Chapter 6: Design Recommendations

The results from the usability evaluation were compared to findings from the expert information interview and PAU performance evaluations. These combined outcomes were reviewed for trends indicating aspects of the PAU design which may be decreasing performance effectiveness or user satisfaction. These findings have been interpreted and combined with design team input to produce a suggested list of design features which need to be addressed and possibly changed with the next PAU prototype iteration. In some cases recommendations for design alterations are offered. Design features requiring consideration are presented here in order of priority. Some changes in priority are expected to occur during the design process when feasibility of design options and their cost effectiveness are better understood.

Safety Issues

There are several aspects of the PAU design which have been identified in the performance and usability evaluations as safety concerns. These areas will require either redesign and/or careful risk analysis prior to marketing.

Column Pinch Point

Problem Definition. It was discovered that a pinch point exists in the juncture at the top of the outer column and the extended handle arm (component which reaches back toward the operator). The space between the two components gaps open when the unit is placed into power operating mode. This gap then closes again when the user switches the column out of power mode by rotating the drive wheels off of the ground. If the user handles the column at the gapped area while switching column positions, the hand can be pinched between the two metal pieces.

Option Recommendations. It may be possible to insert a collar around the inner column which would maintain a gap at all times. This would shift the area which gaps open and closes to a position next to the inner column; out of reach from the hands of the operator. Figure 18 illustrates the concept of a collar placed at the gapping juncture.

If this solution does not alleviate the problem, it may also be possible to guard the area (care must be taken not to create a new pinch point with the guarding).

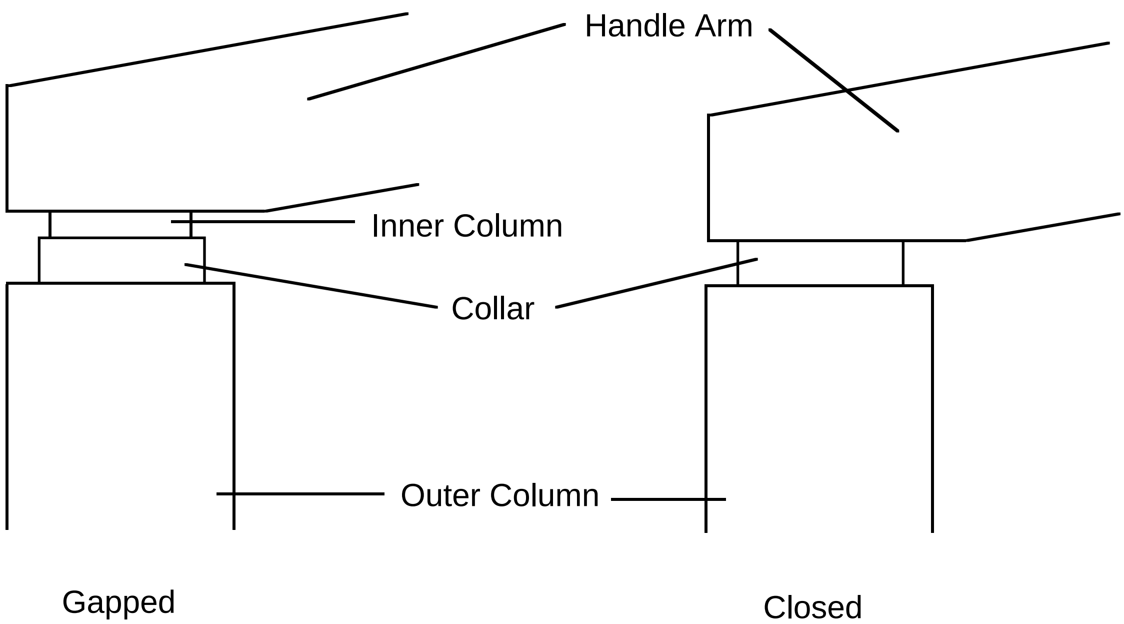

Figure 18. Collar solution for pinch point problem.

Loss of Control When the Drive Wheels Meet Friction Limit

Problem Definition. Once the drive wheels begin to slip against an inclined surface, the wheelchair will no longer move forward, and the operator must apply a braking force to the large wheels of the wheelchair. The force must be applied to both wheels simultaneously to avoid a backward motion of the wheelchair.

During the time required to move the driving hand from the PAU handle to the large wheel, the wheelchair begins to roll down the ramp uncontrollably (determined by the performance evaluation). The braking action inherent in the PAU motor and gear box is not sufficient to impact the backward motion. The momentum gained during this time requires that a large stopping force be applied when the hand reaches the large wheel. Even if both hands successfully reach the large wheels and stop the wheelchair momentum, the power mode configuration of the PAU precludes control of the wheelchair by manual force. This loss of manual control in power mode is a result of the inherent braking force in the PAU motor (the motor resists the input torque from the drive wheels as they move along the ground).

Option Recommendations. One option for minimizing this safety concern is to implement a braking system on the PAU. It would need to be actuated at or near the handle area to maintain one-handed operation of the unit. When slipping occurs, the brake could be secured to permit a safe change to manual mode operation (allowing manual control of the wheelchair). Throughout the design phase of the project, a brake feature was not given priority. It was anticipated that any necessary braking could be accomplished by hand at the large wheelchair drive wheels. A brake added to the PAU will increase the complexity of the design and therefore the cost.

Another option for minimizing this safety risk is to increase the frictional force at the drive wheel/ground interface. This can be done by increasing the downward force applied by the spring between the inner and outer PAU columns. A stiffer spring may produce a sufficient force for propelling the wheelchair up smooth inclines. The increase in spring compression would certainly introduce additional problems such as greater difficulty pulling the column into power mode position. Testing would be necessary to determine if this solution is sufficient. Alternatives such as changing drive wheel material and size can be factored into testing scenarios for optimal performance.

