of our project is to produce a high-quality prototype specifically for use by our sponsor, but if it results in a commercially viable product, we believe that a global market exists for this type of device. Such a product would appeal to any disabled persons who maintain the complete use of their arms and upper body, but either permanently or temporarily lack the use of their legs and lower body. This could be someone who is a paraplegic, or someone who has been in an accident and is temporarily without the full use of their legs. Our product is designed for the user who desires the functionality and increased mobility of a hand-cycle, but also requires the versatility and accessibility available in a standard wheelchair configuration.

An estimated 1.6 million Americans residing outside of institutions use wheelchairs, most (1.5 million) use manual devices, with only 155,000 people using electric wheelchairs.[iii] In March 2003, the German Statistics Office calculated that 1.56 Million German citizens (1.9 % of the population) depended permanently or temporarily on a wheelchair. For Europe as a whole this translates to 7.1 Million people.[iv]

Abledata.com, an online resource that provides objective information about assistive technology, states in the document *Informed Consumer's Guide to Wheelchair Selection, that "*Wheelchair types vary nearly as much as the types of disabilities for which they are designed. A user who maintains the use of their upper body but has no use of their legs will obviously require a much different chair compared to an individual who lacks the use of both their upper and lower body. Similarly, an individual who has suffered a spinal injury and has lost the use of their legs will require a different arrangement than an individual whose legs have been amputated".[v]

Because there are so many wheelchair designs that are customized for the needs of specific users, our product will have a larger target market as a removable attachment that accommodates the user's current wheelchair compared to a permanent hand-cycle wheelchair. Our product will allow users to remain in their customized wheelchairs but still have the added mobility offered by a hand-cycle when necessary. Since our product is an attachment, users don't need to sacrifice the comfort and familiarity of their wheelchair to have a hand-cycle wheelchair.

2.1C Existing Products

We reviewed several existing wheelchairs that had similar functions we want to incorporate in our final design. We used the following existing wheelchairs and wheelchair attachments as benchmarks for defining our specifications.

Quickie GP

The Quickie GP wheelchair will be the basis of our design, as this is the wheelchair currently in use by our sponsor. It is also a fairly standard rigid wheelchair that allows the user to adjust the camber of the rear wheels. Rear wheel camber is necessary for turning at higher speeds.

Figure 7. Quickie GP Wheelchair[vi]

Team Hybrid Coyote

The handcycle attachment that Mr. O'Kelly currently uses is a Team Hybrid Coyote. As mentioned in the introduction, this uses a chain-driven front wheel with a SRAM 7-speed internally-geared hub and a coaster brake. The attachment interface has been modified because the original was cumbersome and prone to failure. The current configuration uses a set of two quick releases at the junction of the head tube with the down tube and another set of two quick releases where the down tube connects with the chair. Thus far, this has been the best attachment, and it leaves much to be desired, so it is the datum on which we are measuring the success of our device.

Figure 8. Modified Team Hybrid Coyote Attachment

Quickie Cyclone

For a while, Mr. O'Kelly used a Quickie Cyclone attachment. This is a device that attaches to a rigid (as opposed to collapsible) Quickie wheelchair, and consists of a front wheel, driven via a chain drive, attached to a set of cranks that can be turned by hand in a "rowing" motion. Additional features of the cyclone are a seven speed drivetrain (accomplished by a SRAM grip shifter on the main vertical shaft of the cyclone and an internally geared hub laced into the front wheel) and a coaster brake. To attach the device to a wheelchair involves rotating the wheelchair, thereby twisting the connecting shaft into place. This is not as convenient as the latching mechanisms used on other devices and that we plan to use on our prototype. This system still is fundamentally encumbered by the limitations listed in the introduction, namely that it is front wheel drive, weighs 25 pounds, and cannot steer under power. Quickie has discontinued this product, probably as a result of these shortcomings. Their only current replacement offerings are fully rigid trike systems, for which the front wheel is a permanent fixture, not a removable attachment.

Figure 9. Quickie Cyclone Hand Cycle Attachment (Red) with Quickie Wheelchair[vi]

Rio Dragonfly

The Rio Dragonfly is the same concept idea as the Quickie Cyclone and is a lot like the attachment that Greg O'Kelly currently uses. The Dragonfly is an attachment with a hand-crank powered front wheel. Unlike Greg's current set up, the Dragonfly attaches to a multitude of other chairs including the Quickie chair that Greg is using now. Rio claims that the Dragonfly attachment can be attached or detached in under a minute by a single user. The Dragonfly is available as a one, three, or seven speed option. The speeds are housed in an internal hub unit. The overall weight and cost of the attachment depends on the number of speeds in the hub. The weights range from 21 lbs for the one speed and 25 lbs for the seven speed. This 25 lb weight is equivalent to what Greg O'Kelly uses now. The cranks are 140mm in length and attached to a top 40 tooth sprocket. A 190 link KMC Z-chain connects the top sprocket to an 18 tooth bottom sprocket. Like Greg's setup, the Dragonfly has a coaster brake and a 16 inch front wheel. This product cannot climb hills well either, due to the aft center of gravity of the wheelchair and user.

Figure 10. Rio Dragonfly Handcycle Attachment with Rio Wheelchair[vii]

Rio Pivot

Rio also makes a product called the Pivot. The Pivot is a dual-lever propelled rear wheel drive wheelchair attachment. The Pivot uses two independent levers to drive each of the rear wheels independently. The Pivot replaces the quick release rear wheels of the current chair. The system consists of a 5-speed dual direction Rio Mobility hub. Shifting is manual and the user must be stopped to change gears. The user has the option of forward or reverse motion. Braking is independent for each wheel creating tight turning and good control. Pivot attachment weighs 22 lbs and the levers are adjustable form 24 to 27 inches in length. The Pivot works on almost any chair without camber. On chairs with camber, the levers are angled inward depending on the current camber amount. The Pivot attachment proves to be a good solution for climbing hills.

Figure 11. Rio Pivot Attachment with Rio Wheelchair[iv]

Quantum Runner

The Quantum Runner wheelchair is a rear wheel drive, lever-propelled wheelchair. The Quantum Runner is a stand-alone wheelchair design, not an attachment to an existing wheelchair, and has currently been developed only as a prototype. The levers provide forward propulsion on the push and pull strokes to their corresponding wheel and are placed forward of the rear wheels. Power from the levers is transmitted through a 4-speed automatic shifting mechanism which shifts gears depending on the user's power requirements. Because the gears shift automatically, the user is not forced to lose momentum to change gears for ascending a hill or obtaining higher cruising speeds. The Quantum Runner uses disk brakes on the rear wheels for stopping and turning assistance where braking power is applied by hand-levers on the propulsion levers.

Figure 12. Quantum Runner Wheelchair[viii]

2.2 Design-Related Research

Since the project proposal, we have researched a number of new ideas, including (but not limited to) flexible shafts, hydraulic drive systems, belt drive systems, internally-geared cranks, round profile gears (as opposed to the involute profile typically found on gears), differentials, and steering and suspension geometry (camber, caster, slip angle, etc...). Each of these concepts was carefully evaluated and either rejected or added to the list of potential components.

The components that did not make it to the final design were the hydraulic drive, the belt drive, the internally-geared cranks, and round profile gears. The hydraulic drive was found to be too inefficient, the belt drive not easily standardized, the internally geared cranks didn't offer enough range of gearing options, and the round profile gears are expensive and not easily standardized.

For the final design, there are four major components that will be incorporated. First, a flexible shaft will transfer power from the cranks to the portion of the device that is under the seat of the wheelchair. This was chosen as the best method, as it allows for the subtle changes in geometry that occur while steering without any sacrifice in efficiency. Second, the attachment of the device to the wheelchair will be accomplished with a latching mechanism that will secure the device and lift the front casters off the ground all in one motion. Third, gearing will be accomplished with an internally-geared hub affixed to the wheelchair frame beneath the user. A chain will go from the hub to the drive wheel of the fourth major component; a differential that will transfer power to the rear wheels. The differential was chosen to maintain the handling characteristics of a wheelchair without an attachment, namely, its ability to turn in place. The differential also prevents slip of the wheels while turning, as one wheel travels a shorter distance through a turn.

Chapter 3: Design Developments

3.1 Specifications List

The customer's needs were translated into engineering specifications using a method called "Quality Function Deployment" (See Appendix A). The list of specifications is provided below.

Table 1. Specifications List

Geometry	Width:	Seat width 45.7cm (18in.) + armrest + tires
	Length:	Must be about same size as current set up
	Height:	Less than 1.1 m (3.6 ft)
	Space Requirement:	Must be able to fit into trunk of midsized car
	Front Wheel:	16 inches (40.6cm) as standard tires
	Rear Wheel:	24-28 inches (70cm bicycle standard)
	Connection:	Minimal changes to the wheelchair for connection Connecting and releasing without any further tools
Driving Behavior	Handling:	Sporty but still comfortable and suited to daily use
	Traction assured:	Must maintain traction while accelerating, turning, up 20% grade, on wet surfaces
	Traction limited:	Should be limited traction on snow and ice
	Control:	Must not be limited by: bevel surfaces, curves, small steer angle, directional stability should be assured by mechanism
Kinematics	Direction of motion:	Translation in x,y,z Rotation around z Rotation around y should be limited to stop roll over
	Translation motion:	Forward motion only, no reverse
	Velocities:	Regular: 5-7 km/h (3.1mph) Maximum: 25 km/h (15.5mph)
	Accelerations:	Acceleration: 2 m/s^2 (6.56 ft/s^2) Braking: 10 m/s^2 (32.8 ft/s^2)
Stresses	Drive train:	Average torque: 10 Nm (7.38 ft lbf) Maximum torque: 50 Nm (36.9 ft lbf) Average power: 120 W Maximum power: 500 W
	Stress type:	Part load of about 80 - 90% Peak load 10 -20 %
	Rotation speeds:	Continuous crank speed: 20 - 40 rpm Peak crank speed: 150 rpm
	Mass inertia:	Keep small by weight reduction
	User weight:	Average: 75 kg (165 lbs) Maximum: 120 kg (264 lbs)

	Load distribution:	If possible more forces on the front axis
	Dynamic loads:	Shocks caused by pavement
	Force transmission:	Manual
		Not constant (alternating)
Power Transfer	Efficiency:	90%
Safety	Braking:	Disc or v-brakes
		Plan of differential
	Driving at night:	Lighting meets German and American specs
	Roll over protection:	Wheelchair may not roll over at any time while in use
	Protection of user:	Covering of rotating and moving components
Ergonomics	Access of controls:	Brake must be easy and quick to use
		Best if working without removing hands from cranks
		Gearshift should be easy and quick to use
		Light should be turned on by one switch
	Kind of usage:	Usually manual control, exceptions may be tachometer
	Crank attachment:	Must not interfere with user while in use
		Must not obstruct view
Usage	Types of usage:	Daily use: going to work, errands, private contacts
		Sporty aspect: small tours, fitness
	Area of use:	Europe and North America
	Duration of use:	Daily: 1-5 hours
		Total: 2000 hours without general overhaul
	Special environments:	Dust, small stones, water, humidity, grass, other substances
	Attachment Time:	No more than 30 seconds, single person operation
	Detachment Time:	No more than 30 seconds, single person operation
Transport	No lifting device:	One person must be able to lift (10 Kg, 22 lbs)
	Type of Transport:	Automobile, bus, train, tramway
Manufacturing	Prototype:	No fixed concept
Assembly	Prototype:	No fixed concept
Maintenance	General:	Maintenance free for 2000 hours
	Break:	Visual inspection and change if ware if too large
	Lubrication:	Bearing lubricated for lifetime
		Gearboxes closed and oil lubricated no need for maintenance
		Chains and open parts cleaning and re lube if necessary
Standards	Standards:	ADA, ASME, DIN, EN, ISO standards as applicable
		TUV and DIN standards for Germany
		Use health insurance company rules for taking over costs
Recycling	Steel:	Material recycling like any other product
	Aluminum;	Material recycling like any other product
	Rubber and Plastics:	Probably thermal utilization
	Lubricants:	Disposal as hazardous substances

3.2 Concept Generation and Evaluation

Initially in the design phase, we paired up into teams consisting of one Hochschule München student and one Cal Poly student. Each team was assigned one or two subsystems to brainstorm and create sketches for. Ultimately, four or five sketches for each subsystem were developed and selected for analysis in the overall system configuration.

3.3 Subsystems

Subsystems are the individual parts of the device that contribute to the whole. We identified four subsystems to develop in our teams of two students. The following are the subsystems we chose to sketch and analyze.

3.3A Steering/ Power Transfer

The subsystem for steering and power transfer includes the method of steering to be used and most importantly was the method by which the rotation of the cranks is transferred to our attachment interface. This is a difficult mechanism to design because we need to transfer power input to the cranks down the head tube and into the attachment, so the rotational motion changes direction two times. We need to keep the current crank function, but we need to find a way to transfer that rotation to the rear wheels. The steering system will work the same way that the current system does, whereby a shaft connecting the cranks to the front fork is run through the head tube and supported by bearings, similar to the head set on a bicycle.

