ABSTRACT

The Anti-Rollback Wheelchair project addresses real life issues that assistive device technology has yet to successfully solve. Current manual wheelchairs do not offer users the capability of maintaining position on an incline or decline without assistance of an aid or endangering safety. The objective of this project was to improve upon an existing device developed by a Rochester Institute of Technology (RIT) Multidisciplinary Senior Design Team. The redesigned system is an accessory adaptable to manual wheelchairs that offers users the ability to stop on a hill via simple hand controls. The system includes a three-pawl engagement mechanism to prevent rollback. A series of analyses including Design Test Life and Shaft Analysis led to a small, lightweight design that can easily attach to the frame of a quick-release manual wheelchair. The system maintains the original functionality of the wheelchair with these added features. The highest risk design concept was ensuring that the all three pawls engaged simultaneously which led to an experiment that could inspect this interaction while also evaluating continuous wear testing. The final result of this experiment indicated that the system would function properly for over 5 years if engaged for 10% of overall average utilization.

BACKGROUND

Users of manual wheelchairs naturally encounter difficulties every time they are required to traverse inclines or declines un-assisted. Firstly, when traversing an incline, wheelchairs tend to roll backwards when the user adjusts their grip on the wheels to ascend the incline, thus impeding forward motion. Secondly, when traversing a decline, users do not have the ability to steer or slow their speed without endangering their hands. In both scenarios, users that may otherwise be independently mobile would require an aid.

In the 2013-2014 academic year, a RIT Multidisciplinary Senior Design Team began designing and prototyping a solution to these two difficulties. The system included an anti-rollback device based on a ratchet and pawl structure. It was designed to be installed onto manual wheelchairs to prevent rollback. This was accomplished by heavily modifying the stock wheelchair frame and axle. In addition, a bicycle braking system was mounted to the system to provide the wheelchair user with the ability to stop, slow or steer on a decline. A major drawback of the system is the adaptability to the other manual wheelchairs that may be found on the market. The system was custom designed and built for use with one specific wheelchair and lacks the ability to be removed or reverted. Thus, once installed the wheelchair could not be reverted back to original factory condition.

The system designed by the previous team provided a proof of concept and functional model. With this, the current team was tasked with the objective to apply this system in a lighter, more marketable form that would either meet or exceed performance benchmarks previously set. To make the system more marketable, adaptability and weight were added to the engineering requirements, and so the objective was not only to redesign, but also to improve the anti-rollback device while maintaining braking. In meeting these requirements the system would be adaptable to a wider variety of manual wheelchair without custom manufacturing or permanent, irreversible
modification. This allows the system to be marketable to a wide variety of wheelchairs at a lower cost per unit in both manufacturing and end sale.

**METHODOLOGY**

The objective of this project was to create a feasible assistive device that would reliably prevent rollback and enable the user with independent braking capabilities in order to meet customer requirements and deliverables. The customer’s main focus was ensuring the system remains attractive to consumers characterized by attributes such as being light in weight, adaptable without compromising function, low in cost (production and sale), easy to both install and uninstall, and remain low in maintenance. After discussing these customer requirements, the team detailed a series of engineering requirements depicted in Table 1 below, which acted as guidelines throughout the design process. A key feature of Table 1 is the assigned level of importance, which ranks a design requirement of low importance at a 1. Similarly, a design requirement of high importance is given a value of 9 signifying the requirement to be of the highest importance. The engineering requirements, along with three additional deliverables were presented to the customer at the conclusion of the project cycle: functioning prototype with associated documentation, scaled-up manufacturing plan, and installation and maintenance manual.