The performance evaluation also found that the operator was required to lean forward in the wheelchair to ascend smooth ramp surfaces. This position increased the downward force at the front end of the wheelchair and therefore increased the friction force at the drive wheels. Design changes to increase the friction force will help to alleviate this problem.

Loss of Control When the Drive Wheels Lose Ground Contact
Problem Definition. When a steep curb transition is encountered by the caster wheels of the wheelchair, the PAU drive wheels are lifted out of contact with the ground. This causes the drive wheels to slip continuously in the air while no control is exerted over the direction of the wheelchair. The wheelchair begins to either fall backward uncontrollably (during ascension), or forward uncontrollably (descension). The resulting motion is quite dangerous and attempts to control the wheelchair manually are not successful due to the loss of manual control as the PAU drive wheels come back into contact with the ground.

Option Recommendations. It may be possible to adjust the vertical range of the inner column to accommodate larger vertical fluctuations in terrain. Changes to the downward bias spring and the spring locator on the inner column (collar), may permit larger deviations in the inner and outer column positions relative to each other. This design change would only extend the current range of motion, it will not cover all terrain conditions. It may not be possible to account for all pathway inclines and therefore, training may be necessary to teach users when to shift to manual operation.

Securing Crossbar Instability

Problem Definition. There is a reaction force created at the drive wheel/ground interface when driving in power mode (as the drive wheel pushes against the ground, the ground pushes back). This reaction force causes some motions in the column unit due to insufficient crossbar strength. Arrows in Figure 19 indicate the motions resulting from the ground reaction force in the PAU.

A moment is created about the lower securing crossbar which pushes the top crossbar back toward the wheelchair. There is also a linear component which pulls the lower crossbar forward. The motions of the crossbars are large enough to be detected by an observer and are seen as slight bending in the center of the bars. These motions are also sufficiently large to be easily detected at the handle by the operator.

No immediate problem exists with this type of design deficiency; it does not impact the effectiveness of the PAU. However, large bending motions of metal components may cause fatigue of the parts. Eventually these components will exhibit signs of wear and become nonfunctional, possibly breaking in an unsafe manner.

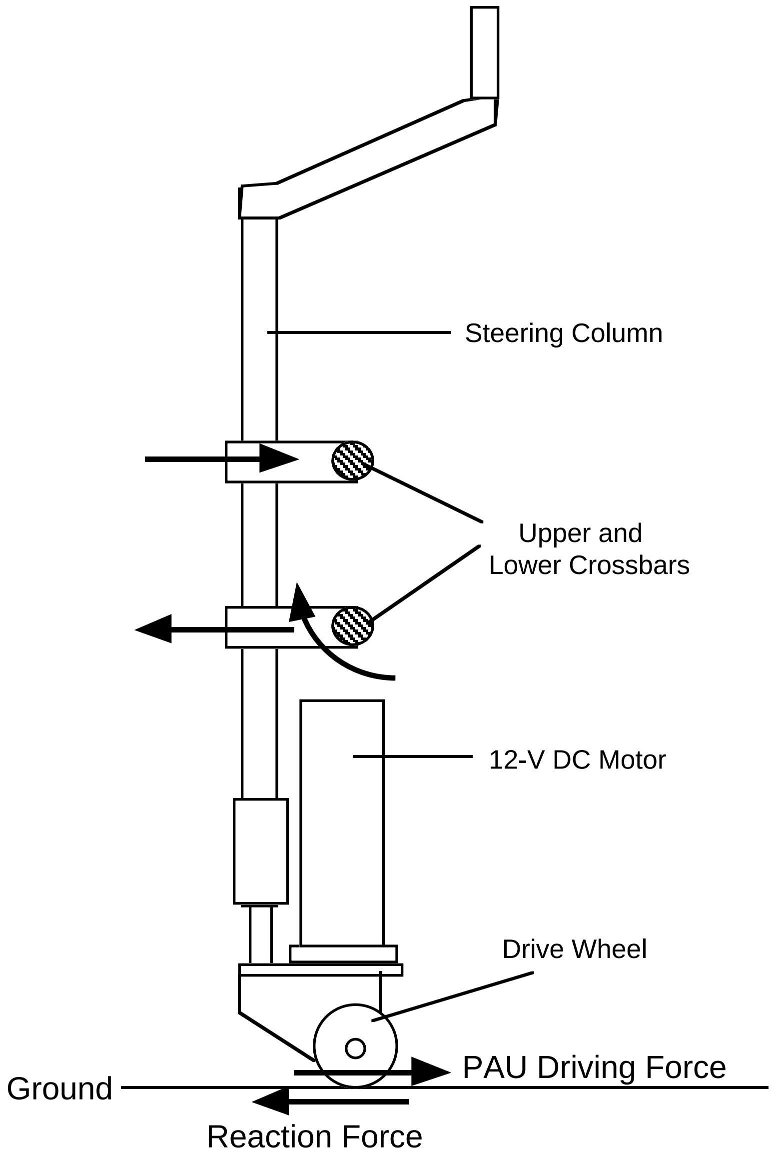

Figure 19. Column motions resulting from the ground reaction force.

<u>Option Recommendations.</u> The securing crossbars should be stiffened to offer a more stable attachment to the wheelchair. Currently, 0.75-inch diameter aluminum tubes (0.125 inches thick) are used for crossbars. A tube with a larger diameter will provide a stronger support for the PAU column section. One-inch diameter tubes may be adequate, though testing will need to be done to confirm this hypothesis. If a change in diameter is not sufficient, then other material options should be considered as well.