3.3A-1 Flexible Shaft

Flexible shafts are used for rotary power transmission in a variety of commercial, industrial, and medical applications. Flexible shafts are constructed of tightly looped coils that can be designed to handle high torque and high speed. Although most commonly used for rotary tools and other high-speed, low-torque applications, flexible shafts can be designed to handle high-torque low-speed application as well. Flexible shafts can make bends up to 90degrees without adversely affecting performance and efficiency.

Figure 13. Flexible Shafts with Sample Styles, Couplings, and Casings.[ix]

Table 2. Advantages and Disadvantages of Flexible Shafts.

Flexible Shaft	
Advantages	*Disadvantages*
• High efficiency • Quiet • Low maintenance • Safe, no exposed moving parts • Easy installation • Low tolerances	• Relatively expensive • Limited availability, not readily available

3.3A-2 Constant Velocity Joint

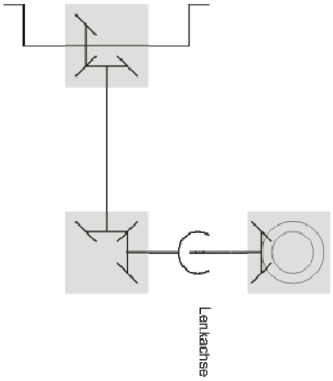


Figure 14. Constant Velocity Joint Diagram, Drawn by Manuel Fischalek.

Forces and torques from the cranks are deflected in a first (upper) gearbox. From this box the transmission is realized by a rigid shaft along the axis of the head tube. Underneath the head tube there is a second (lower) gearbox which changes the rotation sense along the longitudinal axis of the vehicle. In order to maintain the fork's ability to steer, the rigid shaft which leads to the shifting is connected with a constant velocity joint to the gearbox output shaft. This joint has to be positioned in a straight line with the turning axis of the steering system (centre of head tube).

Table 3. Advantages and Disadvantages of the Constant Velocity Joint.

Constant Velocity Joint	
Advantages	*Disadvantages*
• Simple system • Few parts • Light weight • Easy maintenance • Standard part from car industry	• Limited angle for steering

3.3A-3 Universal joints

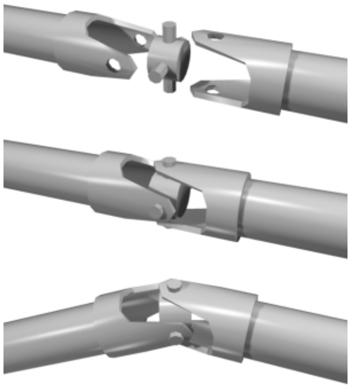


Figure 15. Universal Joint Assembly and Function.[x]

A Universal joint, is a joint in a rigid rod that allows transfer of rotary motion of the rod, while allowing the rod to bend at an angle, usually up to 45degrees. Universal joints (U-joints) can be used in series to increase the angle that a rigid shaft can bend and still permit transfer of rotary motion. U-joints are commonly used in a variety of light and heavy duty applications including automotive applications. U-joints are strong and readily available and can transmit high-torque and high-speed rotation.

Table 4. Advantages and Disadvantages of Universal Joints.

Universal Joint	
Advantages	*Disadvantages*
• Readily available, standard part • High load capacity	• Noisy • Multiple joints needed to make required bend

3.3A-4 Circular gears

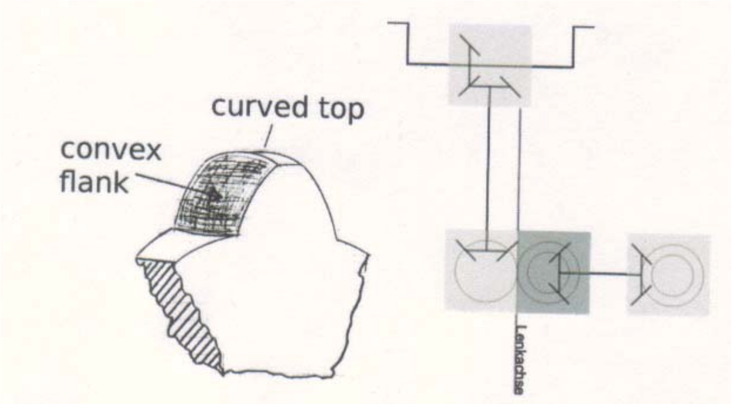


Figure 16. Custom Designed Round-Toothed Gear System for Transmitting Rotaton Sense. Diagram and Sketch by Manuel Fischalek.

The force and torque transmission towards the second (lower) gearbox is similar to Power transmission System № 2. The transmission towards the rear part of the attachment is solved by a spur-toothed gearwheel. By contrast to a normal gearwheel the teeth must be in a special shape: curved on the top and convex on the flank of tooth. Just one of the pair of gearwheels must have this complex shape.

Table 5. Advantages and Disadvantages of Circular Gear Design.

Circular Gears	
Advantages	*Disadvantages*
• Changes rotation sense of crank input	• Complex geometry of one gearwheel • No standard part • Rough and loud behaviour under load • Very heavy solutions because of many gearwheels

3.3B Rear Drive Method

The rear drive method subsystem includes ideas for the mechanism that will transfer power from the attachment interface to the drive wheels. This mechanism needs to be lightweight, quiet, and relatively easy to semi-permanently mount to the wheelchair frame with minimal modification to the wheelchair. We selected our final design analysis from the following configurations because we need to maintain the differential steering that the wheelchair utilizes without having the attachment engaged, and still maintain efficient power transfer.

3.3B-1 Fore Gearbox to Aft Differential

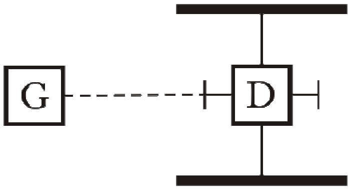


Figure 17. Diagram of Fore Gearbox to Aft Differential Configuration.

The fore gearbox to aft differential idea was based off current drive trains seen in cars. Essentially we figured that the design concept could consist of some sort of transmission and rear differential. The gearbox would provide the different gearing options need to change speed in various driving conditions and climb hills. The gearbox and differential would be connected by either a drive shaft or a chain or belt. The differential would allow power transfer to both rear wheels and allow for uninhibited tire scrub due to turning. The fore gearbox to aft differential would also be very efficient.

Table 6. Advantages and Disadvantages of Fore Gearbox to Aft Differential Configuration.

Fore Gearbox to Aft Differential	
Advantages	*Disadvantages*
• High efficiency • Part availability • Low maintenance	• Relatively expensive • Medium modification to wheelchair

3.3B-2 Friction Drive

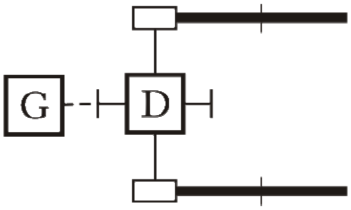


Figure 18. Diagram of Friction Drive with Gearbox and Differential.

The friction drive was an idea based on the concept of easy power transfer. We figured that a friction drive would transfer power to the rear wheel with very little modification to the chair. The friction drive would consist of two smaller wheels with high coefficients of friction applied by a normal force to the wheel. This coefficient of friction combined with a normal force would create a friction force applied to the outer diameter of the wheel. The friction drives force changes with road conditions (wet, ice, dirt, dry), is not very efficient, and is a large safety hazard.

Table 7. Advantages and Disadvantages of Friction Drive System.

Friction Drive	
Advantages	*Disadvantages*
• Easy attachment • Low chair modification.	• Safety Hazard • Low efficiency • Power changes with road conditions

3.3B-3 Rear Differential to Internal Hubs

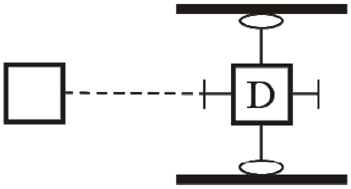


Figure 19. Diagram of Rear Differential to Internally Geared Hub Configuration.

The rear differential to internal hubs idea was based on a combination of bicycle parts and tricycle parts. The internal hubs would be used to transfer power from the differential by way of a shaft. The internal hubs would allow us to simply lace them into the wheels currently available on the wheelchair. This idea would provide high efficiency and create little modification to the wheelchair frame. This system could also eliminate the use of a gearbox given the fact that the internal hubs had different gearing options

Table 8. Advantages and Disadvantages of Rear Differential to Internally Geared Hub Configuration.

Rear Differential to Internal Hubs	
Advantages	*Disadvantages*
• High efficiency • Quiet • Low maintenance • Safe, small amount of exposed moving parts	• Requires removal/modification to quick release axles • Differential not needed due to free wheel ability of the hub, overcomplicated with addition of differential

3.3B-4 Fore Differential to Aft Internally Geared Hubs

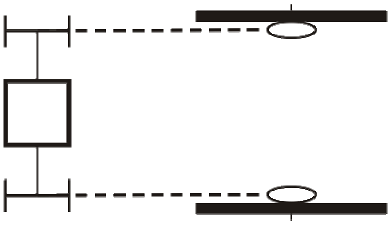


Figure 20. Diagram of Fore Mounted Differential to Twin Internally Geared Hubs Configuration.

The fore differential to rear internal hubs was a spin off from the rear differential to internal hub idea. This idea would differ from the rear differential to internal hub idea in that the differential would be located in front of the rear axle. This idea would reduce efficiency with the addition of extra parts. The extra parts would be a consequence of having dual chains. The fore differential to rear internal hub idea would also create more weight and more moving parts.

Table 9. Advantages and Disadvantages of Fore Gearset to Twin Aft Internally Geared Hubs Configuration.

Fore Gear Set to Rear Internal Hubs	
Advantages	*Disadvantages*
• High efficiency • Quiet	• Poor safety, high number of moving parts • Increased weight

3.3C Couplings

The coupling subsystem includes the attachment interface mechanism where the user can remove the handcycle when not in use. This subsystem also includes the mechanism used to couple the shaft from the front attachment to the subsystem semi-permanently mounted to the wheelchair, where the mechanism that drives the wheels is located. This system also needs to raise the wheelchair's front caster wheels 2 inches off the ground. Ideally, the motion required to lift and lock the system in place would not cause any strain on the user, avoid potentially harmful pinch points for safety, and secure the attachment rigidly to the wheelchair for maximum efficiency.

3.3C-1 Wing Nut

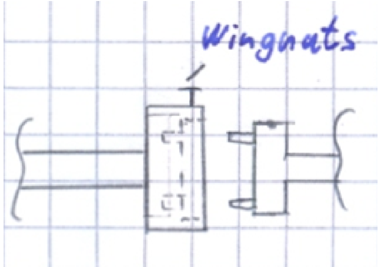


Figure 21. Diagram of Wing Nut Secured Interface. Sketch by Georg Bergmeier.

The use of wing nuts or thumb screws to secure the attachment eliminates the need for tools. The wing nut interface would allow the operation to be done by a single person and would create a connection that could only be created one way. The Wing nuts are light weight, but they could become loose during operation of the connection.

Table 10. Advantages and Disadvantages of Wing Nut Secured Attachment Interface.

Wing Nut	
Advantages	*Disadvantages*
• Eliminates need for tools • Lightweight	• Tend to loosen during operation • Too many parts

3.3C-2 Bicycle Style Quick Release

Figure 22. Quick-Release Mechanism from Mr. O'Kelly's Current Handcycle Attachment.

Mr. O'Kelly's current set up utilizes two bicycle style quick releases to secure the attachment at each connection. This connection interface eliminates the need for tools which is huge advantage. The bicycle style quick releases are light weight and allow for a single person operation. The problem with the quick releases is the number needed to provide the needed clamping force.

Table 11. Advantages and Disadvantages of Bicycle Style Quick-Release Attachment.

Bicycle Style Quick Release	
Advantages	*Disadvantages*
• Eliminates need for tools • Lightweight • Single person operation	• Multiple quick releases needed to provide clamping force needed

3.3C-3 Hinge with Wing Nuts

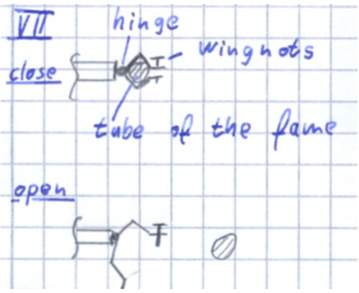


Figure 23. Diagram of Hinge with Wing Nut Secured Interface. Sketch by Georg Bergmeier.

Hinges could open to release the attachment and close to secure it with a pin or other piece of hardware. Unfortunately, there is an existing patent on a product of this nature.

Table 12. Advantages and Disadvantages of Hinge with Wing Nut Secured Attachment.

Hinge with Wing Nut	
Advantages	*Disadvantages*
• Eliminates need for tools	• Multiple parts that can be lost • Existing Patent • Difficult to align

3.3C-4 Lever with Linkage

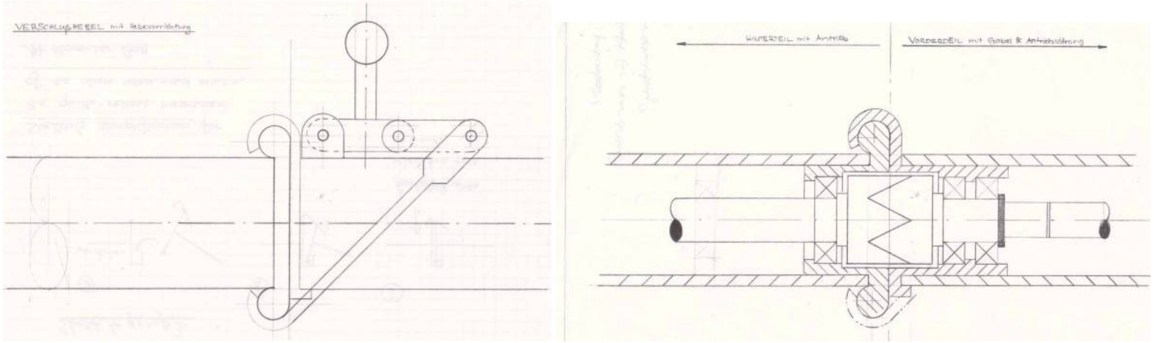


Figure 24. Front View (Left) and Section View (Right) of Lever Attachment Design. Sketches by Stefan Fischer.

