The ATPC-X42 All-Terrain Power Chair

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1. Optimal Design

1.1 Introduction

This project is aimed at designing and building an all-terrain power chair for Annalee Hughes, a ten-year-old girl with cerebral palsy. Cerebral palsy is a neurological disease that is diagnosed in children, usually at birth, and permanently affects muscular movement, as discussed in [1].

Annalee cannot walk nor stand on her own power as a result of the disease, and she also has very poor upper body strength. She loves exploring the large, three-acre property on which her house is set, which includes a barn, small pond, and brush from which blueberries can be picked. However, the property is also very hilly and rocky, making it very difficult for her to travel around the yard in her current power chair. She has tipped over in her power chair while trying to access the yard, which shows the need for a new means of transport. She cannot get up on her own power if the current chair tips over. The all-terrain power chair will erase the danger associated with the traversing of the rugged backyard.

The ultimate purpose of this project is to design an all-terrain power chair with a low center of gravity that allows Annalee to travel on her property without her or her family having to be concerned with her safety. The device is planned to have different features than her current chair, which can be seen below in Fig. 1.

![Figure 1: The client’s current power chair.](image)
The current chair is a six-wheel system with mid-wheel drive. It can be seen that the power is supplied to the middle two wheels, while the front and rear wheels are for front-back stability. The main problem with this is these wheels are not suited for rugged terrain. Thus, the ATPC-X42 will feature four, larger off-road tires, with the rear two being larger than the front two. This is apparent in Fig. 2 below, which is an overview of the preliminary design.

Figure 2: This figure shows the overall design of the ATPC-X42 all-terrain power chair.

The new device will also have a customized chassis that will bring the center of gravity of the overall chair down, a drive train that will have two motors to individually power the rear wheels, a shock-absorbing suspension system, and a seat actuator. It will also contain a joystick control system to mimic the current chair, a kill switch in case Annalee loses control, and a tilt sensor that will set off an alarm if she approaches dangerously steep slopes. The chair will also have
safety constraints such as a five-point harness and seat belt, as well as posture-maintaining constraints.

1.2 Subunits
The complete chair described above is made up of a number of smaller systems that come together to make everything work. Each of these subunits has to be designed so that it not only accomplishes its task, but also integrates into the complete system. The following section details the design of each of these subunits, and describes where they fit in the complete design. They can be broken down into three sections, mechanical, electrical and software.

Mechanical
The mechanical components of the power chair encompass all of the parts that have a role in the structure and mobility of the device. These parts include the seat, chassis, tires, drive train, suspension, and seat actuator. The way in which each of these parts will play a role in the mechanics of the power chair is described below.

Seat
The seat of the power chair plays a vital role in keeping the proper positioning of the operator. Since Annalee is unable to maintain herself in the upright position, it is both an issue of safety and health for the seat to provide the proper posture for her when she is operating the device. The seat also plays an important role in securing the operator via a harness and seat belt. These parts must work in unison to support Annalee without restricting or harming her as she drives the chair around her rugged yard.

The seat will consist of modular rubber parts that will allow the overall size of the chair to increase as Annalee grows. These parts include the base of the seat, the back, the headrest and the upper torso and thigh cushions that will maintain Annalee’s posture. They will be acquired
as individual parts that can be reconstructed upon the obtaining of the chassis. These parts can be seen Fig. 3, which displays all of the seat components put together below.

![Figure 3](image)

**Figure 3:** This figure displays the overall seat assembly, which includes a headrest, back, base, and posture holders.

The overall seat will be larger than the one on Annalee’s current chair, which she has been using for almost two years. The current seat sports a depth of 15 inches, width of 14 inches, and height of 19 inches, not including the headrest. As Annalee gets older, it is important for the seat to be able to fit her, and thus we will acquire parts that are larger than the old seat. The seat will be tested to make sure it can be small enough for Annalee to use right away with the capacity to adapt to her growth.

**Constraints**

There will be multiple constraints used to contain the client within her power chair during its operation. The first are side constraints which can be seen above in Fig. 2. These will support
the client’s body and prevent it from leaning side to side. The constraints, as can be seen, keep
the hips and torso aligned and upright while sitting in the chair.