Power Operation in Reverse

Maneuvering the Wheelchair in Reverse

Problem Definition. The usability evaluation identified a problem with controlling the wheelchair when maneuvering in reverse. All six subjects attempting the reverse maneuvering task experienced difficulty directing the wheelchair in a desired direction. The problem has been prioritized as number one in the critical observation impact analysis and number two in the critical incident impact analysis. Most of the subjects (four out of seven) expressed a concern for this problem on the user evaluation questionnaire. Comments such as "difficult in trying to control what direction it was going in," and "in reverse, when the handle is turned to more than 45 degrees it tends to want to pull out of your hand and turn you 90 degrees," were used to describe the problem.

Design Features Leading to the Problem. The control problem is due to the trailing fork drive wheel design which causes the inner column to pull to 180 degrees from its straight position while moving in reverse. When driving forward, this feature provides a centering effect which is advantageous. Gaal and Johnson (1993) describe a tiller drive PAU without this type of trailing drive wheel design. They report that constant pressure must be applied to the tiller to maintain a straight orientation which is tiring for the operator. From this, it can be concluded that the trailing drive wheel design is a positive design feature and should not be changed.

Reverse Maneuvering Evaluation Task. The resulting difficulty when driving in reverse can be assessed for its impact on user satisfaction by analyzing user requirements. Several subjects in the usability study pointed out that the reverse maneuvering task was not representative of typical wheelchair use. It is recommended that future studies reconsider the validity of the task and redesign the evaluation to more closely match user requirements. The extensive nature of the task may have placed an unrealistic importance on the findings. Only one third of those tested were able to successfully complete the task within the Planned Target Level. Each of the six subjects attempting the task clearly demonstrated the ability to reverse the wheelchair in a controlled manner for a very short distance (length of the wheelchair).

Option Recommendations. If the trailing drive wheel design is maintained, there are options for controlling the wheelchair in reverse. One possibility is to switch the unit from power drive to manual drive for reverse requirements. A second option is to rotate the column unit 180 degrees and then operate the PAU in the reverse direction. This works well once the unit is rotated however, the handle is then extended far from the operator. In addition, it requires good arm and hand strength to rotate the column when stopped or moving slow (it should not be turned 180 degrees when moving fast). There is also a third option of training the users to operate the unit in reverse. This option may be the best if it is found that users only require short motions in reverse mode.

Two-Handed Attachment/Detachment Procedures

Several usability evaluation subjects and two interview evaluation experts identified a problem with the requirement of two hands for PAU attachment and detachment. The experimenter also notes that many subjects attempted to utilize only one hand when possible and reserved the second hand for stabilizing their upper bodies.

Battery Sling Clasps

Problem Definition. The requirement for two dexterous hands to attach and detach the battery sling clasps was identified in the impact analyses as a design deficiency. The problem was prioritized as number two in the critical observation analysis with a frequency of four and criticality rating of 4.3, and problem number six in the critical incident analysis with a frequency of three and criticality rating of 4.0.

Option Recommendations. It is anticipated that the clasps can be replaced with a securing system which would require only one hand for operation. One subject suggested utilizing velcro to secure the battery in the sling. Velcro straps could be made with looped ends to place the hand through for fastening. This would eliminate the need for finger dexterity which would be required to grasp simple velcro straps.

Column Attachment/Detachment with Two Hands

Problem Definition. The requirement of two hands to lift the column unit off of the wheelchair (squeeze and lift) and to attach the unit to the wheelchair, was identified as a problem in the impact analyses. With a frequency of three and criticality rating of 3.0, this was problem number seven in the critical incident analysis. The problem was listed as number fifteen in the critical observation analysis with a frequency of one and rating of 5.3. Subjects identified the location of the release mechanism which much be squeezed, as a contributor to the problem.

Option Recommendations. There are many possible options to alter the design so that the column can be attached and detached with one hand. One subject was able to drop the column unit in place with one hand by taking care to force the ends into position (he did not squeeze the release mechanism to withdraw the poppits). This may prove that the unit can be designed similar to quick-release wheels which pop into place and then release with a button for separation (as suggested by one subject). The locking poppits can be designed to retract with less pressure so that it can be dropped into the securing blocks without holding the release mechanism.

One wheelchair expert suggested applying a lock to the finger grips (release mechanism) so that the poppits will be held retracted for placement. The lock could be actuated with one hand, then the unit lifted into place with one hand. After placement, the lock could then be released to secure the PAU.

One subject suggested using a large single button release placed on the lower side of the top column/crossbar attachment block. See Figure 15 for the recommended placement of the release button on a photograph of the column unit. This position is based on the optimal handling configuration of the column unit when lifting for attachment. The unit is balanced and easily controlled when held at the underside of the top column/crossbar attachment block. One hand can hold the unit at this location and manipulate the entire column unit into position.

Precision is Required for Column Attachment and Detachment

Problem Description. Related to the bilateral handling requirement for the column, is the precision necessary for attachment and detachment. The column unit must be held at a correct angle and placed into position evenly on both sides at the securing blocks. When lifting the column out of the securing blocks, force must be applied at both sides uniformly and in the correct direction. These requirements imply the use of two dexterous hands for most users (one subject was capable of single-handed attachment and detachment). Even utilizing two hands, many subjects encountered difficulties such as overshooting the securing blocks during attachment and catching of the crossbar in the blocks while lifting it out.

This design deficiency did not prevent any of the subjects from performing the column attachment and detachment tasks. It was prioritized as problem number four in the critical incident analysis with a frequency of three and an average criticality rating of 4.3. The critical observation analysis also listed the problem as number four with a frequency of four and an average criticality of 3.9. Subject matter experts in the interview evaluation expressed a concern for the dexterity required for attachment and detachment of the column. One suggested that an assistant may be necessary to accomplish these tasks.

Option Recommendations. The most obvious option for minimizing the precision requirement is to improve the self-guiding characteristics of the securing blocks and crossbar. Flanges on the securing blocks which help to align the ends of the crossbar can be extended to provide a longer approach with a wider angle. This would present a larger target for the user to place the crossbar ends into; permitting a greater alignment error.

Currently, the openings in the securing blocks are angled so that the crossbar must approach the blocks horizontally but dropping slightly down. Figure 20 shows the required handling vector to place the unit into the blocks. The user must therefore move the column unit through a predominantly horizontal motion for attachment and detachment. This requirement is more difficult than simply lifting or dropping the unit vertically. It is recommended that the approach angle of the securing blocks be altered to permit a more vertical handling vector.

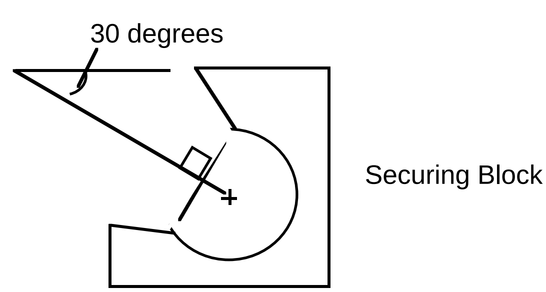

Figure 20. Column unit angle of approach for attachment.

As an example, the block in Figure 20 could be rotated clockwise approximately 60 degrees from its current orientation.

Component Accessibility

Two component systems of the PAU were found to be located in positions which were not very accessible. Subjects determined that placement of the top crossbar release mechanism (finger grips) and the battery sling, caused some problems with user-PAU interaction.

Top Crossbar Release Mechanism

Problem Definition. The expert interview and usability evaluations found that the top crossbar release mechanism is not very accessible. The primary problem identified was that the location of the mechanism required the user to lean forward and search for the release under his or her leg (moving the leg when needed). This location is also not visible from the typical seated position in the wheelchair, therefore, it can be difficult to find and see what is happening. In one case, the subject attempted to release the lower crossbar mechanism while trying to switch column positions. This was prioritized as the number one problem in the critical incident analysis with a frequency of four and criticality rating of 5.3. In the critical observation analysis, this problem was listed as number twelve with a frequency of two and criticality of 4.3.

Related to the accessibility of the mechanism, is the strength and dexterity required to actuate the release. The resistance provided by the springs, the shape and smooth texture of the finger grips, and the requirement that both be pushed together simultaneously, are some design features leading to user interaction problems. Problems such as fingers slipping off the grips, a "pinchy" feel (rough edges), grips not long enough, and the requirement to do two things at once (i.e. squeeze grips and pull column together), demonstrate the design deficiency. Interview evaluation experts considered this to be a concern for some users.

The critical incident analysis prioritized the problem at number eight with a frequency of two and an average criticality of 6.0. Also found in the critical observation analysis, the problem was listed as number 17. One subject identified the process to squeeze the crossbar release mechanism in the user evaluation questionnaire as a particularly bad aspect of the design.

A further consideration when redesigning the release mechanism is a problem identified once in the critical observation analysis. Lubricant inside the crossbar leaked onto the fingers of the subject through the holes in the crossbar where the release mechanism is located. This occurred when the subject's fingers actuated the finger grips.

Option Recommendations. Several subjects in the usability evaluation suggested moving the top crossbar release mechanism up onto the column so that it would be easier to access. This option introduces the concept of remotely retracting the securing poppits in the crossbar. Such a change would increase the complexity of the design, therefore increasing cost and maintenance concerns.

Design efforts can be made to determine the feasibility of this type of change. One possibility is a compromise between the current and suggested configuration. The release could remain along the crossbar (maintaining simplicity) but be shifted toward the center of the unit. A more central location may eliminate the need to move the leg and reach so far. Though the location of the finger grips to the right side of the column (from the operator's perspective sitting in the wheelchair) was considered good by one expert who pointed out that this location is closest to the driver's side seat of a car.

Suggestions were also provided for alteration of the release itself. One expert presented an option which would not require finger dexterity. As seen in Figure 9, the idea included a U-shaped handle (in place of the finger grips) which could be pulled. The expert further suggested that this type of simple release mechanism might be applicable to the plugs as well. A second idea presented by the expert involved a two-bar grip where one bar remained stationary as the second pulls closer to the first when gripped by the hand (both bars would fit inside the squeezing hand). The investigator's interpretation of this option is illustrated in Figure 10.

The idea presented for the locking mechanism on the lower crossbar release mechanism can be applied here as well. If the release could be locked, this would eliminate the requirement for the operator to perform two tasks simultaneously (actuating the release and shifting the column).

Battery Sling Location

Problem Definition. The location of the battery sling under the wheelchair seat resulted in several problems in the usability evaluation. The most important concern for several subjects was the requirement to lean over to attach/detach the battery. One subject did not even attempt the task due to this concern. Another effect on user performance was the need for some users to reposition their wheelchair after the battery was lifted into place. The wheelchair was repositioned closer to the battery sling for easier handling of the clasps. This was necessary because the sling is located up under the wheelchair.

Several subjects positioned themselves so that it was necessary to lean into the wheelchair seatback in order to reach the sling. This position obstructed the view of the sling and appeared uncomfortable. The critical observation analysis prioritized this problem as number three with a frequency of four and a criticality rating of 4.3. The same problem had a frequency of three and criticality rating of 4.0 in the critical incident analysis which prioritized the problem as number five.

A related problem was identified in the expert interview evaluation. One expert introduced a concern for the requirement to turn the wheelchair around in order to place the battery. This may be difficult for a wheelchair user to accomplish from a seated position. Also, experts and usability evaluation subjects discussed the interaction between the drive wheels and the battery as a possible problem. The drive wheels currently come to rest against the battery as the column unit is rotated into transfer position. It is the battery which keeps the column from rotating further down toward the ground (the cross frame section of the wheelchair would stop the column before reaching the ground).