<table>
<thead>
<tr>
<th>Req. No.</th>
<th>Importance</th>
<th>Function</th>
<th>Engineering Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>9</td>
<td>Movement</td>
<td>Force exerted by user to hold position on incline</td>
</tr>
<tr>
<td>S2</td>
<td>9</td>
<td></td>
<td>Grip force exerted by user to brake on decline</td>
</tr>
<tr>
<td>S3</td>
<td>9</td>
<td></td>
<td>Wheelchair will rollback &lt;= 0.5” when ratchet and pawl is engaged</td>
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<tr>
<td>S4</td>
<td>1</td>
<td></td>
<td>Independent braking inputs</td>
</tr>
<tr>
<td>S5</td>
<td>3</td>
<td>Portability</td>
<td>Increase of wheelchair width when in use</td>
</tr>
<tr>
<td>S6</td>
<td>3</td>
<td></td>
<td>Component interference when wheelchair is folded</td>
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<tr>
<td>S7</td>
<td>3</td>
<td></td>
<td>Total system weight</td>
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<td>S8</td>
<td>9</td>
<td></td>
<td>Designed test life</td>
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<td>S9</td>
<td>9</td>
<td></td>
<td>COTS components</td>
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<td>S10</td>
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<td>S11</td>
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<td>Number of models that system can interface within scope</td>
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<tr>
<td>S12</td>
<td>3</td>
<td></td>
<td>Maximum static user weight</td>
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<tr>
<td>S13</td>
<td>1</td>
<td>Maintainability</td>
<td>Time to revert to original configuration</td>
</tr>
</tbody>
</table>

Table 1: Engineering Requirements

When redesigning the device to meet the criteria, the initial constraint was to retain the ratchet and pawl from the anti-rollback system. As a result, the main concept was adapted from the alpha design including the braking system and bearing block concept. However, given that engineering requirement S13 implies that the wheelchair must be reconfigured to its original state, the device’s mounting concept and components were redesigned.

**Use Scenarios and Analysis**

In order to best understand ways in which the system could be used, three conceptual use scenarios were defined to analyze the physical requirements of the components. They included a client reaching an incline/decline, aid reaching incline/decline, and client/aid interaction. From this brainstorming, the following five technical loading scenarios were identified to analyze components when the system is loaded:

1. General Loading Scenario
2. Hill Loading at angle θ
3. Stress Elements
4. Level Ground
5. Tipping (one wheel elevated)

After evaluating these potential scenarios, a Design Test Life analysis and Shaft analysis were performed to estimate the material requirements. First, research revealed that insurance companies fund wheelchair replacement every five years, with wheelchair life ranging from five to fifteen years. Given this information, it was reasonable to design the system to last five years, as well. Further research found that wheelchair users travel approximately one mile per day. Given this information, it can be seen that in five years the wheelchair would travel approximately 1.5 million revolutions [1]. After further analysis, it was determined that the majority of clients would face a scenario requiring them to engage the ratchet and pawl system approximately 10% of the time. This led to a designed test life of the system, referenced by engineering requirement S8, to be 150,000 revolutions. Otherwise known as the 90/10 use scenario.

In addition to the Design Test Life analysis, the Shaft analysis calculated what material principles were required for the shaft to sustain the design test life assuming user weight, potential tipping, and material wear. Figure 1 illustrates the free body diagram used as the basis for this analysis. Note that x5 denotes the location of the center of
gravity of the wheelchair and client. The purpose of the shaft analysis was to choose a material that would yield a factor of safety greater than 1.3. Figure 2 displays a range of potential shaft materials and their respective factor of safety as a function of shaft diameter. The chosen material, 4140PH in purple has a factor of safety greater than the desired 1.3 bold line for all diameters above 0.44 in.

**Building**

The system was built with aid from the Brinkman Lab and the Mechanical Engineering machine shop, utilizing both their machines and knowledge in the production of system components. Many of the system components utilized complex geometry in order to save weight, therefore use of the water jet saved processing time on many of the complex components. The Brinkman Lab supplied the team with access to the water jet to produce the rough form of most of the components.

In the shop the team utilized mills, lathes, drill presses, taps, presses, files and the belt grinder to add in the additional features necessary for proper assembly. After processing the rough form on the water jet the components were brought into the machine shop for secondary and tertiary machining operations. Following these shop operations, components were test fit in a dry run assembly to check for fit and finish. Components were then adjusted where needed to provide a flawless fit using fine grit sandpaper and files before concluding with final assembly of the system.