The client has also requested that a padded 5 point harness be used to keep them upright while
operating the chair. This harness will go over the user’s shoulders, around the waist, and clip in
between the legs to prevent them from slipping out, or leaning forward. Due to the effects of
cerebral palsy however, a harness will have to be modified to allow for easier release and
engagement of the latch. This will be done by loosening the catch mechanism slightly to make it
slide in and out of place easier, while still locking.

The client has also expressed the need for better support while getting into and out of her power
chair. The footrest in her current chair will not stay in the upright position when she is trying to
slide out of the chair, so a footrest with stronger hinges will be used to provide support. The
joystick also gets in the way when she is pushing out of the chair, so it will be mounted on a
hinge that rotates outwards and can be pushed out of the way when it is not needed.

Chassis

The chassis will be acquired from a pre-existing power chair, and will contain the axles,
batteries, drive shaft, motors, and suspension system. The frame to be modified was collected
from a used Jazzy 1122 power chair. It will also be the framework on which the seat is
mounted. The seat will be mounted modularly, so that as Annalee grows, it can be interchanged
and replaced with a larger seat without having to dismantle or redesign the entire chair. It is very
important for the chassis to be able to support the weight of the client, as well as withstand any
external forces generated during operation, such as by rocks or uneven ground. The chassis must
also be large enough to house all necessary sub-components, but small enough to maintain
portability of the device.

Furthermore, in order to increase the overall stability of the all-terrain power chair, the chassis
will be modified to accommodate larger tires that are wider apart. It will also be made heavier
with metal reinforcements to bring the overall center of gravity down. The chassis will be tested
via analysis of the designed part in Autodesk Inventor Professional, and once it is obtained it will
be physically tested with weights that will simulate the weight of the seat and operator. A diagram of the chassis can be seen in Fig. 4 below.

![Figure 4: This diagram shows the basic design of the chassis with the tires attached.](image)

**Tires**

The tires will be one of the key differences between the client’s current power chair and the all-terrain power chair. Four larger tires will be used rather than maintaining the current six-wheel system. It is also important to note that these will be real tires that can gain traction on grass and dirt rather than rubber slabs that do not have good traction when operating off asphalt or flat ground. The tires will all be tubeless tires with proper wheel rims. Two large, off-road tires Fig 5 in the rear will be powered by two electric motors, and their size would account for increased stability and traction. Two smaller, off-road tires in the front will be used as well, but they will be large enough to prevent the compromising of the chair stability. These tires will be mounted to strong metal casters taken from an Invacare Torque SP as in Fig 6. and will assist in changing direction and maintaining a certain direction.
Figure 6: One view of the knobby tires to be used on the power chair [16].

The rear tires will be approximately the same diameter as her current chair however will be much wider than the cheap rubber tires that are on there currently. The tires that will be used will be knobby ATV tires, 145/70X6 sized. This gives a rim diameter of 6 inches. The tires will be about the same diameter of her current chair but much wider (14.5 cm) [16]. The tires will be wide to help with the left-right stability of the chair by maintaining more contact with the ground.

Fig 6: Strong front casters for the power chair. The tires pictured will be removed for wider, larger tires.
**Drive Train**

The drive train will provide the device with a rear-wheel two-wheel drive mechanism. Two individual motors will receive power from the batteries and each will power a rear wheel independently. This will allow the chair to have a tight turning radius, since it will be possible for the left wheel to be in motion while the right is stationary and vice versa. The motors will also deliver the torque that will get the device up and down the hills. The client states the current chair, which uses Sunrise Medical motors (part number 499152), does not have quite enough power to navigate the hills of the property. Thus the new motors used in the ATPC-X42 will provide more torque that will allow easier traversing of the hills. The current chair attains a maximum speed of 6 miles per hour, and the ATPC-X42 will allow approximately the same speed. Two motors from a stronger power chair will be used to operate the chair. The motors with gearboxes will come from an Invicare Torque SP which contains two 4 pole motors capable of going 6 miles per hour. The motor for this chair is shown in Fig. 6, which also shows the stock tires used on power chairs which are not stable enough for rough terrain. By keeping the center of gravity and motors in the back it will increase the stability of the chair. In the motor assembly there will also be a lever to engage and disengage the motor. The current chair has this feature and is required for proper wheelchairs. This allows the chair to be pushed by another person if it is required in the case of a break down or loss of power. Without this if the chair got stuck the wheels would lock and would have to be dragged instead of rolling it elsewhere.