Option Recommendations. A subject suggested hanging the battery on the back of the chair (from the push handles) or placing it on a sliding rack under the chair. On the sliding rack the battery could be placed on the rack and then pushed into position so that it would not be necessary to reach up under the chair to attach and detach. The rack arrangement introduces a new attachment and detachment problem in itself. Such a system would require secure attachments which would need to be removed for the wheelchair to fold. The option to hang the battery on the handles should work well with the smaller size batteries. However, larger batteries may create an unstable tendency to tip the wheelchair backward. Testing should be conducted for this problem before implementing the design.

It may be possible to shift the battery sling farther back on the wheelchair frame so that it is not so far under the seat. Design efforts could focus on ways to attach the sling harness onto the wheelchair frame where desired. The prototype location for the sling is a default location; the most convenient attachment points were used. Again, moving large masses about the wheelchair will require careful testing of the impact it has on wheelchair stability. This consideration should be a part of any design process to hang the battery on the wheelchair handles as well.

A possible design change which may alleviate the need to turn the wheelchair around is to have the sling access located at the front end of the wheelchair. The sling could remain in the current location, but the access flaps can be moved to permit battery placement from the front of the wheelchair.

It was suggested to relocate the battery on the wheelchair so that the wheels of the PAU drive unit do not hit the battery. Removal of the battery may provide an easier transfer process (allowing the column to rotate farther forward). However, it may also introduce a problem by requiring the user to reach farther forward to pull the column up into a driving position.

Location of Wiring Components

Location of Column Unit Plug

Problem Definition. The column unit plug is located on the opposite side of the column as the crossbar release mechanism. A user who is seated on the release mechanism side of the column during attachment or detachment, must reach far across or reposition in order to plug or unplug the unit. This situation was observed three times in the critical observation analysis and was given an average criticality rating of 3.0 (prioritized as problem number 8). The problem was not identified by subjects in the critical incident analysis.

This design deficiency may pose a greater problem, when considering the car transfer scenario. The column unit plug is located on the opposite side of the wheelchair from the driver's seat. A driver must then contend with the column, the car door, and the limiting forward-orientation of the car seat. It is assumed that a wheelchair operator transferring from the passenger side of the vehicle will have an assistant available if needed.

Option Recommendations. An obvious design change for this problem is to move the plug to the opposite side of the wheelchair frame. In this location it would be on the same side of the column as the release mechanism and a car driver's seat.

Another option is to radically change the point of the electrical connections within the unit. There are only two contacts which must extend between the battery and the motor; the positive and negative leads. It would be possible to route the wires for these contacts up through the column unit and out to the ends (or an end) of the top securing crossbar. Leads could be designed to interface with the securing blocks on the wheelchair frame to provide electrical contact when the unit is placed in power operating mode. Another set of wires would extend from the securing blocks back to the battery and remain on the wheelchair at all times. This idea eliminates the need for a wire extension from the column section of the PAU.

If the wires are run internally through the column, there is still the possibility of binding when the column is rotated continuously in one direction. There are two options for controlling this situation. First, a rotation barrier can be designed into the column to limit excursion. This can be accomplished with a simple pin, but it would omit the 360 rotation feature of the PAU. Second, a slip ring can be incorporated into the column so that electrical connections would not be limited by wire rotation. With only two required contacts (for the positive and negative battery leads), a relatively simple slip ring would suffice.

Wires Extending From the Motor to the Plug

Problem Definition. Motor wires which extend to the column unit plug limit the rotation of the column when it is turned in the same direction continuously. The wires can be wrapped around the motor stopping rotation and, when forced, the plug can be pulled out of the socket. This problem was identified twice in the critical observation analysis and given a criticality rating of 4.7. The locking mechanism on the column plug did not keep the plug from pulling out of the socket in one case. Forcefully pulling out the locked plug resulted in a bending of one of the prongs.

In addition, the wire protector and wires from the motor are sufficiently long enough to drop into position between the drive wheels and the wheel gear box housing unit. This results in a popping noise made by the plastic cover on the wires catching against the wheels. No obvious damage is caused, although wear and unforeseen turning configurations could possibly cause damage.

Option Recommendations. One option is to house the wires in a coiled protector which retracts like a spring to take up slack in the line (similar to a telephone cord). This arrangement can still be wound around the motor if turned continuously in the same direction. However, the extendible feature would permit a greater range without forcefully pulling the plug from the socket. If the wire system is replaced with the suggested internal wire and slip ring arrangement (as described above), there will be no problems associated with external wires.

Battery Box Wires

Problem Definition. An expert pointed out that the wire and socket for the battery box swing freely when not plugged into the box. The wire is long enough to catch in the spokes of the wheelchair wheels or other nearby objects.

Subjects and experts mentioned a concern for forgetting to plug in one of the plugs (or forgetting to lock the column unit plug). This was demonstrated in the usability evaluation when one subject forgot the battery box plug and another forgot the column unit plug. Once transferred into the wheelchair a user cannot see either plug and may not know why the PAU won't function. The next design iteration should take special care to consider a reminder (or change of location) for the battery box plug. In the current location, an operator would be required to transfer out of the wheelchair just to connect the plug if it was forgotten.

Option Recommendations. A simple clasp can be placed onto the wheelchair frame which could hold the wire when it is not in use. This would keep the socket and wire from swinging freely and it should be a simple alteration to make.

Another possible solution is to develop an automatic plug-in system with the battery box and sling. A plug (or socket) can be built as an integral part of the sling to mate with the box when it is placed into the sling. This arrangement may be challenging to design due to the motion of the sling when the battery is dropped into position. The motion may make it difficult to manipulate the battery box into the correct position within the sling. If possible, the automatic plug would eliminate the need for loose wires on the wheelchair. A simpler solution is to attach the wire and socket to the sling so that they do not swing freely.