**Testing**

To ensure that all engineering requirements were met, several tests were conducted. The biggest risks to the system were the ability of the pawls to engage and hold the client on an incline with no client input as well as determine the safe operating life of the pawls. This was directly related to engineering requirements S1, S3, and S8. The Ratchet and Pawl Test lead to the development of a test fixture, depicted in Fig. 3, to inspect long term wear characteristics of the ratchet and pawl. The test fixture quantified the wear caused by forward motion of the engaged system. A motor spun the ratchet while the three pawls remained stationary. The goal of the test was to spin the ratchet at a representative client speed of 3 mph for at least 150,000 revolutions, which was representative of the designed 5-year life under a 90/10 scenario. Throughout the test, the ratchet teeth were consistently measured in order to evaluate the wear patterns.

The first test performed, Test A, utilized three identical pawls. These pawls were the first design and named Pawl A. In this test, the springs were anchored to the fixture with an approximate spring force of 1.5 Newtons. The entire test ran for approximately 100,000 revolutions and was reviewed at approximately the 50,000 mark. At this point the pawls were near fully worn. At 100,000 cycles the pawls were completely worn, and an issue in spring
tension was discovered, which accelerated the pawl wear. Due to the unnaturally quick wear it was noticeable that the pawls were no longer engaging the ratchet. As was performed before the test, the ratchet was evaluated under an optical comparator in order to determine if the teeth were being worn away. It was concluded that there was no statistical difference in the size of the ratchet teeth; thus, only the pawl material was reduced. Figure 4 displays the Test A pawl after full wear criteria were met. Given that the hardware was briefly analyzed and checked at 62,000 and 100,000 revolutions, it was estimated that the pawls failed around approximately 75,000 cycles. As a result of these test results, the validity of the test, spring force, pawl design, and component material was reviewed in order to determine next steps.

Knowledge gained from Test A resulted in one main change administered in Test B. Analysis demonstrated that the spring force in the actual assembly would only be about 0.5 Newtons. In Test A, the spring force exerted on the pawls was three times this force. This high spring load was attributed to the unnaturally quick wear of the pawls, therefore the test was ran again with new pawls, still of the Pawl A design. Test B ran for over 180,000 revolutions before all three pawls stopped fully engaging.

In addition to evaluating and implementing the new spring force in Test B, the pawl design was analyzed for potential improvements. As a result, the Pawl B design was developed. This redesign consisted of a thicker pawl tooth while maintaining the geometry of critical pawl surfaces. Driving this design change was the knowledge that regardless of the design there would be wear as a result of the interaction between ratchet and pawl. Thus, design B focused on providing more material to be worn away before pawl failure occurred. This ultimately provided an increase to system life.

**Scaled-up Manufacturing Plan**

As the Anti-Rollback Wheelchair project was a follow on project, it was intended that the redesign would be constructed such that it could be manufactured on a large scale at a low cost. In order to prepare the design for scaled-up manufacturing, a plan was developed to analyze the design, material selection, build, and assembly. In order to produce 1, 100, up to 1000 piece lots, the following equipment and services are required:

- Water Jet
- CNC Machine
- Mill
- Lathe
- Rockwell C Heat Treatment

The design includes several custom components, most in need of tooling and fixtures in order to machine accurately. Thus, the labor for custom components is estimated over $1100 per unit for production of 1000 units. Additionally, raw material costs and purchased components are estimated to be $300 per unit for production of 1000 units. Overall, given the current design of the anti-rollback with brake assist feature, the system would cost approximately $1500 per unit in lots of 1000.

**Installation and Maintenance**

Installation of the anti-rollback system comprised two main steps. The first set of steps was to remove the original hardware from the standard wheelchair. This hardware included the wheels (which were re-used), the shafts, and the shaft collars that passed through the frame. Optional to remove was the wheel lock system, which was replaced by the parking brake on the new (optional with the kit) braking system.