![Invicare Torque SP motor](image)  
**Fig 6**: Invicare Torque SP motor which will be removed from the current power chair.
**Suspension**

The suspension of the device is essential for preventing imbalance and tipping during operation, which has happened with the client’s current power chair. Furthermore, since the device will be operated on rough, hilly, and rocky land, the suspension will play an important role in keeping the operator stabilized and comfortable. Annalee's upper body strength is already very weak, and she will not be able to compensate for any extra forces from the terrain.

In order to accomplish this task, the rear wheels will be attached to the chassis via a spring-shock absorbing mechanism that will dampen impacts the chair experiences with the ground. Overall, this should keep Annalee stable in her seat while operating the device and will provide a relatively smooth ride. The shock absorption system will be tested in Autodesk Inventor to ensure the springs can withstand the forces generated by the ground. Figure 7, shown below, displays how the suspension system will be implemented.

![Figure 7](image)

**Figure 7**: This figure displays how the springs will be attached to the rear of the device to operate as a shock absorption system.

**Anti-tip Wheels**

As part of the safety precautions in place, there will be anti tip wheels in the back of the chair. The current chair simply has two wheels that are in constant contact with the ground at all times.
The four wheel design of this chair offers a lower center of gravity than a conventional six wheel chair, but the risk of tipping backwards is slightly increased [2]. Due to this, in the back of the chair behind the rear wheels will be two smaller wheels that are on small axle. The axle will be lifted off the ground and if the chair tilts backwards too much the anti tip wheels will make sure that the chair does not flip backwards.

**Seat Actuator**

The seat actuator is a motor that will elevate and lower the orientation angle of the seat. The actuator receives a linear signal automatically from either the tilt sensor or manually from the actuator controller and translates that into a mechanical force up or down. When the chair is traveling down a hill, the motor of the actuator will provide torque at the hinge of the chassis that connects the chassis portion the seat rests on to the part that houses the rest of the components. This will cause its angle with the ground to increase. The operator will then be looking parallel to the ground rather than into it, and it will prevent Annalee, who has a weak upper body, from falling forward out of the seat and into the harness. It will provide torque in the opposite direction when she is traveling uphill to prevent her from looking at the sky as well. The amount of elevation or depression will depend on the grade of the slope Annalee is traveling on, and it will be automated with respect to the tilt sensor.
Electrical

The electrical portions of the subunits come together to control and operate the mechanical portion of the whole project. The electronics portion provides the power to the chair in order to fulfill all day operations. The key parts of the electrical subunits are the batteries, charger, killswitch, joystick, and controller.

Batteries

The batteries are the most important part of the electrical subunits. Without proper batteries the wheelchair will not operate properly and may shutdown abruptly. A Deep Cycle battery is required to operate the motors and actuators in the wheelchair. With the use of deep cycle batteries it allows for up to 80% discharge before the batteries need to be charged again. This is essential for all day use and traversing the different terrains that the wheel chair will be used on. The batteries that will be used will be Optima deep cycles [3]. One battery has 55Ah and 12V. 55Ah represents the amount of current that can be delivered. This is a high amount compared to other chairs however this is what is necessary to get all day heavy usage. Two will be used in series in order to provide enough energy for the system to operate.

Charger

Because the system is electrically operated there needs to be a charging unit in order to recharge the batteries. A multi stage charger is necessary for this task. The function of the multi-stage charger is to charge as fast as possible without overcharging. The charger senses the battery’s state-of-charge and tapers the current as it approaches 100% charged. This maintains the battery at a full state without boiling away the water in the electrolyte [4]. The charger will also have an indicator to show the charging level. With a good charger, recharge time can be as little as 1 hour from 50% capacity.
**Tilt Sensor**

The tilt sensor is a device that is able to determine if an object is not level. The sensor that will be used is produced by a company called Rieker Incorporated and called a SlopeAlert [5]. The sensor is produced for use in rugged machinery and has a two axis sensor that will sound an alarm if the grade exceeds a preset value, which for this project’s purposes will be ±10°. The system is enclosed in a weatherproof box which is protected against shocks as well as extreme temperatures. The sensor operates off of an 8-30VDC power supply, which will be easily distributed from the battery. An output from the sensor will be connected that will feed into a microcontroller to be discussed later. This will allow for automatic control of the seat actuator. This device does not take up much space, and will fit easily into the chassis of the chair as shown in the manufacturer’s specifications illustrated in Fig. 8 below.