A lever with a series of linkages could be utilized to provide the rotational moment needed to lift the front casters off the ground while securing the attachment. See Appendix A for motion diagram of this device.

Table 13. Advantages and Disadvantages of Lever with Linkage Attachment Design.

Lever with Linkage	
Advantages	*Disadvantages*
• Eliminates need for tools • Reduces weight • Easy to use • Fast attachment time	• Lever must be long enough to provide required moment arm.

3.3D Gearshift

The device needs to allow the user to climb hills and achieve a cruising speed of 10mph. In order to accomplish this, the most likely addition would be a gear set of some sort. We have developed the following ideas to select from.

3.3D-1 Derailleur

Figure 25. Standard Bicycle Rear Gearset with Derailleur.[xi]

The standard derailleur and cog configuration found on bicycles could be utilized to provide the shifting mechanism. However, these tend to be noisy, have lots of exposed parts and require quite a bit of maintenance. Also, they do not shift while the vehicle is stationary.

Table 14. Advantages and Disadvantages of Standard Bicycle Derailleur Gearset.

Derailleur	
Advantages	*Disadvantages*
• Parts readily available	• Adds more parts to design • Reduces ground clearance and requires special mounting • High maintenance • Must be cranking to shift gears

3.3D-2 Internal Hub

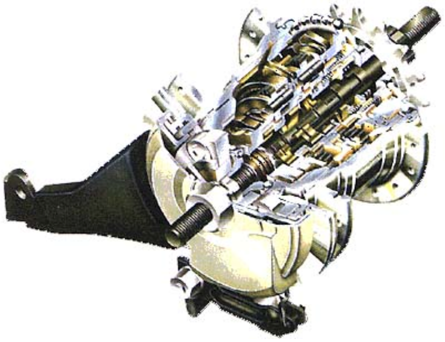


Figure 26. Cross Section View of a Shimano Nexus 8-Speed Hub.[xii]

Internally-geared hubs come in a range from three to twelve speeds, and if fixed to the frame, could provide the gearing needed to climb hills and coast on flat ground at the required cruising speed. These do shift somewhat while the vehicle is stationary. This is the same type of shifting mechanism on Mr. O'Kelly's current hand-cycle attachment.

Table 15. Advantages and Disadvantages of Internally Geared Hubs.

Internally Geared Hub	
Advantages	*Disadvantages*
• Parts readily available • Shifting while stopped • Low maintenance	• Requires re lace of wheels

3.3D-3 Automatic Gear Shift

Figure 27. Examples of Automatic Shifting Hubs[xiii]

There are also internally-geared hubs available that shift automatically, rather than manually. The automatic gear shifting hub uses centrifugal force to change gears. As the user pedals faster the rotational speed increases and the gears change. Theses automatic shifting hubs are extremely expensive and do not work for aggressive riding. All the automatic shifting hubs currently on the market claim to not climb hills well.

Table 16. Advantages and Disadvantages of Automatic Gear Shifter.

Automatic Gear Shift	
Advantages	*Disadvantages*
• Shifts based on speed. • Low Maintenance	• Scarceness of parts • Expensive • Low availability

3.3D-4 Internally-Geared Cranks

Figure 28. Schlumpf/ Triebwerk Planetary Gear System.[xiv]

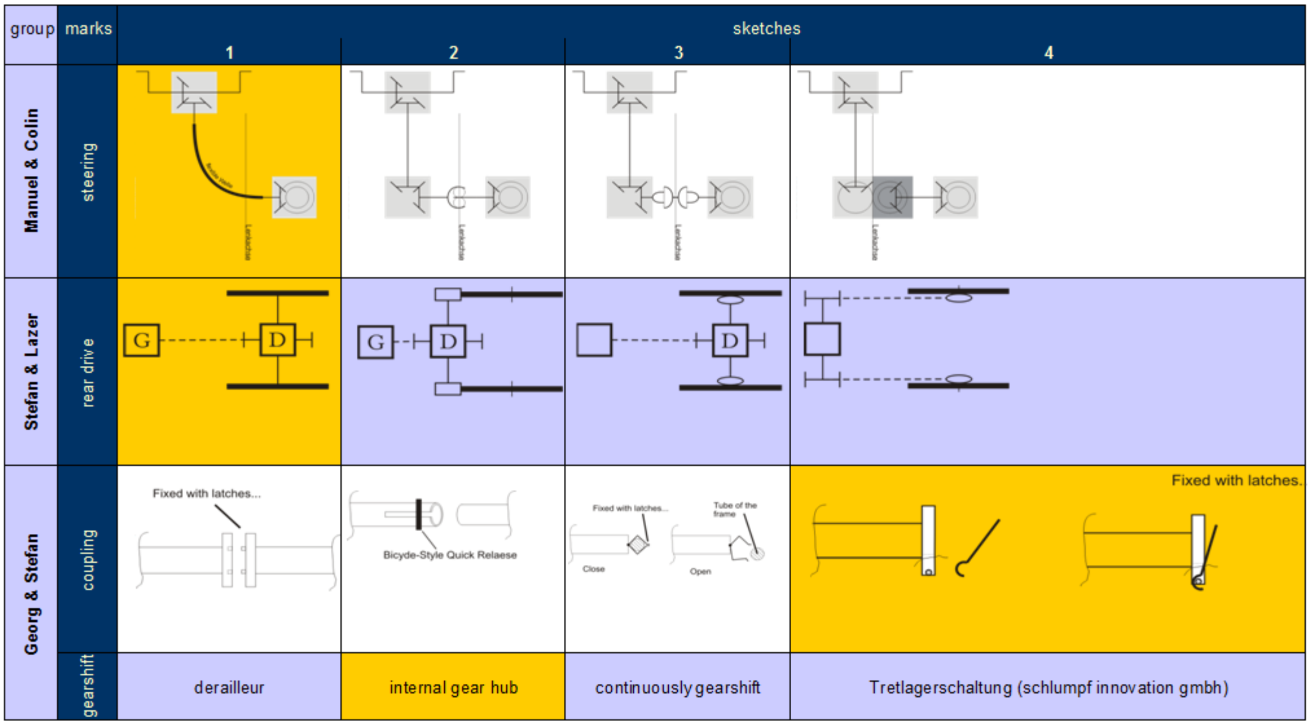
A few companies manufacture cranks with a planetary gear system built into a housing, with up to seven gears. They are durable systems which are designed to shift while the vehicle is stationary.

Table 17. Advantages and Disadvantages of Internally-Geared Cranks.

Internally-geared Crank	
Advantages	*Disadvantages*
• No need for shift cables • Reduces Weight • Reduces part count • Shifts when stopped • Low Maintenance	• Expensive

We put all of these subsystems into a decision matrix to evaluate each and combined them into complete systems in order to determine the best possible combination for our final design.

Table 18. Decision Matrix for Subsystem Ideas.



group	marks	sketches			
		1	2	3	4
Manuel & Colin	steering				
Stefan & Lazer	rear drive	G D	G D	D	
Georg & Stefan	coupling	Fixed with latches...	Bicyde-Style Quick Relaese	Fixed with latches... Tube of the frame Close Open	Fixed with latches.
	gearshift	derailleur	internal gear hub	continuously gearshift	Tretlagerschaltung (schlumpf innovation gmbh)

3.3E Braking Solutions

Solutions for stopping the device were not included in the process of concept generation and evaluation because we believed that adding a braking system was something that could be accomplished more easily after we had settled on the best design for transmitting power, attaching the device, and gearing.

We have since selected a combination of the coaster brake that is included in the internally-geared hub that we are using to stop the rear wheels with a “back-pedaling” motion of the cranks; and a standard bicycle v-brake on the front wheel, actuated by hand, using a brake lever attached to the grip part of the crank assembly.

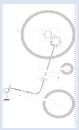
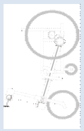
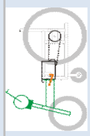
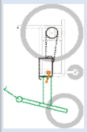
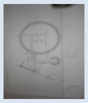
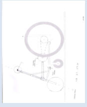
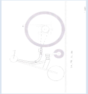
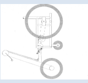
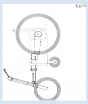
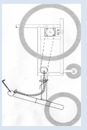
3.4 Concepts

We tried to standardize the process of generating concepts by using a blank wheelchair template for our sketches. We assigned names for each concept based on the options for each as given by the decision matrix. For example, Concept 1143 will consist of idea-1 for power transfer, idea-1 for rear drive type, idea-4 for coupling, and idea-3 for gearshift.

3.5 Concept Evaluation

We developed twelve sketches for the overall system configuration based on combinations of the sketches drawn for the various subsystems. These were then put into a decision matrix, and evaluated against our sponsor's current setup (the datum) for relative number of parts (the fewer the better), easy usage (easy to attach to wheelchair), ease of maintenance and durability, easy production (minimal complexity), and finally, driving behavior (stability, steering, and efficiency). Each category was assigned a number on a scale of zero to four, with zero being far under the performance of the datum (unacceptable), a one being slightly under the performance of the datum (acceptable but not preferable), a two being equal to the datum (sufficient), a three being slightly better performance than the datum (good) and a four being far above the datum (ideal). The scores for individual attributes were summed to give the total score for each system configuration.

Table 19. Decision Matrix Used to Evaluate Concepts.

	Benchmark of the Combinations of the Morphologic Box										
ME-POWERED CP-HM											
combinations	**1142**	**3142**	**1144**	**1141**	**1244**	**3232**	**3122**	**1412**	**1442**	**4412**	**1143**
few parts	3	1	3	2	2	1	2	3	2	2	2
easy usage (easy attaching to wheelchair)	4	4	4	1	3	0	2	2	4	1	3
easy maintenance (high durability)	4	2	3	2	2	2	1	2	2	1	2
easy production (low complexity)	3	1	4	3	2	1	2	4	3	0	2
good driving beahiour friction, low yawing, low weight)	4	2	3	2	0	0	3	3	3	0	4
total	***18***	***10***	***17***	***10***	***9***	***4***	***10***	***14***	***14***	***4***	***13***
ranking	1	5	2	5	6	7	5	3	3	7	4

Rating Scale: 0-unsatisfactory, 1-just acceptable, 2-good, 3-ideal.

3.6 Top 3 Concepts

Our evaluation resulted in the selection of our top three concepts, but they are slight variations of our top concept. This is because some of the concepts developed for particular subsystems were better than others in that category, and were therefore used on all of the best complete system designs. The description and sketch of our top concepts are provided below. The top concepts use the flexible shaft and the lever coupling with variations of the drive placement and the gearing method.

Variation 1 – 1142 (Highest Scoring Concept Overall)

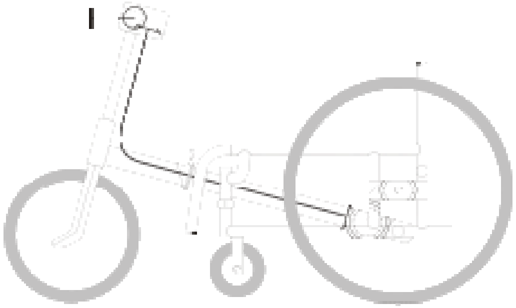


Figure 3. Concept Idea 1142, Sketch by Manuel Fischalek

Power transfer method: Flexible Shaft

Rear Drive: Rear-Mounted Differential

Coupling: Lever with Latch

Gearshift: Internally-Geared Hub

Advantages

- Easy attachment
- Minimal number of parts
- Smooth, stable operation

Disadvantages

- Requires chain between internally-geared hub and differential

Why it works best:

The flexible shaft is the best option for power transfer, as it has fewer parts than the other system, and transmits torque despite the changing steering angle. The rear-mounted differential solves the requirement for differential steering, and coupled with an internally-geared hub, provides a range of gearing options that will be relatively quiet during operation and shift while the vehicle is stopped. The use of a lever in conjunction with the appropriate linkage and a latch would easily bring the wheelchair to the correct angle to lift the front casters off the ground and secure the attachment, all in one smooth motion.

How it meets the specifications:

The drivetrain components would provide smooth power transmission with minimal losses, and not interfere with the steering function. The differential would maintain a similar steering radius to that of the wheelchair on its own. The internally-geared hub would provide a range of gears to achieve the specified cruising speed and ability to climb the specified grade. Ease and speed of attachment would be accomplished with the lever and latch mechanism.
The only disadvantage to this design is the need for a chain between the internally-geared hub and the differential under the user's seat. Guards will have to be put into place to keep clothing and body parts out of the mechanism for safety.