The second set of steps was to install the new hardware to enable the anti-rollback feature as well as the optional braking package, which may be included in the kit. Installation of the anti-rollback system involves the assembly of two halves of the entire system, utilizing three bolts overall. This simplified version was achieved by shipping the anti-rollback subassembly as a pre-assembled system from the factory. For this reason, a more detailed maintenance manual will follow, which details the full disassembly and care that the system requires.

Maintenance of the system comprises of an annual visual inspection and a biannual maintenance checklist to replace worn components. If at any point components appear worn during the annual visual inspection or a sudden change in system characteristic or sound occurs, immediately contact your local wheelchair specialist or perform the maintenance specified below. Wear components on a 2 year basis consist of the brake pads, pawls, and springs. For system use past 8 years, inspection and replacement of the ratchets should occur.
RESULTS AND DISCUSSION

The final prototype was evaluated according to the engineering requirements derived from customer needs and preset deliverables previously described. Upon completion the delivered prototype successfully addressed all engineering requirements. Of the 13 defined requirements, 10 met or exceed the projected values. Table 2 depicts the results of each test associated with the engineering requirements. In addition to these requirements, the functioning prototype with associated documentation such as the CAD and bill of materials, Scaled-up Manufacturing Plan and Installation and Maintenance Manual has been delivered to the customer at RIT.

<table>
<thead>
<tr>
<th>Req. No.</th>
<th>Importance</th>
<th>Engineering Requirements</th>
<th>Unit of Measure</th>
<th>Marginal Value</th>
<th>Ideal Value</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>0</td>
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<tr>
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<td>5</td>
<td>6</td>
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<td>S3</td>
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<td>Wheelchair will rollback &lt;= 0.5” when ratchet and pawl is engaged</td>
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<td>0</td>
<td>0.75</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td>S5</td>
<td>3</td>
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<td>0</td>
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<td>S6</td>
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<td>Designed test life</td>
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<td>S9</td>
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<td>COTS components</td>
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<td>63%</td>
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<td>Number of models that system can interface within scope</td>
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<td>75</td>
<td>100</td>
<td>90</td>
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<tr>
<td>S12</td>
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<td>Maximum static user weight</td>
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<td>260</td>
<td>300</td>
<td>260</td>
</tr>
<tr>
<td>S13</td>
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<td>Time to revert to original configuration</td>
<td>min</td>
<td>60</td>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2: Engineering Requirements with Achieved Actual Values

Engineering requirements S1 an S3 are associated with the functionality of the anti-rollback sub-system. After engaging the ratchet and pawl components, the user can maintain position on an incline without exerting any force. This is important as it gives the user an opportunity to rest while traveling uphill. After the user engages the system, the wheel could potentially rollback between 0.0” and 0.75”. As this is a prototype, this distance is attributed to the loose fit of the wheel lock to the shaft. The actual rollback allowed by the ratchet and pawl sub-system is less than 0.5”. In a full scale production of the system, the wheel lock will be made of steel as opposed to aluminum to ensure an accurate and sustainable fit.

Additionally, requirements S2 and S4 control the interaction between the user and the braking sub-system. When traversing a decline, the user must grip a brake handle in order to slow, steer, or stop the wheelchair. The force required to squeeze the hand brakes until the brakes are fully engaged is approximately 6 lbs. Given that the average grip force of mature women is greater than 40 lbs, it can be concluded that the brakes could safely be engaged by the majority of users [2]. Furthermore, there are two independent braking inputs. As a result, the user has the capability of steering the wheelchair when traveling downhill. This is particularly useful when a hill or ramp is curved.