*Figure 8: SlopeAlert enclosure showing mounting brackets and dimensions as well as output array.*
**Kill Switch**

A kill switch will be implemented for the increased safety of the all-terrain power chair. This will be in the form of a button that will cut off the power from the battery to the motor. This will also function as an on/off switch for the power chair. When set in the off position, the battery will not drain, and the motor cannot operate. This switch will be located on the joystick for ease and safety.

**Joystick and Actuator Control**

The joystick will be used as the controlling mechanism. The power supply to the motors will be controlled by the joystick. When the joystick is set to the neutral position there will be no power sent to the motor, and the wheels will be in stationary position. Whereas, when the joystick is pushed forward, backward, left, or right, the chair will follow the respective direction. In addition to this the joystick will be used to control the speed of the power chair. The joystick is made from the resistors that provide the input to the pulse width modulator (PWM) circuits [6]. Pulse width modulation controls the motor speed by driving the motor speed with short pulses. These pulses vary in duration to change the speed of the motor therefore, the longer the pulses, the faster the motor turns, and vice versa. The joystick will be obtained from an Invicare Torque SP. The joystick has a speed control to determine the maximum speed during use. As said before the joystick will also have the on/off kill switch for the motors. When activated there will be no power to the motors and therefore no movement. The joystick will be the same as the client’s current model, which is pictured below in Fig. 9 along with the seat actuator controller. The actuator controller will operate the same way the joystick will, with a forward motion tilting the chair forward, and putting the joystick in reverse will tilt the chair back.

![Joystick used to operate the power chair.](image)

*Figure 9:* Joystick used to operate the power chair.
Software

The software portion of the subunits allows for user modification. The chair’s motion and response times can be adjusted in the microcontroller accordingly with proper settings thus producing the ideal configuration for our application.

Joystick Controller

The user is responsible for the high-level control of the device, which include route planning and navigation actions. In use of the device the user indicates the desired direction and speed of travel using the joystick. Various navigation routine modifies this command, if necessary to provide safety and/or improved navigation through a combination of slowing the device and changing its direction of the device.

The controller, also known as the power module is the main command center for the power chair which will control the motors via power distribution. The power module that will be used is by Penny and Giles. They are 80 amp speed controllers which come standard with most power chairs. The coding of the controllers help with torque and speed, which is a crucial part of the power chair. The module simply connects the batteries, both motors, and joystick to its interface. Reprogramming will be done as well to fine tweak the chair to perform up to specifications. Using a hand held programmer designed for the Penny and Giles module will allow for tweaking of various options. Some of the main options that will important to adjust will be the acceleration and deceleration. The current power chair tends to be slow when traversing hills, therefore a high acceleration will allow the chair to traverse a hill when necessary. One key thing that needs to be changed is the turning acceleration and deceleration. Currently there is a delay in the turning acceleration and there is a too long of a delay for deceleration when turning. By adjusting the settings the chair will be able to turn exactly when the user wants and not turn when she doesn’t.
**Tilt Sensor Controller**

A microcontroller will also be responsible for taking inputs from the tilt sensor and sending commands to an actuator for automatic chair level adjustment. As stated above, the joystick will be controlled using the Penny and Giles controller, but the tilt switch will be programmed using a Microchip PIC16F877 microcontroller in C. PIC16F877 is one of the most commonly used microcontroller, some of the main features of PIC16F877 are the following there are only 35 single word instructions which have 35 input/output ports and low power, high speed technology [7]. The microcontroller will input signals from the SlopeAlert sensor, and sensing the magnitude of the signal will adjust the seat height accordingly. Clearly, since the chair will be operating over rough terrain most of the time, this actuation will only trigger over steep grades where the operator will struggle to keep themselves upright.
2 Realistic Constraints

When building a product it is important to consider what factors can limit the production and usability of the item. Once these issues are recognized, methods to keep them under control must be created so that the product can operate as well as possible with the given limitations.

2.1 Health and Safety

Since this project was created because of the failure of her previous chair, the ability to keep the client upright over rough terrain is the foremost constraint of the chair. The chair should also support Annalee in a proper way and allow her to control the device comfortably. This device also aims to increase the client's quality of life while in the chair by improving her ability to get in and out of her chair unassisted. In addition to the safety of client, the safety of the workers is also very important. When modifying the base of the chair, a metal cutter will be needed to push the rear wheels further back on the chassis, which will have to be done with care. Also, wiring up the system will take caution when working near the deep cycle batteries. The client’s and the workers’ health and safety must come first and foremost while designing this device.