Variation 2 – 1144

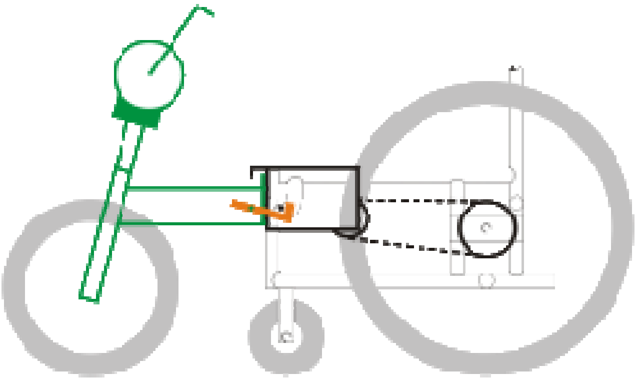


Figure 30. Concept Idea 1144, Sketch by Stefan Fischer.

Power transfer method: Flexible Shaft
Rear Drive: Fore gearbox to aft differential

Coupling: Lever with Latch
Gearshift: Planetary gears in cranks

Advantages

- Simple, low maintenance design
- Easy attachment
- Shifting from stop is possible

Disadvantages

- Planetary gear mechanism is expensive

Why it works best

Because most of the parts for this design are off-the-shelf, there is little fabrication necessary for this design. Most of the necessary manufacturing time will be for assembling the various components.

How it meets the specifications

This assembly has few moving parts so it is easy to manufacture and easy to assemble. This lever-latch design makes attachment of the device quick and easy– the device is locked into place, the coupling is engaged, and the wheelchair is inclined such to raise the casters, all in a single motion. The flexible shaft can handle the low-speed, high-torques we expect. The planetary gear mechanism and the flexible shaft are both enclosed in custom housings so there is little or no maintenance needed to maintain smooth operation. The flexible shaft eliminates the need for a complex network of gears and joints to transfer the rotation of the cranks to the longitudinal axis of the wheelchair, so the efficiency of the power transfer is maintained.

Variation 3- 1442

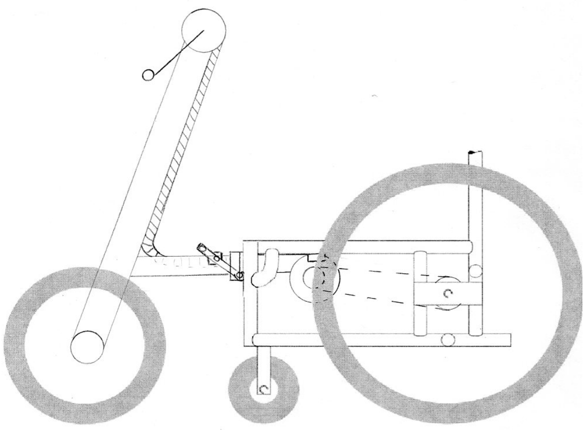


Figure 31. Concept Idea 1442, Sketch by Bjorn Sorenson

Power transfer method: Flexible Shaft

Rear Drive: Fore Gear Set to Rear internal hubs : One chain per rear wheel w/ freewheels

Advantages

- Simple, low maintenance design
- Easy attachment
- Shifting while at a stop Utilizes off-the-shelf parts
- Easy attachment
- Smooth, Stable Driving Behavior
- Use of two freewheels eliminates need for differential

Coupling: Fixed with latches

Gearshift: Internal Hub

Disadvantages

- Fore gear set increases part count
- Use of two chains will be noisy, dirty, and add complexity

Why it works best

This system takes advantage of a flexible shaft. This shaft will allow for easy turning while maintaining a power transfer to the rear wheels. The coupling works with a simple latch interface. This latch will allow a single person operation.

How is meets the specifications

The internal hubs will allow the user to meet all of the speed specifications by easily changing gears. With the latch interface the user will be able to attach and detach quick and easy. The flexible shaft will transfer the power to the rear wheels while maintaining efficiency and allowing a tight turning radius. The flexible shaft and internal hubs will be able to handle the torque required to reach the maximum speed in all types of driving conditions. Overall, the complete system will be lightweight and have a low number of parts. Parts needed to build this system can be purchased off the shelf and reduce manufacturing time.

3.7 Other Concepts

The following are the other concepts generated by combining various subsystem ideas from the decision matrix above. These ideas scored lower on the Benchmark Evaluation so we are not considering them to be viable solutions for our final design.

Concept 1141

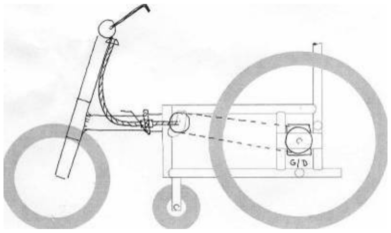


Figure 32. Concept Idea 1141, Sketch by Colin Neunuebel.

Power transfer method: Flexible Shaft
Rear Drive: Rear-mounted differential

Coupling: Fixed with latches
Gearshift: Traditional Derailleur System

Advantages

- Easy attachment
- Uses off-the-shelf parts

Disadvantages

- Requires entire bicycle drivetrain under chair, noisy, dirty, exposed parts presents safety hazard.
- High number of parts presents increased maintenance hassle.
- Cannot shift while stopped

Concept 1143

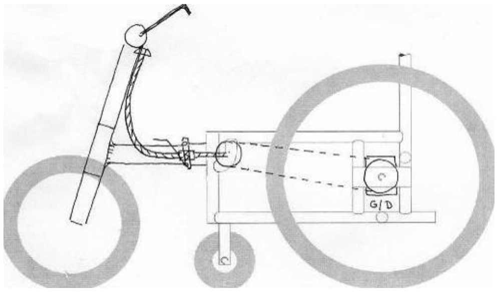


Figure 33. Concept Idea 1141, Sketch by Colin Neunuebel.

Power transfer method: Flexible Shaft
Rear Drive: Rear-mounted differential

Coupling: Fixed with latches
Gearshift: Continuous (automatic) gearshift

Advantages

- Simple, low maintenance design
- Easy attachment

Disadvantages

- Automatic gearshift is complex and not readily available
- Gearshift method does not allow shifting at a stop

Concept 3142

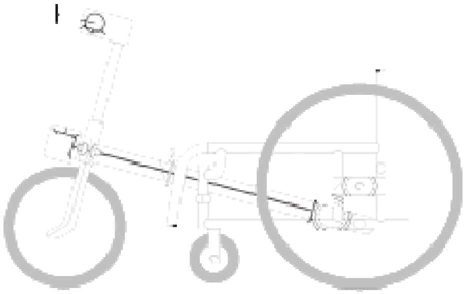


Figure 34. Concept Idea 3142, Sketch by Manuel Fischalek.

Power transfer method: Universal Joints
Rear Drive: Rear-mounted differential

Coupling: Fixed with latches
Gearshift: Internally-Geared Hub

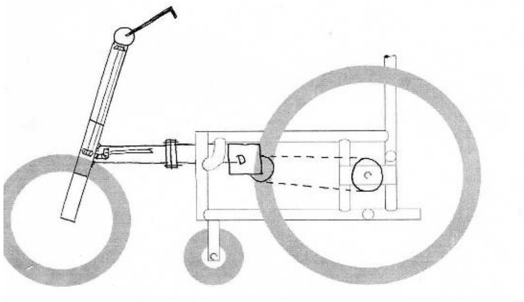
Advantages

- Easy attachment

Disadvantages

- Universal joints will complicate manufacture
- More moving parts than is necessary increases maintenance
- Questionable steering performance

Concept 4412



cept 4412. Sketch by Colin Neunuebel.

Power transfer method: Circular Gears
Rear Drive: Fore Gear Set to Rear internal hubs : One chain per rear wheel w/ freewheels

Coupling: Wing Nuts Secured
Gearshift: Continuous (automatic) gearshift

Advantages

- Simple mechanism for attachment

Disadvantages

- Complex system for transferring power
- Lots of parts
- Low ease of use

Concept 3122

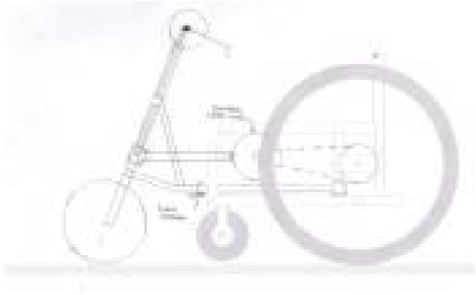


Figure 36. Concept Idea 3122. Sketch by Lazer Vandenhoek.

Power transfer method: Universal Joints
Rear Drive: Fore gearbox to aft differential

Coupling: Bicycle quick release
Gearshift: Internal gear hub

Advantages

- Gearshift method allows for shifting while at a stop.

Disadvantages

- Requires a lot of moving parts
- Coupling system is hard to allign

Concept 1412

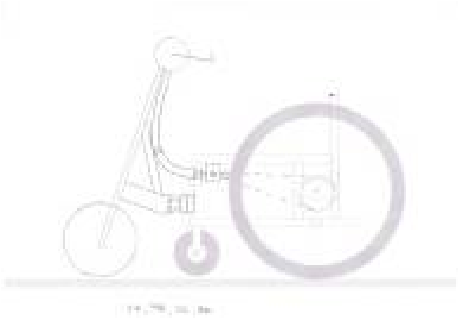


Figure 37. Concept Idea 1412. Sketch by Lazer Vandenhoek.

Power transfer method: Flexible Shaft
Rear Drive: Fore Gear set to Rear Internal Hubs

Coupling: Wing Nut
Gearshift: Internal Gear Hub

Advantages

- Simple, low maintenance design
- Good Driving Behavior

Disadvantages

- Hard to align wing nut interface
- Low safety due to wing nuts

Concept 3232

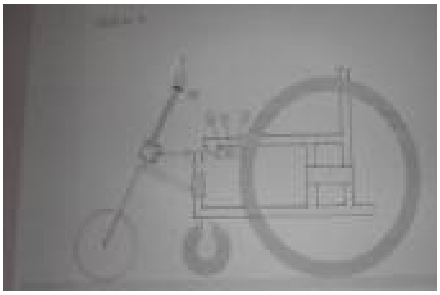


Figure 38. Concept Idea 3232, Sketch by Georg Bergmeier.

Power transfer method: Universal Joints
Rear Drive: Friction Drive

Coupling: Fixed with Clamp
Gearshift: Internal Gear Hub

Advantages

- Shifts while not in motion

Disadvantages

- High maintenance
- Lots of parts
- Friction drive slips when wet
- Coupling system would be challenging to align

Concept 1244

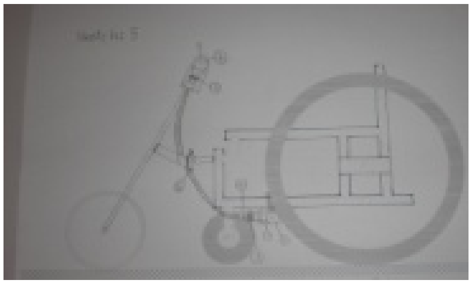


Figure 39. Concept Idea 1244, Sketch by Georg Bergmeier.

Power transfer method: Flexible Shaft
Rear Drive: Friction Drive

Coupling: Fixed with latches
Gearshift: Planetary Gear set

Advantages

- Flexible shaft reduces number of parts

Disadvantages

- Friction drive loses efficiency when wet
- Planetary Gear set is expensive
- Lots of parts

Chapter 4: Description of Final Design

4.1 Plans for Construction and Testing

Naturally, in the months ahead, we will have to build this device and test it for failure modes. We plan on using as many off the shelf components as possible in order to minimize manufacturing time as well as standardizing the device for ease of maintenance and replacement of parts. We are all competent fabricators to some degree, having taken welding, casting and machining classes at the university.

4.2 Detailed Design Description

We are proceeding with the design that scored the highest in our selection process (see Variation 1-1142). The user will turn a hand crank that spins on bearings, and translates the torque via bevel gears to a flexible shaft. The flexible shaft will mate to a solid shaft, that ends in another set of bevel gears, that will drive (via a chain), the drive cog in an internally-geared hub, which will provide a range of seven gears for different conditions. The output of the hub will drive a chain to a differential. Special hubs with threaded fasteners have been incorporated to allow for "quick release" of the wheels. To attach/detach the device, we will be using a lever and latch mechanism, which should secure the device and lift the front casters off the ground in one motion. A sleeve within the coupling will engage the solid shaft of the wheelchair gearbox by sliding a lever on the top of the coupling. An isometric view of the complete assembly has been included below. For detailed drawings, please see Appendix E.

Figure 40. Complete Assembly Drawing of Prototype

4.3 Material, Geometry and Component Selection

The primary consideration for materials in this project is the strength to weight ratio. The device is an attachment, and as such, must be easily removed, stowed, recovered and reattached. We plan on using hollow tubing rather than solid stock for the axles and main tubes of the device's frame. Fortunately, the trend in bicycle component manufacture is also towards lightweight components which maintain their strength, so it will be possible to shave ounces off the front wheel, fork, brake and cranks through careful component selection.

As for the geometry of the device, the greatest limiting factor is the flexible shaft. Due to the torque requirements, the minimum radius for the shaft is 12 inches. This takes up a considerable amount of space, since the entire wheelbase of the wheelchair and current device is less than 39 inches. The only other major consideration is the angle of the head tube, because this radically affects the handling characteristics. Initial analysis of some of the subsystems can be found in Appendix B.