The next two requirements, S5 and S6, ensure that the wheelchair retains its original dimensions. The purpose of these requirements is mostly to guarantee that the user is still comfortable using the chair with the addition of the system. Requirement S5 refers to the overall wheelchair width to ensure that the user can still comfortably reach the hand rims and travel through standard door frames. Requirement S6 reflects the ability to fold the wheelchair for transportation without interference such that the overall folded width is no greater than in the original situation. After measuring the wheelchair before and after the system was installed, it was determined that there was no additional width added when in use or folded.

One concern after the original prototype was developed was the addition of weight to the wheelchair. The original prototype weighed over 22 lbs which was a turn off to potential clients given that it is a hindrance during transport. It is vital to reduce excess weight whenever possible in order to meet customer expectations and appeal to
future users. As a result, the entire system adds approximately 7 lbs to the wheelchair. This includes the fact that some hardware and the parking brake was removed from the original wheelchair configuration.

As previously discussed, requirement S8 was tested using the Ratchet and Pawl test fixture. The test resulted in surpassing the paws’ designed life expectancy of 150,000 revolutions. Similarly, the ratchet was tested for a combined total of over 280,000 cycles. Thus, it can be concluded from this test that the ratchet and pawl sub-system would function properly for over 5 years if engaged for 10% over this period at average utilization.

In order to drive down costs and simplify the design and build of the system, requirement S9 dictates that 65-75% of components should be off the shelf. In other words, only about 30% of components require custom design, ordering, and labor. When determining the percentage of custom versus off the shelf component, each item on the bill of materials counted as one, regardless of the quantity required in the unit. As a result, 63% of the overall unit was off the shelf and did not require custom ordering or manufacturing. As this falls just outside of the marginal value, there is an opportunity to further standardize the design.

Regarding the budget and requirement S10, the team was originally granted $400 to prototype a new anti-rollback with brake assist system. Due to low volume of parts and materials, as well as the cost to heat treat the shafts, the actual cost to prototype this design was approximately $500. This figure excludes the rotors, calipers and cables, as they were reused from the previous prototype. With all of the knowledge gained throughout this process, the estimated cost to build another prototype is $5000. This is assuming the prototype is professionally manufactured utilizing a CNC machine among other equipment. However, as described in the Scaled Up Manufacturing Plan, increased volumes and tooling reduces production cost to $1500 per lots of 1000.

Another vital customer requirement, adaptability, was captured by requirement S11. A Breezy Quick Release Wheelchair was donated to analyze and demonstrate the prototype. Thus, the ideal state of the prototype would be adaptable to all Breezy Quick Release models. Currently, the system is adaptable to all Breezy Wheelchairs with the exception of transportation chairs due to their small wheel and shaft size. With slight modifications, the system could be adapted to fit a larger variety of wheelchairs from various manufacturers.

Requirement S12 reflects the customer’s need for the wheelchair to be safe and functional for a wide variety of users. The weight limit of the Breezy Quick Release wheelchair used for the system was 260 lb. Thus, we analyzed and successfully tested the system under a 260 lb load to ensure that the components would not fail under the maximum load use scenario.

Lastly, requirement S13 addresses the timeliness of wheelchair reversion to its original configuration. A team member with knowledge of the system was able to completely revert the wheelchair with system to its original state within 25 minutes. This time includes disconnecting all controls from the wheelchair.

CONCLUSIONS AND RECOMMENDATIONS

This project was intended to redesign a previously functioning hill-holding prototype to better appeal to consumers while simultaneously preparing the design to potentially launch to market. The P15007 Anti-Rollback prototype has met customer requirements by successfully addressing the majority of the engineering requirements. The device has retained the ratchet and pawl concept that functions as an anti-rollback system. The braking system is refined to include locking functionality in addition to original slowing and braking abilities.

In order for the system to be brought to market, there are a few recommendations that could be explored to refine the design and present it as an even more appealing option for clients. These recommendations include:

- Maintain quick-release functionality of wheelchairs by adding a pin in manufactured shaft
- Review design to reduce variation in size and length of fasteners
- Weight reduction through component design
- Material selection
- Alert system to ensure client is aware of system reaching end of life

REFERENCES


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