Crossbar/Securing Block Interface

Upper Crossbar Interaction with the Securing Blocks

Problem Definition. It can be difficult to pull the upper crossbar into the securing blocks from the free rotation position (transfer to manual or power mode switching). Some subjects had difficulty with the resistance of the securing blocks against the ends of the securing bar. The critical observation analysis lists this problem as number 11 with frequency of two and criticality of 4.7. It was identified as a problem only once in the critical incident analysis with a criticality of 2.0.

This resistance between the crossbar and securing blocks also can make the column switching process from power mode to transfer mode not smooth. The difference in friction when the crossbar moves from the securing blocks into free rotation causes a jerky motion. The upper crossbar sometimes gently hits the back of the user's leg due to the momentum created by pushing forward on the column to get out of the blocks. Prioritized as problem number nine in the critical observation analysis, it had a frequency of three and an average criticality rating of 2.1.

There is little room for error in when aligning the crossbar with the securing blocks. If the sides of the wheelchair frame move with respect to one another, the crossbar may not fit into the blocks. This situation occurred with the first wheelchair user subject in the usability evaluation. Subject three was not able to complete the transfer mode to manual mode switching task (he could not pull the upper crossbar into the securing blocks). This was due to the weight distribution of the subject in the wheelchair; primarily at the front edge of the wheelchair seat. The subject was not able to move back against the wheelchair seatback due to his size, and therefore caused the sides of the wheelchair frame to pull together at the front edge of the seat. This resulted in a decrease in the width between the securing blocks which in turn made the task of pulling the crossbar into the blocks, quite difficult.

Option Recommendations. Fluctuations between the sides of the wheelchair may be controlled to some extent by increasing the self-guiding characteristics of the interface. This is a challenging design issue and it is anticipated that adjusting the tolerance between the components is a key factor.

The problem resulting from the subject weight distribution at the front of the wheelchair frame was alleviated by placing a board and cushion on top of the sling seat of the wheelchair. The board served to distribute the subject's weight more evenly across the wheelchair frame.

Component Wear

Problem Definition. Both securing blocks and the crossbar are fabricated from aluminum alloy with an anodized surface. Wear on the parts has removed the anodized surface at the crossbar/securing block interface. This results in a meeting of two rough aluminum surfaces which tend to stick together and increase the resistance to motion between the parts.

Option Recommendations. There are several factors which can influence the wear on the components. First, the material itself can be changed to a harder material which will not stick to the same extent as soft metals like aluminum. Second, the surface treatment can be changed to provide a harder surface. There are different degrees of anodizing processes and an aluminum component can be treated with a surface that is harder than the current prototype surface. Third, additives can be placed onto the surface to lubricate the contact areas, minimizing wear. Finally, the precision with which the components are fabricated and designed to fit together can be improved for smoother contact motions.

Crossbar Misalignment

Problem Definition. In one case a subject had extra difficulty pulling the crossbar into the securing blocks because the bar had been slightly rotated out of alignment. This can happen because the bar is held in position by friction contact (not interlocking).

Option Recommendations. An interlocking attachment method can be designed to secure the crossbars to the column. For example, a pin system may apply adequate force to prevent rotation of the bars around the column. It is necessary to maintain the vertical adjustment feature of the crossbars along the length of the column. Therefore, the pin may need to glide inside a groove cut vertically on the column.

Column Position and Motion in Transfer Mode

Forward Extended Column Position in Transfer Mode

Problem Definition. The extended position of the column in transfer mode can collide with the user during transfer. Shins can become pinned between the column and the piece of furniture the user is transferring to/from. Also, the foot of the user can knock into the column when lifting the leg over for transfer. The problem was prioritized as number three in the critical incident analysis with a frequency of four and criticality rating of 3.0. It was listed as problem number five in the critical observation analysis with a frequency of four and average criticality rating of 2.4.

Most of the experts in the interview evaluation expressed a concern with the column extending out in front of the wheelchair during transfer. The reasons for concern varied and included the following:

- -- When transferring to and from an automobile, the column will interfere with the car door. Also, there will be less room to place both legs between the car and the column (before the leg is lifted over the column).
- -- Many wheelchair users have trouble maintaining balance. Activities which involve shifting weight, such as lifting one leg over the column during transfer, may jeopardize the balance of the operator.
- -- Although the majority of experts anticipated that most users would be capable of lifting a leg over the column, one expert wheelchair user was not able to do so. She identified the column as "a big obstacle." In order to transfer her into the wheelchair to use the PAU, she suggested first placing the column section on the ground. While seated in the wheelchair, she then wheeled over top of the column section, and an assistant lifted it behind her lower legs into position on the wheelchair. This sequence for attachment did work, but was quite awkward. All subjects participating in the usability study were able to lift one leg over the column for transfer.

Option Recommendations. Two suggestions were offered by the experts for alleviating the extended column problem. The first idea was to design a telescoping column section which could collapse into itself when clearance is required. The second suggestion was to design the column in two sections which could be separated. The upper part of the column could unplug from the lower section which would remain on the wheelchair. The expert indicated that this type of arrangement is currently used in airplane control sticks which can be removed from the floor of the cockpit. Either option would drastically increase the complexity of the design and it may be more cost effective to not make a change.

Free Rotation of the Column in Transfer Mode

Problem Definition. A related problem identified in the critical observation analysis is the free rotation characteristic of the column in transfer mode. Because the unit moves freely, when the operator attempts to lift a leg over the column it can catch and lift the column up. Also, while he or she is seated, the legs of the operator can push into the upper crossbar which in turn rotates the column up higher. These situations were observed with four different operators during the usability evaluation. Each condition contributes to the difficulty of transferring over the extended column.

Option Recommendations. The free rotation of the column in transfer mode may be eliminated by providing a locking mechanism for the forward position. This added mechanism would further complicate the design. A lock would also secure the forward position of the upper crossbar which may push into the back of the legs of the operator. This situation should be carefully tested for consequences before feature implementation.