Component selection is based on availability and ease of maintenance. Where possible, standard bicycle components are being used so that replacements are easily found, and any bicycle mechanic can perform the required maintenance. Again, for parts that we will be manufacturing, strength and weight have driven the material selection and design.

The components we are planning on using and their related costs are listed below:

Table 20. Project Components and Cost Analysis

Function	Off the Shelf Component	Material (If Fabricated)	Cost			
			Base	Tax	Shipping	Total
Grips	Generic Bicycle Grips		10	0.725	0	10.725
Handlebars		Aluminum Bar Stock	10	0.725	0	10.725
Cranks	Generic Bicycle Cranks		45	3.263	0	48.2625
Crank Bearings	Generic Bicycle Bottom Bracket		25	1.813	0	26.8125
Top Bevel Gears	Bevel Gears (Pair)		100	7.25	0	107.25
Stem		Aluminum Bar Stock	10	0.725	0	10.725
Head Tube		4130 Chromoly	25	1.813	0	26.8125
Headset	Generic Bicycle Headset		25	1.813	0	26.8125
Fork	Generic Bicycle Fork (16" Wheel)		50	3.625	0	53.625
Front Wheel	Generic Bicycle Front Wheel (16")		25	1.813	0	26.8125

Front Inner Tube	Generic Bicycle Inner Tube (16")		3	0.218	0	3.2175
Front Tire	Generic Bicycle Tire (16")		20	1.45	0	21.45
Basket	Generic Bicycle Basket		20	1.45	0	21.45
Connecting Tube		4130 Chromoly	25	1.813	0	26.8125
Self-Centering Spring	Standard Tension Spring		7	0.508	0	7.5075
Flexible Shaft (w/ Couplings)	S.S. White		200	14.5	15	229.5
Lower Bevel Gears	Bevel Gears (Pair)		100	7.25	0	107.25
Latching Mechanism		Stainless Steel (Handle, Linkage, Pins)	50	3.625	0	53.625
Shifter	Shimano Nexus 8spd.		0	0	0	0
Gearbox	Shimano Nexus 8spd. Internally-Geared Hub	Includes Shifter ->	230	16.68	0	246.675
Chain	Generic Bicycle 8spd. Chain		15	1.088	0	16.0875
Differential	Pfau-Tec		150	10.88	15	175.875
Axles		Steel	10	0.725	0	10.725
Axle Joints		Steel (Brackets, Pins)	10	0.725	0	10.725
Brakes	Bicycle V-Brake and Lever		50	3.625	0	53.625
Brackets and Mounting Hardware	Standard Hardware Store Variety		40	2.9	0	42.9
Miscellaneous (Welding and Machining Supplies, etc…)	Misc.		20	1.45	0	21.45
Totals			1275	92.44	30	1397.4375

For the time being, this is the complete parts list. Prices were estimated based on current retail price. Ratios of typical prototype cost to mass production costs were not readily available. Currently, most handcycle attachments retail in the $800 range. The device we are constructing is somewhat more complex, as it contains a differential and a method for driving the rear wheels. As a result, it seems reasonable that our product should retail for $1000. If it were possible to reduce production cost by 50% on a scale of 100 units, the resulting profit would be $300 per unit. This should be a reasonable reduction, because the gears, flex shaft, differential and shifting components are the largest cost items, and a bulk discount for each of these components would significantly reduce the overall per unit cost.

4.4 Testing

A Design Verification Plan and Report has been created for testing our product (see Appendix C). Testing will be accomplished primarily by four different methods.

1. Visual Inspection- Many of our specifications can be easily measured with standard tools (ruler, scale, etc...)
2. Computer simulation/analysis- Before construction even begins, a complete model of the device and all of its parts will be developed in CAD software. This software enables a certain amount of geometric, weight and force analysis.
3. Hand Calculations- Mechanical design principals will be utilized to theoretically test for yield and fracture strengths, handling characteristics, etc... If in doubt, preliminary models of certain parts might be constructed and put through destructive testing before implementation of the actual component.
4. Test Drive- Ultimately, we will have to drive what we have built and evaluate its performance. It will then be given to Mr. O'Kelly to drive and evaluate as well. There is no substitute for real world performance analysis.

4.5 Safety Considerations

There are several primary safety considerations for this project. The first of these is "rollover". Our system is providing the power to move forward through traction at the rear wheels. In a wheelchair, since the center of gravity is so far aft, driving the rear wheels increases the likelihood of the user tipping over backwards onto their back. Mr. O'Kelly's current wheelchair has an extra set of casters mounted on arms in the rear to provide support when one wheel is off. We will most likely modify these to provide a reaction against tipping over backwards. Testing will be necessary to insure that it is not at all possible for the user to tip over backwards.

The second safety consideration is keeping the user safe from the moving machinery. The latch mechanism provides a potential pinch point, and the user's hands and clothing could be caught in the gears and chain. Wherever possible, the machinery will be enclosed in housing, and the latch will have to be designed to avoid any harm to the user. Careful design and testing should prevent any potential for injury from these components.

A third safety consideration is insuring that the crank mechanism does not come into contact with the user's legs. If the user is cranking while turning, there is the potential for the crank to get stuck in the user's lap, and they may not be able to turn back out of the steering angle. Since Mr. O'Kelly wants the cranks raised higher than they are on his current setup, it should not be a problem for him, but if we make the crank height adjustable for a range of users, this will have to be taken into account.

Finally, handling and braking characteristics will have to be rigorously tested to insure that the user can turn under high speeds to avoid obstacles (while going downhill, for example) and go from a high speed to a stop in a safe distance.

4.6 Maintenance and Repair

This device is being designed with as many "off the shelf" components as possible. As can be seen in Table 20, the majority of the parts are standard bicycle parts, so any bicycle shop should be able to provide replacements. Maintenance will include standard maintenance for the chain (clean and lube once a year, or seasonally in wet weather). Because the gearing is internal to the hub, and the differential is a sealed part, these components should not require any maintenance. The latch pivots might require oil once a year if the movement becomes difficult. Brake pads will have to be periodically checked for wear and replaced when they become too thin. Tires will also have to be checked for wear and replaced when tread becomes too low.

4.7 Analysis Results

To anlayse our design, we have used several of the engineering tools that we have learned (see Appendix B for examples). Once 3-D models were made in a CAD program, the weight was analysed to insure that the product would not be too heavy. The components that are permanently fixed to the wheelchair weigh just over 20lbs, and the attachment weighs just over 16lbs. This is a little on the heavy side, but fortunately, the majority of the weight will be carried on the wheelchair, and the lighter of the two halves is the part the user actually has to lift. Furthermore, the rear portion of the wheelchair has some components which may be machined to reduce the weight from the original castings (this is pending further analysis).

As for the strength of the device, most of the necessary testing will be on the components that we have to manufacture ourselves. This is because the off-the-shelf components are all from the cycling industry, which are tested for the greater loading that results in pedaling with the legs instead of rowing with the arms. During the initial live presentation of our design, the gusset between the head tube and down tube was scrutinized by the audience, and deemed worthy of some revision. We have since done some finite element analysis (see Appendix C), which proves that the original design was probably sound, but we are considering a new, adjustable connection, which should be even stronger.

Chapter 5: Design Verification Plan (Testing)

Analytical testing of the performance of the model will be ongoing from here on out as iterations of the design evolve. In addition to this mathematical analysis, we have developed a Design Verification Plan (see Appendix C) to physically test the performance of the prototype once it is assembled. We feel that post-assembly testing is sufficient, as the parts will either be off the shelf, and therefore tested for more severe usage conditions, or will be subjected to mathematical analysis if we are manufacturing them.

Chapter 6: Project Management Plan

One of the first things we did for this project was establish a Gantt chart (a type of timeline, see Appendix D) for the project as a whole. This is a way to track both the projected and actual number of hours spent on the project for comparison. It also keeps us on task, by providing an overview with all of the important deadlines.

As was mentioned earlier, in the design phase, we paired up one CalPoly student with one HM student for each of the subfunctions. The project up to this point has been highly collaborative, but once it was time to design the specifics of the model, and now that we are actually ready to build the prototype, we have divided the project into the rear half of the device (all of the components which will be fixed to the wheelchair), which will be handled by the HM students, and the front half of the device (the attachment), which will be handled by the CalPoly students.

Whereas we are buying as many off the shelf components as possible, it is our goal to manufacture as many of the custom components ourselves as we are able. Due to the different facilities available to each half of the team, it is possible that some components may have to be manufactured by the half of the team that is not working on that particular half of the project. As a result, shipping times for components and materials will factor heavily into our production schedule.

Chapter 7: Manufacturing and Testing

We put much effort, thought, and time into generating ideas for this system. Once we decided on a final design, a complete 3-D CAD model was developed (see Appendix E). We have made every attempt to use off the shelf parts, but the fact that this hasn't ever been done means that it is still a very manufacturing-intensive project. Prior to manufacturing, the final design met all of the specifications and requirements. Since there were no problems with the 3-D CAD model, we proceeded on to manufacturing.

The HM students built the drive train components and parts of the attachment that are on the wheelchair. The Cal Poly students built the front section with the wheel, cranks, flex shaft, basket, and brakes.

7.1 Manufacturing

The final design incorporated many parts that were available off the self, but it also included a lot of custom machined and fabricated parts. Manufacturing was split up between the front hand cycle attachment and the rear wheelchair section. Due to the fact the H.M. students and the U.S. students could not meet in person to complete the task of manufacturing, the decision to split the manufacturing up seemed like the easiest way. Manufacturing began on April 9th and was completed on June 3rd. Final assembly was completed by the U.S. students at California Polytechnic University in San Luis Obispo, California once all of the manufactured parts arrived from Germany. To complete the manufacturing process students had to utilize machine shops available to them on their respected campuses. All of the students came into this project with limited machining, welding and fabrication skills, so the entire process would be an experiment in "learn by doing".

7.1A Equipment Used in Fabrication

The students used a variety of machines and tools to manufacture and assemble the final design. To complete all the manufacturing required for the final design, the students used the following machines:

- Computer Numerically Controlled (CNC) Mill
- Lathe
- Drill press
- Vertical and horizontal band saw
- Chop saw
- TIG and MIG welders
- Pneumatic tools
- Tube bender and notcher
- Hydraulic press
- Variety of hand tools

7.1B Materials Used

In order to get the strongest parts with the lightest weight possible, the majority of the parts were fabricated from 6061-T6 aluminum. This alloy of aluminum is ideal for welding and machining. Aluminum was purchased in billet form, bar stock, and tube stock as necessary.

For parts that would be subjected to larger loads and so required more strength, such as the head tube and steer tube, 4130 chromoly steel was used. This is a common alloy used in bicycle fabrication so it was a logical choice for our application. 4140 heat-treated steel was used for the bottom bracket spindle and the shaft between the gearbox and the flexible shaft.

7.2 Rear Wheelchair Section Fabrication

The manufacturing of the Rear Wheelchair Section was the responsibility of the HM students and most of its components were fabricated in Germany. It was essential that these parts be completed in a timely matter in order to allow for testing of the parts in Germany and then shipping to the US and to allow for assembly and testing in the US.

The first parts to be fabricated in Germany were the axle mounts with quick release mechanism and the frame clamps. These parts were shipped with the Pfau-Tec differential and the Shimano hub in late April and they arrived in the US in early May.

Due to the fact that the H.M. students did not have access to welding equipment, the sub frame would be manufactured in the U.S. The fabrication of the sub-frame began soon after the first parts arrived from Germany. We received the plans for the sub-frame and ordered the necessary aluminum tube stock.

While fabricating the subframe, we ran into some minor issues with measuring units. The part was designed in metric units, but the tooling we used (tube bender and tube notcher) and the tube stock we ordered were all in inches. The first solution was to simply convert all units and build according to the plans, however the tube stock was not the same size as specified in the plans (1 ½” versus 35mm=1.37”). Eventually, we decided that the simplest and fastest way to solve this was to redraw the part in Solidworks using inches since not all of the specified dimensions in the original design were important to proper operation and fit of the subframe. We preserved the most critical measurements and proceeded with fabrication.

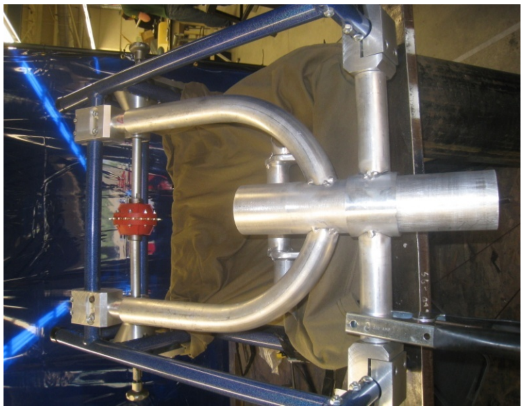


Figure 5. Subframe assembly mocked up and tack welded in wheelchair frame.

To make sure that all of the parts of the subframe were assembled so that it fit on the wheelchair frame and the drivetrain components fit properly, we “dry-fit” all of the tubes in the wheelchair frame and tack welded everything. Once we decided that all of the parts fit correctly, we removed the subframe from the wheelchair frame and finished welding all of the tubes.

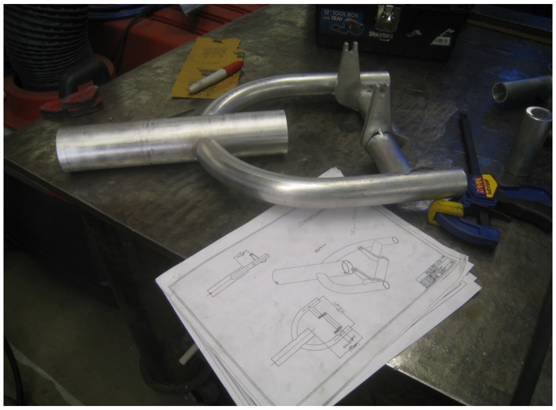


Figure 6. Subframe assembly tack welded and ready for final welding.

Figure 7. Final welding of subframe.

The final part to be completed was the coupling mechanism. There was a long delay on finishing this part because special tooling was needed to cut a spline in the drive shaft inside of the coupling. The tooling arrived at the HM shop on May, 18 and after one week of fabrication and brief testing it was shipped along with the wheelchair gearbox, the splined shaft that connected the coupling to the wheelchair gearbox, the coupling mechanism, and the hardware and instructions for assembly. These parts finally arrived in the US on June 3rd at approximately 12pm.

7.3 Attachment Fabrication

The “learn by doing” environment allowed the students to make manufacturing errors while using unfamiliar machines. Extra raw material was ordered for this very reason. Almost every component presented challenges that we could not have anticipated from the drawings.

7.3A Gear Box and Headset Components

The first component we fabricated for the attachment was the Gearbox and Headset assembly. The gearbox housing was made of 3/8” aluminum plates secured with socket-head cap screws. It was very important that all sides of the gearbox were made square and accurately sized so that the gears inside would mesh correctly and that the shaft would turn without binding.

We discovered when we started milling the plates that it would be difficult to get the plates square and all the correct size even with the precision mills available at the Cal Poly machine shop due to our limited machining experience. After several tries, we opted to ask the techs at the Mustang 60 shop to make the gear housing with CNC equipment.

7.3B Using the CNC Mill

Originally, we were going to mill the plates to size, and have the techs CNC mill them to spec. We learned the hard way that the vice holding the part had to be squared off with the table holding the vice. This being our third attempt, we decided to have all of the plates in the gearbox cut from stock and machined to spec by the CNC machine.

7.3C Steering Assembly

7.3D Junction

7.3E Wheels

7.4 Final Assembly

The largest modification was made to the 7-speed hub mounts. These mounts needed to be relocated to correct chain tension and chain alignment.

7.5 Testing

After final assembly of the device, it was time to test it.

7.5A Initial Tests

Right away, we could tell that there were going to be issues with this design. The HM students tested their coupling device to the best of their ability, but without the rest of the device assembled, there was no way to test it under load. The coupling successfully lifted the front casters of the wheelchair off the ground, but the sleeve that slid over the wheelchair gearbox’s drive shaft had to be perfectly aligned, which was not smooth once the interface was attached to the rest of the device. Consequently, it took a pry bar to engage the splines, rather than the use of just the handle provided.

Secondly, the device overall was too long, which made the reach required of the user to exceed normal expectations. The coupling stuck out too far from under the wheelchair, and since we did not have the machining capability to cut new splines onto the drive shaft, we could not cut the shaft and shorten the downtube on the wheelchair side. Furthermore, the space required by the flex shaft couplings made it impossible to shorten the downtube length on the attachment.

We decided to test the device anyway, and managed to drive the device out of the shop. Unfortunately, we only got about 10 feet before the flexible shaft broke. We believed that the bend radius was too tight, but since it was 2:30 AM the day of the design expo, there was nothing left to do but make the project look presentable and wait for another chance to get back in the shop.

7.5B Final Re-working of the Design and Final Tests

The week after the expo and graduation, we reconvened to see if the device was at all feasible. Armed with a new flex shaft, and some ideas about how to prevent a second flex shaft failure, we set to work. It was determined that in the previous configuration, the flex shaft was being bent in the single direction for which it was designed, but was also being bent around the head tube when steered, which probably contributed to the first failure. We used a u-joint at the top of the attachment, where the shaft meets the gear box to handle the steering bend, so that the flex shaft would only have to make one bend. This worked, and by putting the device “up on blocks”, we tested the drivetrain without the added load of an operator. It worked well, but when a drag load was applied to the tires, the flex shaft started to deflect laterally, and all power was lost. From this, it was determined that the flexible shaft had to be secured in order to transmit the maximum amount of power (it should be noted that this was nowhere in the literature we researched on these mechanisms). To test the theory, we zip-tied the flex shaft in as many points as possible, which appeared to work.

Additionally, to keep the flexible shaft below its minimum bend radius of seven inches, and to improve the problem with the reach, we flipped the fork around, effectively reducing the overall reach.

We still were not ever able to get the coupling sleeve to slide smoothly over the shaft of the wheelchair gearbox, but we were able to get it to engage with the use of an extra lever, so we decided to lock it in place and road test the device.

Fortunately, the final road tests were successful. We each got to take the device for a spin around the engineering campus grounds, and the device steered and braked just fine. However, it was clear that the device was heavily overgeared. We designed the attachment gearbox with a 2:1 ratio (gear on the crankshaft, and pinion on the flexible shaft), but with the shifter set in first gear, the device still required a push start, and second gear was a real workout, even on flat ground. Gears 3-7 were basically unusable, as they caused the flex shaft to bind again. After several laps, it was determined that the flexible shaft was suffering from the same distortion that it had in the previous iteration, but this time we believe it was torque rather than an unreasonable bend radius. We decided not to test it to complete failure, as we wanted to deliver the device in as close to a working condition as possible to Mr. O’Kelly.

Chapter 8: Conclusion

As a learning experience, this project was definitely a success. We learned about all aspects of the design process from ideation to prototyping and testing; and we also learned how to conduct business internationally, which was unique to this project. Unfortunately, as a ready-for-production prototype, this project still needs quite a bit of revision.

8.1 What Worked

When we started this project, the primary goal from both our respective instructors was to establish solid communication with the other half of the team overseas. To this end, we tried several approaches, including regular email communication, a Google group to transfer files and share ideas, and weekly Skype conference calls. After a few weeks, the Google group ceased to function, but the regular emails and Skype conferences allowed us to progress towards a single, final design. So far as the international component of this project is concerned, we feel that we had a great success, in that we were able to design and build a single, highly complicated device, despite being separated by geography and a language barrier (although fortunately for us, the HM students spoke English; none of the Cal Poly students speak German).

As for the device itself, a majority of the specifications were met. The customer requirement that the wheelchair suffer minimal modification was met by using bolt-on connections. When the attachment portion of the device was not in use, the wheelchair steered normally, through the use of the differential, and ultimately, the wheelchair that Mr. O'Kelly loaned to us for this project was returned 100% to its original state.

The device did increase the user's mobility by driving the rear wheels of the wheelchair, and could still be detached so as not to be permanently in the user's way. The device could be attached or detached by the user without additional assistance in under30 seconds. The coupling properly lifted the casters of the wheelchair off the ground while securing the attachment to the wheelchair in one fluid motion.

Furthermore, the construction of the device was sound and maintenance would be minimal and easy to conduct. In a lot of cases, since we were manufacturing from idealized drawings, our machining tolerances were so precise that we had to go back and remove several thousandths of an inch to allow the proper clearance. During final assembly, almost everything fit together perfectly, and minimal revision was necessary where the mating of parts was concerned. All of the moving parts could be serviced by a mechanic in a bicycle shop. We all learned a tremendous amount about manufacturing processes, and feel much more confident using the equipment found in a standard machining/fabrication shop.

Lastly, the device handled well in the road tests. It steered in an extremely tight radius and was stable going downhill at high speeds. The front brake stopped the wheelchair almost instantly, and the coaster brake in the internally-geared hub worked properly, even through the differential. In terms of driving performance, power transfer was its only shortcoming.

8.2 Necessary Revisions & Suggestions for Future Work

As mentioned above, there are several flaws with the design that keep it from being a completely working design. Paramount among these is the use of the flexible shaft to transmit the necessary torque. It is possible that a different gear ratio (either 1:1 or 1:2) might be sufficient to reduce the stress on this component, but having two failures seems to imply that it is being used in application for which it was not designed. If a flexible shaft were to be used in future iterations, a method of securing it more rigidly would have to be investigated to minimize lateral deflections. Regardless of the power transfer mechanism, a different gear ratio for the device is inevitably required.

Second, the length of the tube protruding from under the wheelchair needs to be shorter. When Mr. O'Kelly saw the final product, he mentioned that the ideal would actually be to have the end of the coupling flush with the end of the seat of the wheelchair (ours protruded 3-4 in.). This would also be critical in shortening the overall length of the device and therefore would bring the maximum reach in to a more reasonable length.

Third, the internally-geared hub was mounted in vertical dropouts. We now know that systems with chains need a mechanism for adjustment, and since both chains of this device are dependent on each other, it was somewhat of a nightmare to get just the right length and tension in both simultaneously.

Lastly, the interface within the coupling that mated the flexible shaft to the rigid shaft did not work properly. Since the alignment of the sleeve and the shaft has to be so precise, and because there is a resistance for them to mate, it was difficult to get the sleeve to engage. We recommend a heavily tapered shaft so that the sleeve slides easily over the shaft and engages the splines more as the user pushes on the lever.

It should also be mentioned here that the device was heavy. Like 70 lbs. heavy. The weight was pretty evenly distributed between the attachment and the parts that were added to the wheelchair (about 35 lbs. front and back). To keep the device lightweight, aluminum was used wherever possible, but more of the manufactured parts could have been machined specifically to reduce the overall weight.

8.3 Final Result

The final product was delivered to Mr. O'Kelly on Friday, June 19, 2009. He mentioned that the project was intended as a "proof of concept", and appreciated the work that went into it, although both he and the students are disappointed that it is not currently useable as a working product. For us, it has been a great learning experience, and despite its shortcomings, we all agree that we have learned enough about the design, manufacturing, and testing process to enter industry at the end of our academic careers.

Appendix A. Quality Function Deployment

Hand Driven RWD
Wheelchair

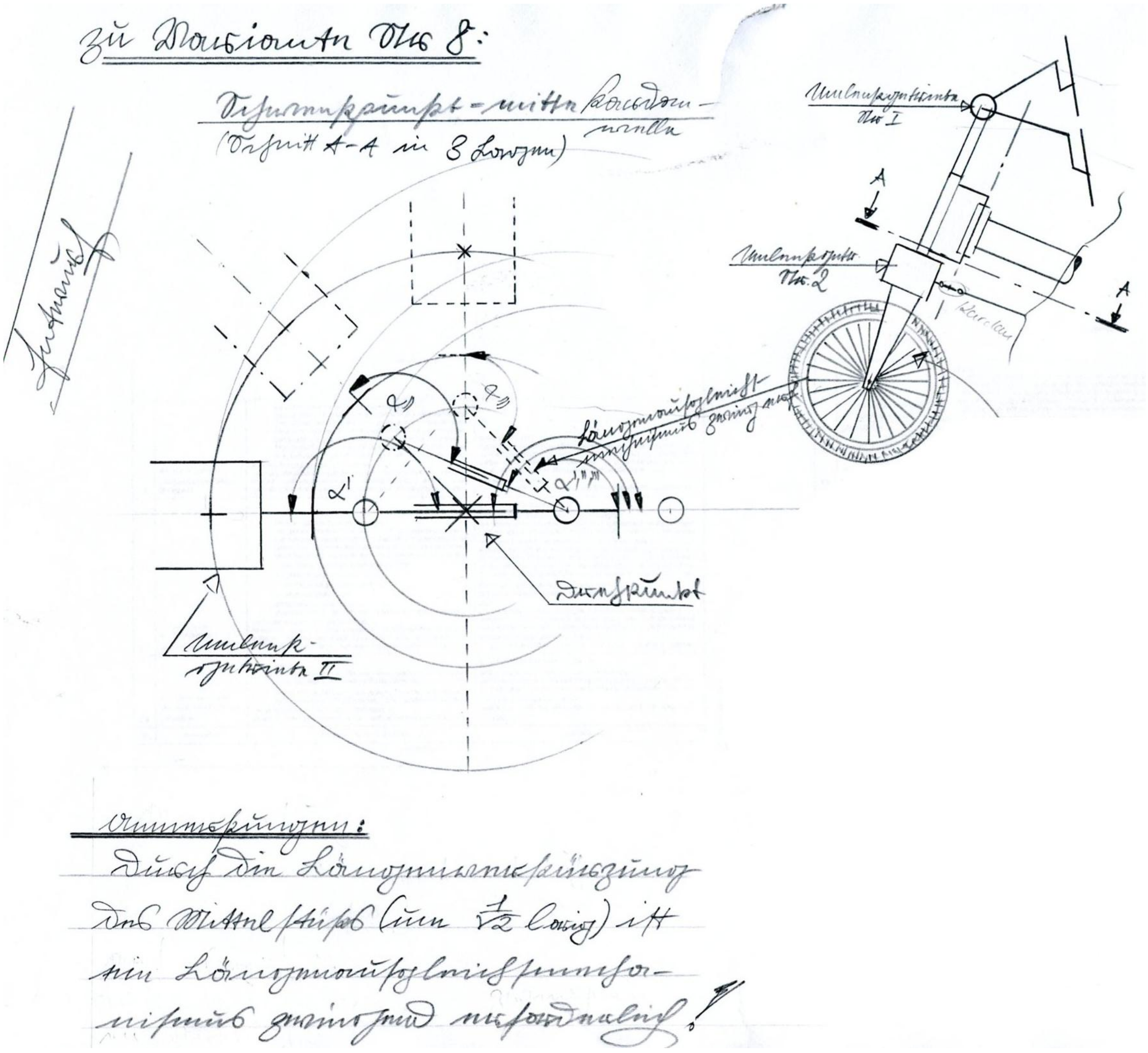
Sponsor: Greg O'Kelly Potential Additional Customers: Other Persons with Disabilities

Customer Requirements		Engineering Requirements													Benchmarks			
	Weighting (Total 100)	Rear Wheel Drive	Brakes	Steering	Attachments/Add-Ons	Shifting/Drivetrain	No Pinch Points/Exposed Machinery	Rider Weight Limit	Efficiency/Power Transfer	Adjustability	Materials	Durable Construction	Crank/Power Input Interface	Attachment Interface	Quickie Cyclone	Rio Dragonfly	Quantum Runner	Rio Pivot
Must Climb Hills	5	9				9			3		1				0	0	5	5
Hand-Powered	5		3	3					9				9	1	5	5	5	5
Detachable	5	9	3	1		9	1	3	3		3	3		9	1	4	0	5
Ability to Stop	5		9	1											5	5	5	5
Manueverable	5	3	1	9						3			1	3	2	2	5	5
Carrying Capacity	3				9			3				3			4	4	0	0
Quick to (Dis)Connect	3	9		1		3	3				3		1	9	1	4	0	1
Easy to (Dis)Connect	4	9		1		3	3				3		1	9	1	4	0	3
Minimal Modification	4	9	3	1		9	1	3	3		1			9	5	5	0	4
Lightweight (Attachment)	4	1	1	1	1	1		9	3	1	9	9	3	9	1	1	3	3
Low Maintenance	3	3	3	3		3	1		1	1	3	9	3	3	5	5	3	3
Inexpensive	3	3	3	3	1	9		1	9		9	3	3	3	1	1	0	4
One Person Operation	5													9	3	3	5	5
Cruising Speed	4	3	3	3		9			9	1	3		9		4	4	5	5
Safe	5	3	9	9		1	9			1	1	3	1	1	3	3	2	2
Won't Break	4	1	1	1		1		9			9	9	1	3	5	5	4	4
Unobtrusive to the User	4		1	9	1	3	3		3	3			9	3	2	2	3	2
Ergonomics	3		1	3	1	3				9			9	1	2	2	4	4
Smooth Operation	4	1	9	9		9			9		1		9	3	2	2	5	5
Size	4			9	3	1		3	1	1	1		1	9	3	3	5	5
Forward/Reverse	2	3	1			3			3				3		0	0	5	5
Aesthetically Pleasing	1				3						3				2	2	2	2
Upgradeable	1	1	1	1	1	3		3			1		1	1	3	3	3	3
Accommodate a Range of Users	4				3	1		9	1	9			3		2	2	1	4
Manufacturability	3			3		3					9	9	1	1	4	4	4	4

9 = strong correlation   3 = some correlation   1 = weak correlation   blank= no correlation

Appendix B. Preliminary Analyses

Constant Velocity Joint Diagram



zu Variante Nr. 8:

Schwenkpunkt-mitte Kardan-welle
(Schnitt A-A in 3 Lagen)

Anmerkungen:
Durch die Längenveränderung des Mittelstücks (um $\frac{1}{2}$ länge) ist ein Längenausgleichsmechanismus gewährleistet und erforderlich!

Figure 8. Analysis on concept of constant velocity joint for power transfer from attachment to wheelchair drivetrain

Efficiency

As we talked about the efficiency of bicycles last time, I looked up in the internet and found the following words:

Die Fahrradschaltung hat einen Wirkungsgrad von 95 Prozent (einfache Nabenschaltung) bis 99 Prozent (hochwertige Kettenschaltung). Der Gesamtwirkungsgrad eines Fahrrades beträgt je nach Pflegezustand, Fahrweise und verwendeter Technik unter 70 bis über 90 Prozent. Der Mensch wird oft unterbewertet, die technischen Merkmale des Fahrrades zu hoch. Der Mensch besitzt einen technischen Wirkungsgrad von etwa 25 Prozent.

Which mean in English: the drive train and gearing has an efficiency of about 95% (simple hub shifting) to 99% (for a high quality chain shifting). The overall efficiency is about 70% to 90% due to the maintenance condition of the bike. The efficiency of the human body is about 25%.

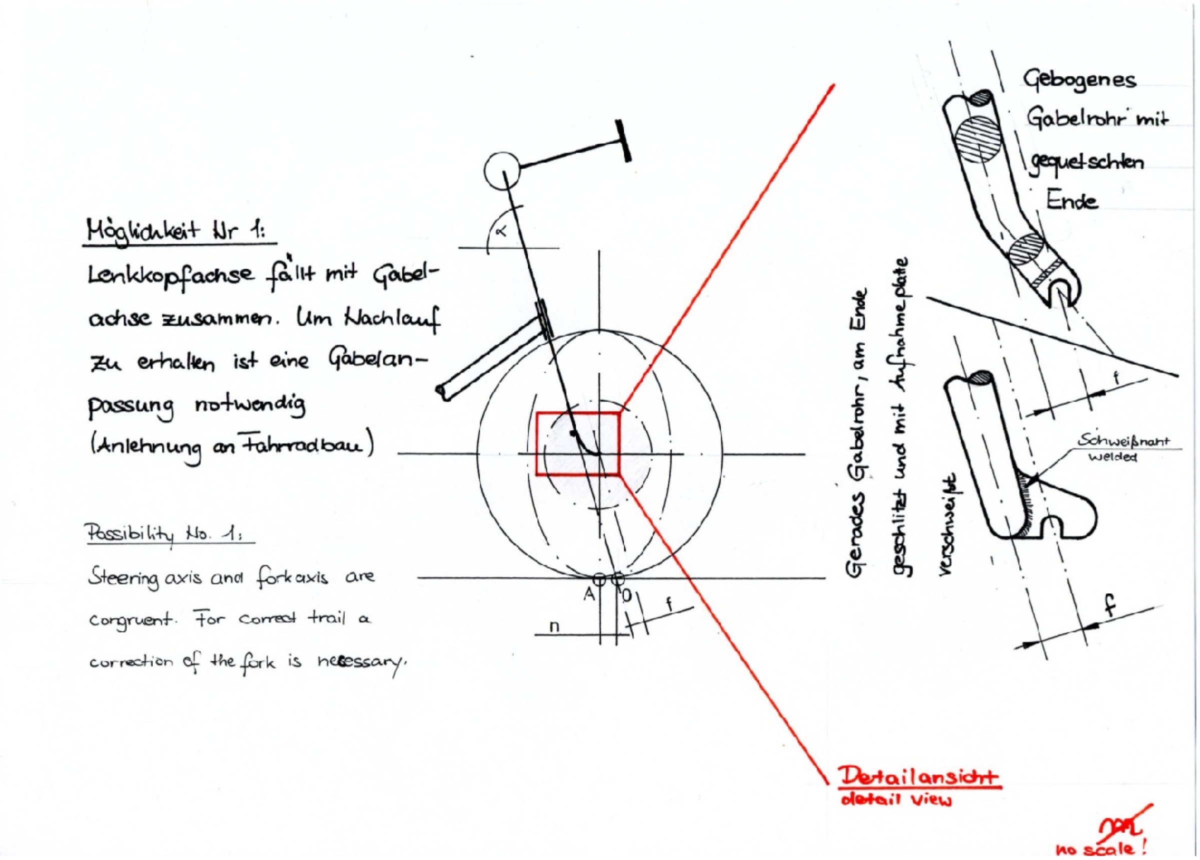
So the high 90's you found, are only for the drivetrain.

We discussed how to analyze the efficiency and concluded to leave out effects of rolling friction and wind resistance.

Trail

The following is a sketch which shows two possibilities to have a trail of about 5 cm (2 inches).

Both are common in the world of bicycles. The upper one is the more old fashioned and the lower on the maybe cheaper an in modern mountain bikes built in solution.



Möglichkeit Nr 1:

Lenkkopfachse fällt mit Gabelachse zusammen. Um Nachlauf zu erhalten ist eine Gabelanpassung notwendig (Anlehnung an Fahrradbau)

Possibility No. 1:

Steering axis and fork axis are congruent. For correct trail a correction of the fork is necessary.

Gebogenes Gabelrohr mit gequetschten Ende

Gerades Gabelrohr, am Ende geschlitzt und mit Aufnahmeplatte verschweißt

Figure 9. Diagram of possible configurations for achieving desired trail on attachment.

Calculation of Head Angle, α, for Desired Trail

Data for Similar Products:

Touring Bicycles:	Head angles: 72°-73°	Trail: 43-60mm
Racing Bicycles:	Head angles: 73°-74°	Trail: 28-45mm

Assumed Dimensions of Attachment:

Front Wheel: 16in = 406.4mm, diameter = 203.3mm, radius

Head angle: 65°-73°

Fork Offset = 38mm, standard

Goal: 45mm trail

$$Trail = \frac{203.3mm * \cos(68) - 38}{\sin(68)} = 52.83mm$$

If...

Head Angle=69°, Trail = 37.3mm

$\boxed{\text{Head Angle=67°, Trail = 45mm}}$

Note: Head angle, α, measured from horizon

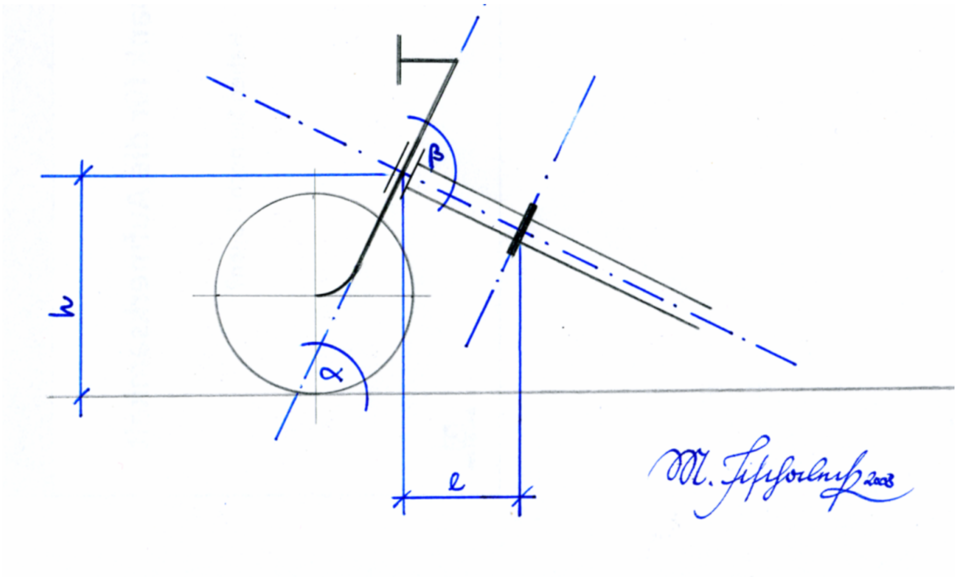
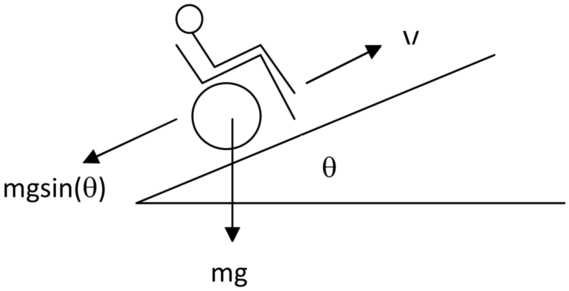


Figure 10. Diagram of attachment dimensions used for determining head angle, α, for desired trail.

Estimation of Power Needed to Propel Wheelchair Uphill for a Given Velocity

Assumptions:



- Weight: 300lb
- Slope = 20%, θ=11.3degrees
- 90% Efficiency
- Velocity=2mph=2.93ft/s

P=Fv

P=300sin(11.3)*2.933ft/s

P=174.2ft-lb/s

746Watt=550ft-lb/s (Shigley)

P=233.5Watt

$0.90P_{\text{no efficiency}} = P_{\text{actual}}$

$\boxed{P_{\text{actual}} = 260\text{Watts}}$

FEA Analysis on Gusset Estimate Deflection due to Steering to Pull

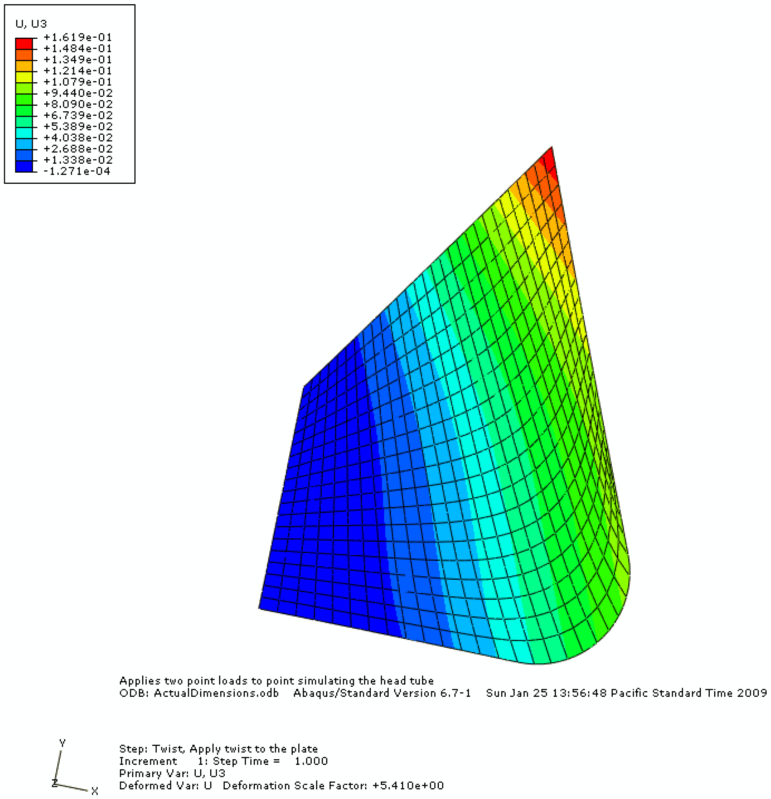


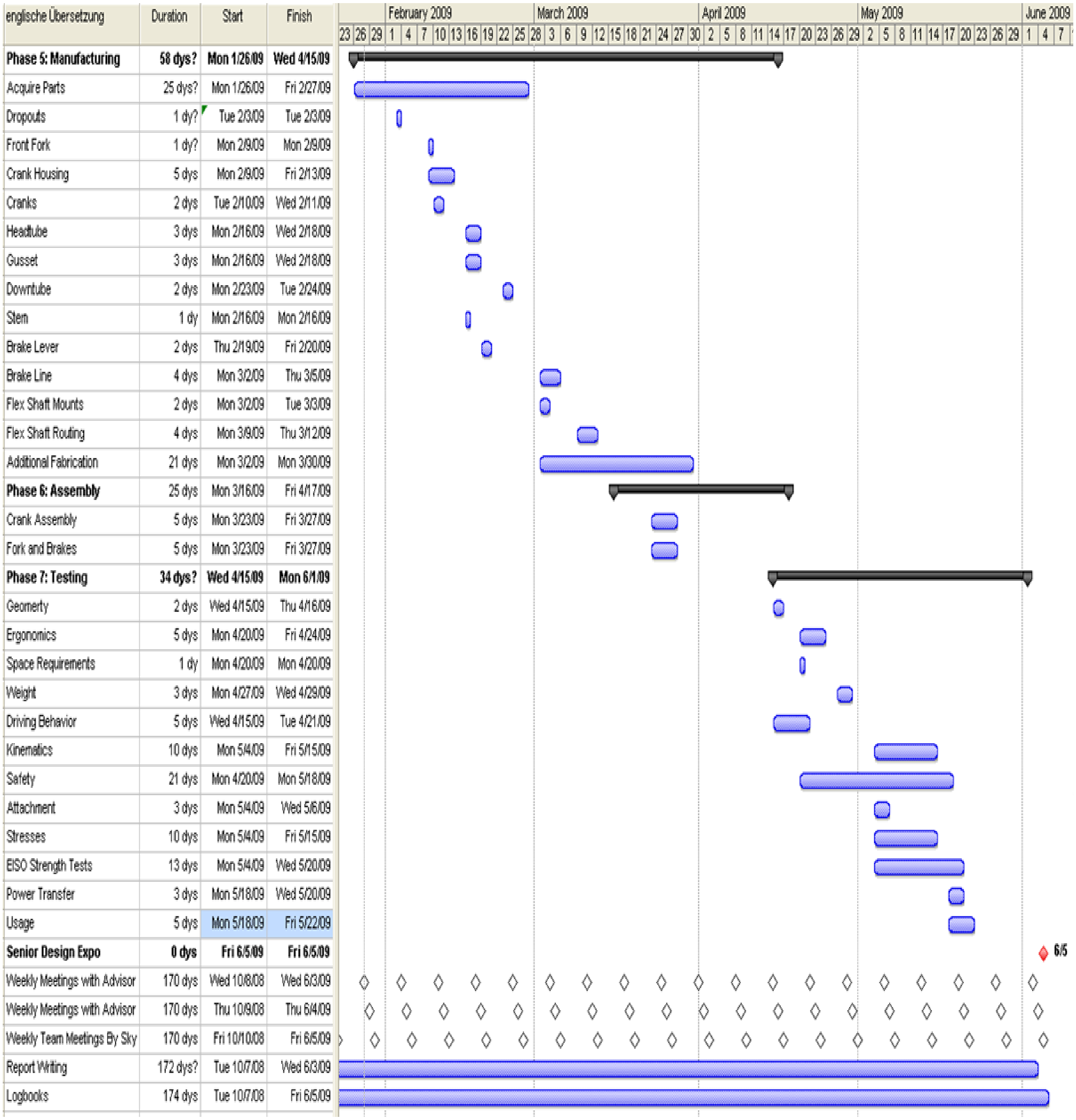
Figure 11. Results of FEA analysis on 1/4" steel gusset plate with 2-200lb loads applied at right edge normal to the plane of the gusset. (Units of deflection contour plot in inches)

To simulate the effects of steering torque or pull applied when the user pulls to the side on the cranks, 2-200lb point loads normal to the plane of the guset have been applied to the right edge of the gusset plate as shown. The left edge of the gusset has been constrained from translating and rotating in all directions (all degrees of freedom constrained). The results show that the maximum deflection of the plate is 0.169in.

These loads and boundary conditions were chosen to approximate the forces due to moment, and because the capability of the person performing the analysis is currently too limited to more accurately simulate the actual loading on the gusset. As the user becomes more familiar with the process of FEA, a more complete analysis will be performed on the part.

Appendix C. Design Verification Plan

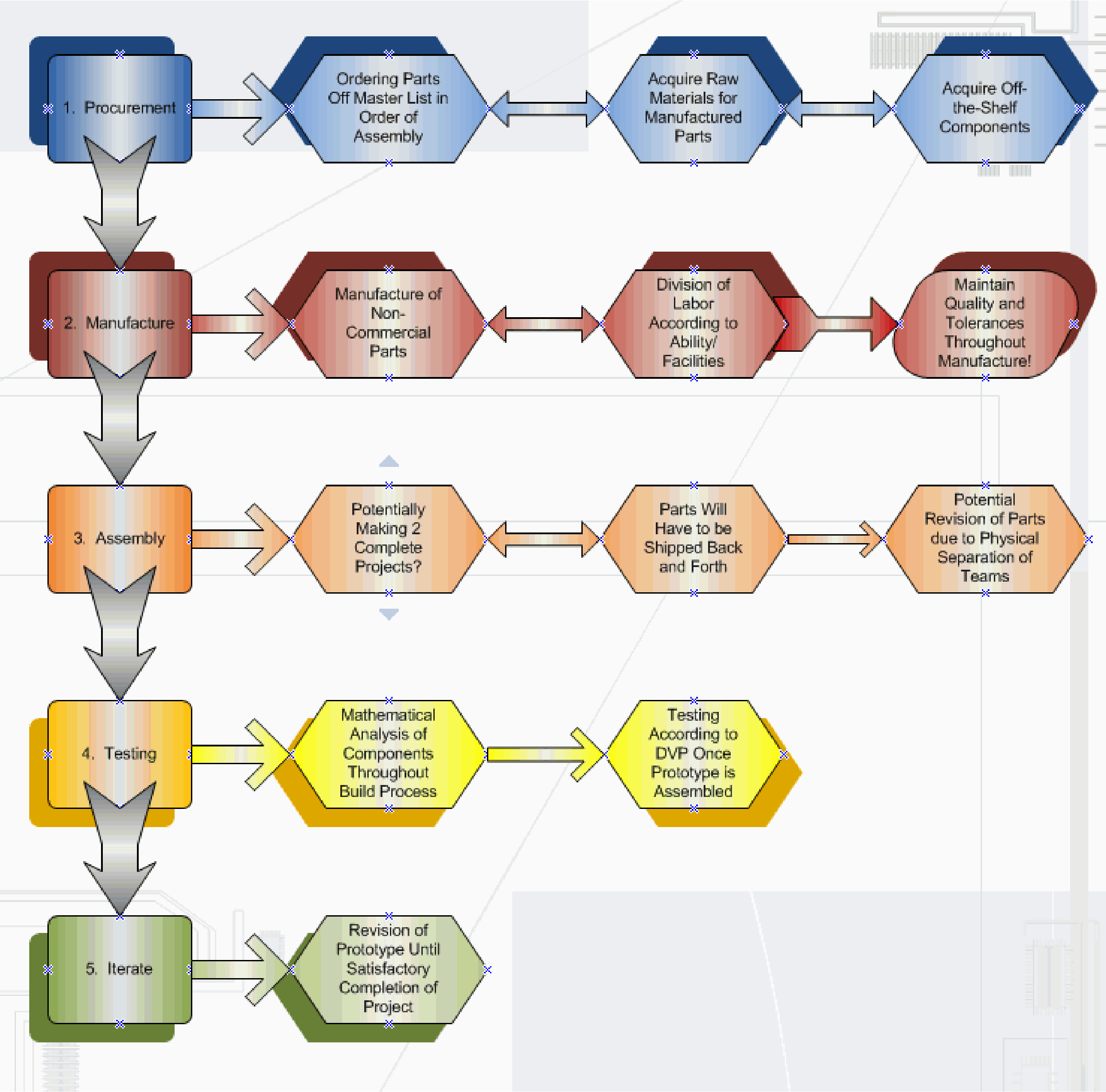
Appendix D. Gantt Chart



englische Übersetzung	Duration	Start	Finish
Phase 5: Manufacturing	**58 dys?**	**Mon 1/26/09**	**Wed 4/15/09**
Acquire Parts	25 dys?	Mon 1/26/09	Fri 2/27/09
Dropouts	1 dy?	Tue 2/3/09	Tue 2/3/09
Front Fork	1 dy?	Mon 2/9/09	Mon 2/9/09
Crank Housing	5 dys	Mon 2/9/09	Fri 2/13/09
Cranks	2 dys	Tue 2/10/09	Wed 2/11/09
Headtube	3 dys	Mon 2/16/09	Wed 2/18/09
Gusset	3 dys	Mon 2/16/09	Wed 2/18/09
Downtube	2 dys	Mon 2/23/09	Tue 2/24/09
Stem	1 dy	Mon 2/16/09	Mon 2/16/09
Brake Lever	2 dys	Thu 2/19/09	Fri 2/20/09
Brake Line	4 dys	Mon 3/2/09	Thu 3/5/09
Flex Shaft Mounts	2 dys	Mon 3/2/09	Tue 3/3/09
Flex Shaft Routing	4 dys	Mon 3/9/09	Thu 3/12/09
Additional Fabrication	21 dys	Mon 3/2/09	Mon 3/30/09
Phase 6: Assembly	25 dys	Mon 3/16/09	Fri 4/17/09
Crank Assembly	5 dys	Mon 3/23/09	Fri 3/27/09
Fork and Brakes	5 dys	Mon 3/23/09	Fri 3/27/09
Phase 7: Testing	**34 dys?**	**Wed 4/15/09**	**Mon 6/1/09**
Geomerty	2 dys	Wed 4/15/09	Thu 4/16/09
Ergonomics	5 dys	Mon 4/20/09	Fri 4/24/09
Space Requirements	1 dy	Mon 4/20/09	Mon 4/20/09
Weight	3 dys	Mon 4/27/09	Wed 4/29/09
Driving Behavior	5 dys	Wed 4/15/09	Tue 4/21/09
Kinematics	10 dys	Mon 5/4/09	Fri 5/15/09
Safety	21 dys	Mon 4/20/09	Mon 5/18/09
Attachment	3 dys	Mon 5/4/09	Wed 5/6/09
Stresses	10 dys	Mon 5/4/09	Fri 5/15/09
EISO Strength Tests	13 dys	Mon 5/4/09	Wed 5/20/09
Power Transfer	3 dys	Mon 5/18/09	Wed 5/20/09
Usage	5 dys	Mon 5/18/09	Fri 5/22/09
Senior Design Expo	**0 dys**	**Fri 6/5/09**	**Fri 6/5/09**
Weekly Meetings with Advisor	170 dys	Wed 10/8/08	Wed 6/3/09
Weekly Meetings with Advisor	170 dys	Thu 10/9/08	Thu 6/4/09
Weekly Team Meetings By Sky	170 dys	Fri 10/10/08	Fri 6/5/09
Report Writing	172 dys?	Tue 10/7/08	Wed 6/3/09
Logbooks	174 dys	Tue 10/7/08	Fri 6/5/09

Appendix E. Technical Drawings

Appendix F. Build Plan Flow Chart



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