2.2 Sustainability

Sustainability constraints are another issue in designing this device. Since the client is a ten year old girl, she is continuing to grow, and a chair which can’t grow with her would be a waste of time and money. To counteract this, the seat will be replaceable so that a larger one may be installed at a later date. The motors will also be strong enough to transport her if her weight increases. The chair’s design overall will consist of as many easily acquired parts as possible so that in the event of a part’s failure, it can be easily found and replaced. The ability to recharge the batteries will also increase the sustainability of the project, since deep cycle batteries can last a long time if they are cared for properly. Lastly, since the chair will be operated outdoors, it must be as able as possible prevent dirt, mud, water, and rust from getting into the circuitry and interior which would reduce the chair’s lifespan.

2.3 Environmental

The actual environmental factors are key constraints to think about. The device should be applicable in extreme working temperature whether it is hot or cold. The device should also be gentle on its operating surface since this will often be the client's yard, but also could be a park
or field. In order to eliminate pollution the device will run off an electric motor rather than a gas motor.

2.4 Social

One social constraint is to make sure Annalee can enjoy outdoors activities, rather than creating a device that confines her as her current power chair does. Letting her explore the outdoors and be able to reach new areas would help to decrease the social gaps caused by her palsy. Another social constraint is to make the device as quiet as possible so to not disturb the surrounding rural neighborhood while it is in use.

2.5 Economic

Economic constraints are very important in designing the device. Power chairs which are on the market and have the title “all terrain” cost upwards of $16000[8]. Since this is a project sponsored by the National Science Foundation, a budget that high is impossible. Thankfully, access to used power chair components has been obtained, and most of the chair will be able to be acquired for free or for cost. Knowing the budget will still help to finally determine what materials can be purchased to modify the power chair from it's current condition into one which can handle the outdoors. Since the budget cannot be exceeded, it will set the limitation on what can be used to improve the design.

2.6 Manufacturing

Manufacturing constraints will come into play when modifying the chassis. Accessibility to the internal components should as easy as possible even though the frame will be extended and reinforced. The drive wheels will also be moved back on the chassis, so a factor of safety must be considered to make sure that they are mounted properly and securely. The chair will weigh approximately 300 pounds, and will carry a passenger who currently weights 56lbs but will continue to grow. Assuming that the client will not grow past 200 pounds, this means the chair should be able to withstand over three times that weight (1500lbs) without failure. It is also important to make this product as reproducible as possible, which means the manufacturing should be well-recorded and easy to replicate.

2.6 Political and Ethical
The last major constraints are political and ethical. The manufacturing of a product that might be physically and/or mentally destructive for clients and workers is a key political constraint. Also, designing the device without considering safety and health of the client, workers and/or the public is a major ethical constraint.

2.7 Engineering Standards

The standards of power chair production will also be maintained throughout this project to keep it as similar to the client’s current chair as possible. Normal top speed for a power chair is 6.5 miles per hour which will be kept the same. The joystick control will also be kept so that there will be a pre-existing familiarity with the methods of operation. When reinforcing the frame, welds will be done through stick-welding or TIG welding to standard for aluminum [9].
3 Safety Issues

In designing this device safety is a major concern when the device is both active and not. The main safety issues arise from the mechanical components of the all-terrain power chair, since the purpose of designing this device is so that the rough and uneven terrain that comprises the client’s yard can be easily and safely accessed. Therefore, for the purpose of increasing the stability of the chair, the chassis will be well-modified in order to accommodate larger, wider wheels. With more ground contact governed by wider wheels, the left-right stability of the chair will be significantly increased. Furthermore, the chassis will be also be widened for the same purpose, and it will be reinforced to lower the chair's center of gravity.

The suspension also adds to the overall safety of the chair due to Annalee's poor upper body strength. As she operates the device on the uneven, rocky property, the suspension must be able to absorb the forces generated by the ground on the chair. If this is not accomplished, the ride will be very rocky, and will be harmful to Annalee, as she will not be able to secure herself in the seat. Rather, the ride will be uncomfortable and her posture will not be secured.