Controls

Finger Trigger Strength and Dexterity Requirement
Problem Definition. The long duration of the battery life performance test produced a significant finding concerning the trigger control. The investigator operating the wheelchair and PAU experienced fatigue in the finger and hand which actuated the PAU controls. This fatigue was significant within the first lap of the first trial (576 feet) and should be considered an important issue in the next generation of design changes. The problem was identified by only one subject (able-bodied pretest subject), however, the subjects were not asked to operate the PAU continuously for any long period of time.

Finger strength and dexterity are required to pull and control the finger trigger. One expert with weak hands used both hands to operate the unit and appeared to put forth a good effort to pull the finger trigger. It appeared to some of the experts that the controls as they are eliminate quadriplegic consumers. This was also anticipated by the design team, but surprisingly, one quadriplegic expert and a quadriplegic usability evaluation subject were both able to maneuver the PAU and wheelchair quite well. The expert actuated the trigger by pressing it against the medial side of the second metacarpal. The usability subject rotated the handle 180 degrees and actuated the trigger with the proximal end of his thumb. If the intended consumer of the PAU is to include quadriplegic wheelchair users, a different set of controls will need to be implemented.

Option Recommendations. Utilizing a lever to apply voltage to the motor would decrease the required strength and dexterity for actuation. A vertically oriented lever, similar to a bicycle brake, could be mounted against the handle of the PAU. The lever would need to be spring loaded and shaped to meet the fit of a gripping hand. It may be advantageous to orient the control on the operator side of the handle so that it can be actuated by the palm or the thumb.

Experts introduced the idea of developing a joystick control. This type of arrangement can be considered but would greatly increase the complexity of the product. Joystick controls require that the steering be accomplished via a motor and the motor controls must be programmed for joystick use.

An additional option is to reduce the spring force in the current trigger switch. The switch is spring-loaded to provide an automatic shut-off when there is no input at the handle. This spring stiffness can be decreased to minimize required user strength while still providing for the automatic shut-off.

Finger Trigger Control Response

Problem Definition. The response of the trigger control does not compensate for motor and drive wheel reactions. Wheels can slip on takeoff and vibrate the handle (associated with a slight pull to the side). One subject squeezed and released the trigger during operation instead of applying continuous control. There is also a tendency of the unit to unexpectedly accelerate at takeoff and while driving. One expert commented that the wheelchair jumps when it is triggered. This quick take-off caught her by surprise.

The problem is prioritized as number 13 in the critical observation analysis with a frequency of two and an average criticality of 3.7. It was also identified by one subject in the critical incident analysis and is listed as problem number ten with a criticality of 6.5.

Option Recommendations. The control unit (which controls voltage response) for the finger trigger is designed by the control manufacturer. A purchaser of the voltage control system should clearly indicate to the electrical component vendors that a control permitting a "jump start" is dangerous for this application.

Turning the Handle for Steering

Problem Definition. One expert commented that too much effort was required to turn the unit when it was not moving. The problem exists while moving as well and was identified by a subject in the critical incident analysis who described it as "a lot of torque in the neck when driving." In some cases the usability evaluation subjects used small jerky adjustments to turn the wheelchair with the PAU instead of continuous adjustment. The experimenter observed this problem in three cases and it was assigned a criticality rating of 3.1 in the critical observation analysis. It was only identified once in the critical incident analysis with a criticality of 1.0.

Lack of a differential in the paired drive wheels causes a slight resistance to turning which can result in jerky motions as the resistance is overcome and the column turns abruptly. It is the resistance created by the wheels turning at the same rate but moving through different distances which makes it difficult to turn. This is exaggerated by the distance between the wheels and the friction between the wheels and the ground. The design team was unable to locate an off-the-shelf differential unit which matched the size constraints and strength requirements of the PAU. It may be possible to design a differential for this application, however, the expense for such a design effort is estimated to be far beyond the benefit it could provide for the product.

Another problem identified with turning the handle is the requirement to move the steering handle in the opposite direction of the intended turn. This was confusing initially for some of the operators, though experience did help with the confusion. The problem was prioritized as number nine in the critical incident analysis with a frequency of two and a criticality of 4.3. It was only observed once in the critical observation analysis and listed as number 27. One expert pointed out that this activity goes against intuition, but mentioned that it may be a successfully trained behavior.

Option Recommendations. The optimal solution to overcome the strength required to turn the handle is to incorporate a differential into the paired drive wheels. This would permit the wheels to rotate at different rates on turns to compensate for the extended distance the outside wheel travels. It is difficult to locate or design a differential which matches the confined space available for the drive train. Further options for reducing the resistance include moving the drive wheels closer together and changing to only a single drive wheel.

One expert suggested a handle configuration which would offer more leverage such as a two handle steering system. This is the type of handle built into the Roll-Aid power add-on unit where both hands have a place to grip and maneuver. Two handles may also provide a more intuitive direction orientation for steering. This type of design change would require the user to reach farther forward (assuming the handles would be located in line with the column). Also, one handed operation may not be as easy with this type of arrangement.

A suggestion offered by a design team member to overcome the confusion over direction, is to place an arrow along the top of the steering arm of the PAU. Pointing forward, the arrow would aim at the direction the wheelchair moves when the tiller is steered. For example, if the handle is moved to the right, the arrow would point to the left and the wheelchair would move to the left as well. A label such as this can be part of an initial training period with the device.

Forward/Reverse Switch
Problem Definition. The investigator observed a wheelchair user maneuvering the PAU and wheelchair within a house. The tight quarters required that the unit shift constantly from forward to reverse and back. This continual need to switch between the two positions was not anticipated and perhaps a more convenient switch would be appropriate. Most users must remove the driving hand from the handle in order to operate the forward/reverse switch. It is also small in size; requiring some dexterity to move between positions. There is currently no label on the switch to indicate direction.

Option Recommendations. One expert mentioned that the forward/reverse switch should be marked to indicate which position corresponds to which direction. Another expert suggested matching the mental image of forward and reverse by placing a rocker control switch on top of the handle. This could be oriented with the forward location toward the front and the reverse location toward the rear.

A usability evaluation subject suggested placing the forward/reverse switch in a position that is easier to manipulate. The subject proposed a button on the handle body oriented perpendicular to the side of the handle. The investigator's interpretation of the control idea is shown in Figure 16.

Additional Design Deficiencies

Handle Component Cannot Withstand Vertical Loads
Problem Definition. The handle which is oriented vertically on the PAU is not able to withstand a strong vertical load. This was determined when the handle was grabbed in an attempt to move the entire wheelchair by lifting the handle. The weight of the wheelchair pulled down on the handle attachment area as the mover pulled up on the

handle. These forces resulted in the handle separating from the handle arm and the destruction of the slip ring component. Due to the convenient location of the handle, it is anticipated that this would be a common use of the product.

Option Recommendations. The housing for the slip ring component should be reinforced to withstand vertical loads. This use was not anticipated with the initial design and therefore the unit was weak along the long axis of the handle.

Consideration of Large Operators

Problem Definition. When reaching forward, the handle arm of the PAU will uncomfortably push into the body of a large operator. This is due to the orientation of the handle arm back toward the operator and the difficulty in rotating the handle out of the way while stopped in power mode. This problem was identified in the critical incident analysis when an operator was required to reach forward to release the finger grips for switching column positions. The problem was prioritized as number 16 with a frequency of one and criticality rating of 4.0.

The handle arm orientation became prohibitive to operation with one obese subject in the evaluation. Testing was stopped for safety concerns when it was determined that the handle could possibly harm the subject. As mentioned by another subject, many wheelchair operators are overweight due to the relatively nonambulatory lifestyle. A product which does not accommodate large persons will lose a significant percentage of the market. One expert in the interview evaluation specifically cited large operators as potential consumers for the new PAU. He pointed out that they are typically not able to independently operate manual wheelchairs up inclines or over long distances.

Option Recommendations. One subject suggested making the handle arm adjustable for operators of different sizes. This would also be an advantageous feature for accommodating users of different arm lengths. A possible way of providing variability is to manufacture different size components and assemble them as per order. Those operators requiring a shorter handle arm would lose some leverage while steering, so a two-handled option may be necessary to compensate.

It may also be possible to adjust the distance from the front edge of the wheelchair to the PAU with different size column/crossbar attachment blocks. This would maintain the steering leverage of the long handle while positioning the handle farther from the operator.

Motor Whine

Problem Definition. One negative aspect of the PAU performance consistently observed is a whine produced by the motor when operated at submaximum voltage. The sound is in addition to the expected operation noise produced by the motor and it is only produced when the motor is operated at less than maximum voltage. This occurs when the finger trigger control is actuated partially (not full depression). The noise was identified twice as an incident in the usability evaluation: once by a wheelchair operator and once by an able-bodied pretest subject.

The measured broadband sound pressure level of the motor whine was quite low at 42.4 dBA. This level was below voice conversation (Berger, et al., 1986). However, the tonal nature of the motor whine, predominantly at 4000 Hz, probably contributed to the annoyance factor of the noise.

Option Recommendations. It is unclear if this problem would be influenced by a different voltage control system because the sound emanates from the motor itself. There are ways to alter motor speed and torque settings which may influence the whine. This problem should be discussed with motor vendors and motors should be tested for noise problems prior to large quantity purchases. Currently, the noise can be avoided by adjusting the voltage applied to the motor at the finger trigger control.

Reasonably Foreseeable Misuse

Based on observations and discussions with subjects, experts, and laboratory personnel, it is anticipated that the PAU may be utilized inappropriately in many possible ways. The following is a list of possible misuses the design team foresees as potential problems.

- A person attempting to move the wheelchair, without sitting in the wheelchair, may find the handle of the PAU a convenient place to grab. The handle has not been designed with sufficient strength in the vertical direction to pull the entire wheelchair (a person standing may lift upward while attempting to pull the wheelchair with the handle).
- A PAU consumer may attempt to convert his or her manual wheelchair into a full-time power wheelchair with the new device. It is not the intent of the product to function all day, everyday, as a power wheelchair. Components have not been fatigue tested, and the impact of such strenuous use is unknown.
- A tie down may be secured to the PAU in an effort to stabilize the wheelchair in an accessible bus or van (these tie downs are usually secured to the wheelchair frame). In such a case, it is unknown what effect a sudden vehicle motion may have on the PAU/wheelchair interface. A strong force may dislodge the PAU from the wheelchair, possibly freeing the wheelchair and endangering the occupants of the vehicle.
- A PAU user may attempt to utilize the handle as a stabilizer for posture maintenance. For example, wheelchair operators are often required to lean strongly to one side of the wheelchair to relieve sitting pressure (referred to as a weight shift). This motion can sometimes be rapid, throwing most of the users body weight to one side of the wheelchair. A stabilizer, usually the opposite side large wheelchair wheel, maintains the position of the operator in the wheelchair. It is anticipated that the PAU handle may be mistakenly utilized as a stabilizer in this way. The handle was not designed for this purpose and it may break or move unexpectedly if such a force is applied.
- The extended position of the column while in transfer mode (rotated forward) may encourage the use of the column to ram open doors, clear obstacles, etc.. Striking objects with the column/handle would result in damage to the PAU and possible harm to the user as a result of moving components.

These possible misuses of the PAU should be considered in the next generation of design changes. Priority should be given to potential safety concerns such as the accessible vehicle tie down scenario. For example, it may be necessary to label the PAU with a statement such as "Do not secure tie downs to this attachment."