It is also extremely important for the chassis to be built strong enough in order for it to bear the weight of the seat and the operator, as well as any external forces. If it is not properly tested to ensure quality, then it is possible for the chassis to break at any moment, whether during operation or not. If the chassis were to break during operation, the client would be in extreme danger. Thus, it is imperative the chassis is built properly and tested so it will definitely never break. The same issue applies to the seat, which must be secured together since each separate piece is modular. The wheels must also be secured, because if a wheel came off during operation, it would also pose a great threat to the operator’s safety.

The electrical component wire which carries the current will be protected so that it does not cause be any environmental hazard. Therefore all used and unused wires should be secured and electrically isolated from each other and any other possible connection. In order to be safe from chemical hazard the battery should be well sealed. The motor will be covered using heat insulator so that the heat coming from the motor will not be a fire hazard for the user during or
after operating the device. The soldering used to connect wires also needs to be secure and protected, if a wire becomes loose or crossed during operation, it could cause for a short or malfunction of the power chair which would result in a lack of control or shut down. This would leave the client stranded in the chair outside, which could become dangerous if there weren’t other people around or if the weather was poor.
4 Impact of Engineering Solutions

The goal of this project is to create a power chair which can bring our client outdoors without the worry of tipping the chair for a cost much lower than the current market standard. Since the project is to be created for only one client, its impact globally will be negligible. If, however, it was to be marketed and sold, it could have a profound impact economically, environmentally, socially, and globally. This chair will cost much less to produce than current power chairs [8] marketed for use outside on rough terrain. If mass-produced, there would stand to be a large market for a power chair with a low cost which can bring people who have disabilities closer to a normal standard of living.

The environmental impact of a marketed all terrain power chair could have both positive and negative effects. On the positive side, it would bring a new demographic of people to nature and the outdoors, which could increase the concern for wildlife preservation, national parks conservation, air quality control, and other environmental issues due to the new group of people being exposed to these issues directly. A negative impact would be due to the increased presence of power chairs in parks and other places. Increased travel by treads would cause wear on lawns, creating an eyesore. The power chair itself could also cause an eyesore to other people, but in order to make it more aesthetically pleasing, it would have to be redesigned which would increase the cost.

Another side effect of marketing low-cost all terrain power chairs would be increased exposure to society for its users. People would begin to see users where they never have before, on hiking trails, in hilly fields, and at parks. This would increase a person with disabilities’ exposure to the outside world, and would decrease the stigma that is present in society that people with disabilities are different in a negative way.

The global impact of an all terrain power chair would be the most difficult to imagine, but would function to increase awareness of cerebral palsy as well as other disabilities. It would also increase the ability for the disabled to travel, boosting tourism. This would all come back in the end to improve the quality of life for disabled people worldwide.
5 Life Long Learning

Many new skills were learned in order to design and construct this project which will be carried with the group beyond college. The first thing learned in this project was about cerebral palsy. It was important to find out that a person with cerebral palsy often has full mental function, such as in Annalee’s case. The disability associated with cerebral palsy is a lack of muscular control, which creates the need for a power chair in the first place.

This project has also helped build teamwork and social skills. Since it is a group project, the work needed to be divided efficiently and quickly to meet deadlines. Communication with the client requires respect and intelligent interviewing to find out what the client desires and what they dislike about their current situation.

Learning the components of a normal power chair was essential to the project. The electric motor needed a gearbox to connect to the wheels, and proper gear ratios were required to receive enough torque. The amount of horsepower and rpm provided by the motor was also an important factor to consider when considering which motor to use.

The programming required to control the steering and actuator required the most learning for this project. They were controlled by a microcontroller programmed in C, which meant understanding of the underlying commands was needed, and the tilt sensor needed to be programmed to provide automated control to adjust the seat position.

In order to draft the design for the power chair, accurate 3D drawings needed to be created. Autodesk Inventor is a CAD program that allows for 3D modeling and simulation of mechanical components, and is a professional grade utility used in the work environment. Knowledge of how to operate this program will be very useful for projects requiring R&D.

Lastly, in order to modify the chassis, the machine shop needed to be used. This took knowledge of welding and metal cutting as well as the material properties of the metal used. Precise measurements, cuts, and welds needed to be applied in order to maintain the measure of safety required for a medical device and prevent an unsuspected failure during use.
References:


