

# Mechanism Design of a Multi-Motion Automobile Door

by

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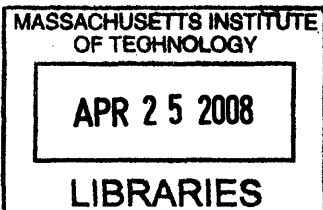
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## **Abstract**

This thesis describes the design and prototype construction of a multi-motion automobile door. This design is intended to provide a unique option for the opening of an automobile by enabling the door to open in two separate directions. A novel design of the door hinge will be presented in this paper which will allow the vehicle door to open in both the standard fashion by being hinged at the front of the vehicle, as well as backwards by being hinged at the rear of the vehicle. The direction in which the door opens can be chosen by the user.

A small section of this paper will look at one additional multi-motion door concept. This second design is a split door in which half of the door opens in the standard fashion, while the second half opens up like a gull-wing door.

Thesis Supervisor: Alexander H Slocum  
Title: Professor of Mechanical Engineering



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# Chapter 1

## Introduction

A major car manufacturer was interested in developing a multi-motion car door. Two concepts were initially proposed. The first concept involved splitting a vehicle door in half and allowing the bottom half to open in a standard way and the top half to open up and out. This design was prototyped and will be discussed briefly in this thesis. The second concept door will be discussed in much greater detail.

Concept Door Two will be hinged on both the front and the rear of the door allowing it to open in two separate directions depending on the user's choice. The "backwards" direction is sometimes referred to as a "suicide door" and is used frequently in pick-up trucks and more recently in other car models, typically in the rear door. These doors are also referred to as coach doors, rear-hinged doors, rear access doors, or freestyle doors depending on the car manufacturer.

The hinge designed for this door model must allow the door to open in either direction, but lock tight when the door is closed to prevent the door from falling off when the user opens the other side. Multiple prototypes of this door have been built during the design process. The first prototype is controlled purely mechanical means, while the second prototype is controlled entirely through electrical means. In order to open Prototype II, the user can push a button, and the hinge will disengage, allowing the user to open the door. When the door is shut, a sensor is triggered, reengaging the hinge and locking the door shut.

A major safety requirement for this door is that a mechanical override system be developed for at least one side of the door. In case of an emergency, the occupants of the car need to be able to get out of the car easily and without the electrical system. This was the final stage of the design and proof-of-concept was shown in Prototype III.

# Chapter 2

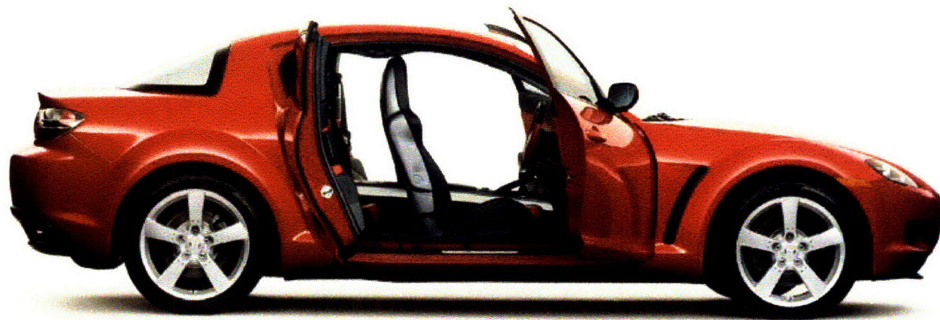
## Prior Art

The two main functions of interest of a car door is how it opens and how it latches closed. Although there are many different ways a car door can open, the one of interest in this paper is known as the “suicide door.” Section 2.1 will provide a history on “suicide doors” and their comeback in the automotive world in the last decade.

The design of latching mechanisms did not get much attention from automotive manufacturers until about the mid-1950’s. However, with new safety legislation getting ready to be implemented, the design of this mechanism was revisited and new designs began to appear on the market. Section 2.2 will outline the history of the development and evolution of door latching systems in automobiles.

### 2.1. Suicide Doors

The term “suicide door” is the common expression used among car enthusiasts to describe an automobile door which is hinged at the rear of the car rather than at the front. The door opens backwards in this case, swinging from the front of the car outward towards the rear of the car. The door handle and the hinges are located on the opposite sides of the door as in a traditional door; the handle is located near the front of the car while the hinges are mounted closer to the rear of the car. Throughout the remainder of this thesis, the term “rear-hinged door” will be used in lieu of “suicide door.” Figure 2-1 is an example of a current car model featuring a rear-hinged door.



**Figure 2-1: Mazda RX-8 featuring suicide door in the rear<sup>1</sup>**

The rear-hinged door dates back to even before the first cars were being manufactured. Horse drawn carriages often had opposite opening front and rear doors, similar to those illustrated in Figure 1. This style of door made entering and exiting the carriage much easier, especially for women in long skirts. (Popely 2001; Mayersohn 2003)

By the 1930's, rear-hinged doors on the automobile were quite popular and could be found on a wide variety of models, from the everyday Ford to the high-end Rolls-Royce. During this time, most of the rear-hinged doors were found of the rear door, although there were some models where the front door was also rear-hinged (Krebs 1999), as shown in Figure 2-2.



**Figure 2-2: 1935 Chevrolet Master Deluxe front and back rear-hinged doors<sup>2</sup>**

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<sup>1</sup> [www.mazdausa.com/MusaWeb/displayPage.action?pageParameter=modelsGallery&vehicleCode=RX8](http://www.mazdausa.com/MusaWeb/displayPage.action?pageParameter=modelsGallery&vehicleCode=RX8)

<sup>2</sup> <http://auto.howstuffworks.com/1935-chevrolet-standard-and-master-deluxe1.htm>

Although it is unknown where the term suicide door comes from, there is some logical speculation as to its origin. The original rear-hinged doors could open independently of each other and these cars did not have any safety mechanisms to prevent the rear-hinged door from opening while the car was moving. If a passenger accidentally pulled on the lever-like handle prevalent in these early cars while the car was moving, the door would be flung open by the air flow. In the days before seatbelts were standard, a passenger could easily be thrown from the car. Another safety issue is posed when the car is stationary and the rear-hinged door is left open. If a passing car were to hit the open door with a person standing between that door and the car, serious injury could result. (Krebs 1999; Popely 2001)

By the 1960's, the rear-hinged door was almost non-existent in the automobile industry. The last models to include this feature were the 1961-1969 Lincoln Continentals and the 1967-1971 Thunderbirds. (Krebs 1999)

Within the last decade, rear-hinged, suicide doors have been making a comeback in the auto industry. These doors can be found on many extended-cab trucks. The back doors operate such that they cannot be opened without the front door being opened first. This design encompasses the safety factor that was missing in the original designs of the first half of the twentieth century, preventing the occupant from opening the rear-hinged door while the car is in motion.

More and more car manufactures are bringing these doors back to their car designs as well. One of the first companies to reintroduce the rear-hinged door was Saturn in their 1999 SC2 sports coupe. The rear-hinged door in this model was similar to that in the trucks; the rear door could only be opened once the front door was opened.

In this design, the car manufacturers have removed the "B" pillar, the support between the front and the rear doors, from the car. In order to compensate for this missing structural component and ensure that the car held up in side impact crash testing, Saturn installed "a beam, foam padding and a piece of sheet metal pleated like an accordion...to absorb crash energy" (Krebs 1999).

Understandably, car manufacturers are purposefully staying away from the term "suicide door." Saturn refers to them as the RAD feature in their Ion couple; Mazda calls them freestyle doors in their RX-8 sports car; Rolls-Royce calls them coach doors; and

Volvo simply says the “doors are hinged at the rear instead of the front” (Mayersohn 2003).

Saturn’s motivation behind offering this new style was to provide their drivers with easier access to the small backseats. Easier access makes it easier for passengers to get in and out of the car; it makes it easier to load and unload luggage, groceries and kids; and it also makes it easier to get in and clean. Honda, on the other hand, is targeting a younger generation with their rear-hinged doors on the Element. Their goal with the rear-hinged doors is to “open up the interior, offering a hangout for young buyers and their friends” (Mayersohn 2003).

In addition to the style described above, where the back door can only open once the front door is opened, Rolls-Royce has implemented back door, rear-hinged doors which open independently of the front doors on their 2004 Phantom. They have implemented a safety lock, however, which electronically secures the back doors while the car is in motion. This safety feature will likely be included in the 2008 Phantom Drophead Coupe expected to hit the market in the Summer 2008 which will feature front rear-hinged doors. (Green 2008)



**Figure 2-3: Rolls-Royce 2008 Phantom Drophead Coupe<sup>3</sup>**

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<sup>3</sup> [www.motortrend.com/future/future\\_vehicles/112\\_0702\\_2008\\_rolls\\_royce\\_phantom\\_drophead\\_coupe/](http://www.motortrend.com/future/future_vehicles/112_0702_2008_rolls_royce_phantom_drophead_coupe/)

Car manufacturers are not the only ones interested in bringing back the rear-hinged door. A quick internet search results in a plethora of websites offering custom kits for Do-It-Yourself suicide door installations. These kits come complete with custom hinges for your vehicle as well as detailed instructions and warnings for installing your very own “suicide door.”

## **2.2. Car Door Latching Systems**

Based on data from 2002, the world market for automobiles is approximately sixty million per year. Assuming that there are on average three and a half latched doors per automobile, the total number of latches required per year is approximately 210 million.

Furthermore, assuming that each latched door requires two hinges, each automobile requires seven hinges, with a total number of hinges per year around 420 million. With such a large market for car door latches and hinges, there is a considerable opportunity for a new latch and hinge design to make an impact in this market.

Automobile latching systems have three main functional requirements: 1) they must prevent the car door from opening, especially during a crash; 2) they must prevent unauthorized, forced entry of the vehicle by thieves; and 3) they must be easy to use by the driver and/or occupants of the car.

In stark contrast to these modern day requirements, the first automobiles latching systems were simple slam latch mechanisms. These latches are similar to those commonly found in homes and consist of a spring-loaded retention mechanism attached to the door and a raised catch feature located on the car frame. An example of this type of mechanism is illustrated in Figure 2-4 below.



**Figure 2-4: Example of simple slam latch on 1970 Land Rover<sup>4</sup>**

Many of the cars in the 1920's and 1930's were soft tops and therefore it was common to find cars without locking mechanisms on their doors. In addition, many cars did not have side windows and on those models there were not even door release mechanisms on the outside of the car.

These slam latches remained popular in the automobile industry until the 1950's when the safety of these mechanisms started to be questioned. Based on the design and placement of the slam latch in the car, it was common for the door to pop open during a crash. Before the 1950's, it was believed that it was in the passengers' best interest to be thrown clear of the vehicle in the event of an accident. However, as more and more cars were taking to the road, accident patterns were becoming apparent and the benefits of being thrown from the car came under serious review. As a result, the physical strength and retention capabilities of latching mechanisms became a more significant design concern.

Beginning in the late 1950's, legislation started to be discussed and prepared in the United States government focused around the prevention of car door latch opening in the event of a crash. Car manufacturers began designing and implementing changes to their designs beginning around this time, even though it was not until 1962 that the Society of Automotive Engineers (SAE) published "Ground Vehicle Standards J-839

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<sup>4</sup> Attridge, A., D. Walton, et al. (2002). Developments in Car Door Latching Systems. Birmingham, University of Birmingham: 12.

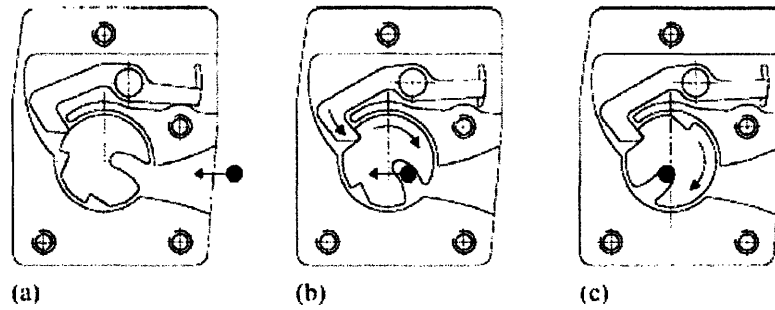


Recommended Practice Standards” in which they specified, for the first time, required bursting loads on car doors. During this time, revisions to old mechanisms as well as completely new designs began to penetrate the market.

One of the first new design changes to be incorporated into the latching mechanisms is known as the “first safety” latch position. This feature was to be a requirement of the new legislation that was being written at the time. It was an intermediary latching position which the latch went through before becoming fully engaged and securing the door shut. This feature was first incorporated in the current slam latch mechanism, but as the requirements for the latch evolved, it became evident that the old design was not going to be able to meet these new requirements. New designs continued to incorporate this new safety feature and it remains a component of latches even today.

One of the most significant new designs during this time period was the disc latch. It was the first design to incorporate safety regulations which would soon be passed in the “Federal Motor Vehicle Standard No. 206” in January 1967. This legislation was the first to require door latches to withstand an acceleration of up to 30g’s in both the transverse and longitudinal directions without disengaging from its fully latched position. In addition, it was required that the latch, when in its fully latched position, also withstand a longitudinal load of 11 kilo-Newton and a transverse load of 8.9 kilo-Newton. Whereas the old designs were becoming larger and bulkier to incorporate these new design requirements, the disc latch was a compact solution which could satisfy all the upcoming legislation requirements.

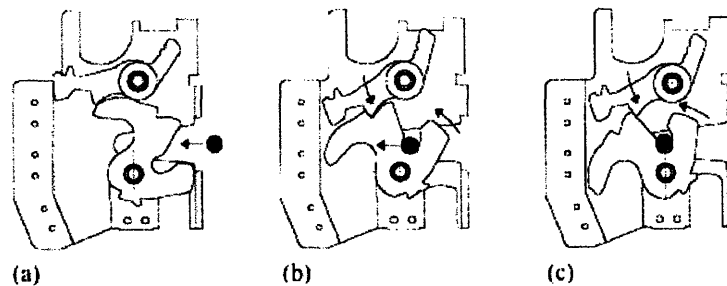
The disc latch is similar to the current bear claw design most often used today. A striker most often found on the car frame fits into the disc, which then rotates to the first safety position and then to the fully latched position. The disc is then held in place by the pawl, or claw, in either tension or compression. A schematic of this design is shown in Figure 2-5.



**Figure 2-5: Disc latch: (a) prior to engagement; (b) first safety position; (c) fully latched<sup>5</sup>**

The main difference between this and the current design used today is that in today's design the disc rotates about a center bearing. In the disc latch, the outer perimeter of the disc was the bearing surface and it ran against the surrounding housing. The problem with this did not arise until some time after it was first implemented when the design was brought to Australia and problems with dust became an issue. Dust particles infiltrated the space between the bearing surfaces and eventually prevented the disc from turning.

As a result of these failures, the new bear claw design was conceived. The outer surface bearing was replaced with a center bearing. This eliminated the problem of seizing the bearing and also allowed designers to change the shape of the disc since it was no longer acting as a bearing surface. Consequently, weight and space saving designs became feasible. This led to the bear claw design which remains an industry standard to this day. A schematic of this design is shown in Figure 2-6.



**Figure 2-6: Bear claw design: (a) prior to engagement; (b) first safety position; (c) fully engaged<sup>5</sup>**

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<sup>5</sup> Attridge, A., D. Walton, et al. (2002). Developments in Car Door Latching Systems. Birmingham, University of Birmingham: 12.

Over the last decade, more attention has been focused on vehicle safety in the event of an accident in which the vehicle rolls over. Stricter regulations have been placed on the latching mechanism as a result. Designers and manufacturers must now be sure to consider the forces and accelerations the latch may be subject to in all directions rather than just in the transverse and longitudinal directions.

Previously, the latch was disengaged through a rigid link that connected the latch mechanism to the door handle. This design, however, had several disadvantages. It was possible to insert something between the window and the door, catch the rod, and pull on it. In some cases, this would unlock the door and thieves could access the vehicle. The second disadvantage was a safety concern in case of an accident. Upon impact, it was possible for the rigid metal rod to penetrate the door panel and impale the driver or occupant of the vehicle. A second possibility in the event of a crash was that the rod would become deformed and would pull on the release mechanism of the latch opening the door.

In order to prevent these failures from happening, the system was redesigned, replacing the rigid metal rod with a steel cable encased in an outer sheathing. The length of the cable and sheath is long enough such that in the event of a crash, the cable is long enough to prevent the latch mechanism from being unintentionally triggered and releasing undesirably. This is the system most commonly used in motor vehicles today. (Attridge, Walton et al. 2002)

# Chapter 3

## Prototype I – Schrader Coupling Hinge

In the initial scope of this project, the concepts for two new, radical vehicle door designs were posed. Two vehicle doors, the mating car frames and a T-slot aluminum frame stand were supplied by the manufacturer for use in the building of the prototypes for each of these new concepts.

Details concerning the designing and building of Prototype 1 for each of these concepts will be discussed throughout this chapter. Prototype I was successfully completed due to the hard work of Keith Durand, a fellow graduate student, Radu Gogoana, an undergraduate assistant, and myself.

### 3.1. Multi-Motion Door A

One of the concepts presented at the start of this project was a multi-motion door which was split in half. The bottom half of the door was to open towards the front of the car in a traditional manner while the top half of the door was to open up towards the sky, as shown in Figure 3-1.

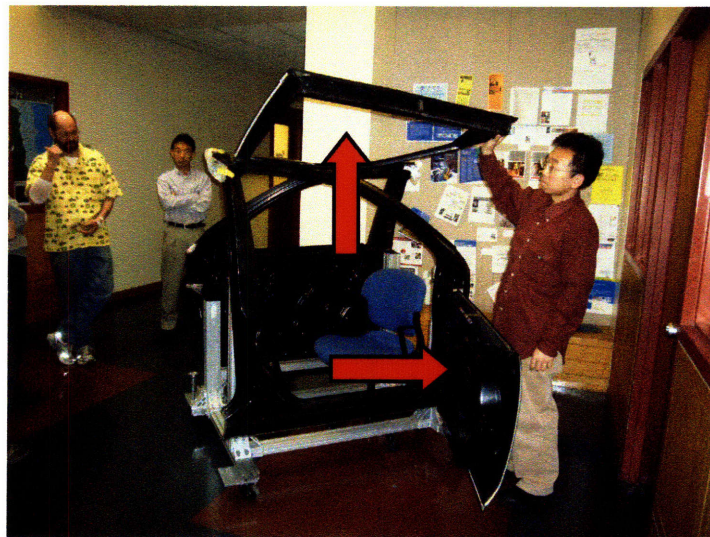


Figure 3-1: Multi-Motion Door A

One of the doors and its frame was mounted on the aluminum stand. A logical position just above the outside door handle and just below the window was designated as the split line. The doors we were provided with were completely bare, except for structural and safety features built into the door frame. There was also some foam insulation around the window perimeter. The position at which it was chosen to cut the door did not pose any significant barriers for cutting. Before beginning to cut, the top part of the door was clamped to the frame to prevent it from moving during cutting and to keep it from falling as the door was being cut. Using a plasma cutter and a straight edge as a guide, an undergraduate assistant working on this project, Radu Gogoana, was able to split the door in half with relative ease.

Because of the position where the door was split, the bottom half of the door lost some of its structural stability. The door frame is made of two thin pieces of sheet metal and when the top half of the door was cut off, there was no longer anything holding these two pieces of sheet metal together at the top of the bottom half of the door. In order to stiffen the bottom half of the door, Keith welded a reinforcement piece between the two outer door panels, as shown in Figure 3-2.

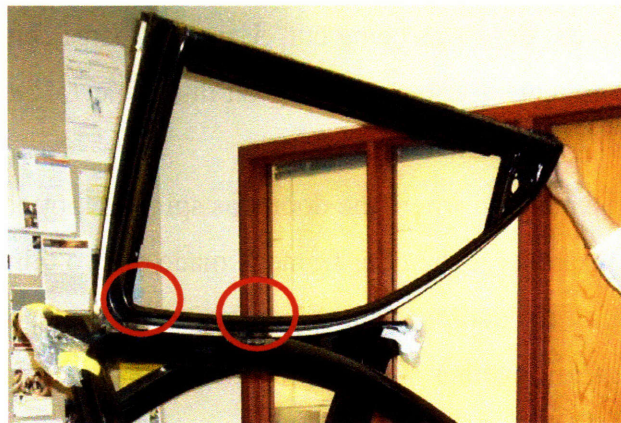


**Figure 3-2: Reinforcement piece welded between two door panels**

Once the door was separated, each piece had to be hinged to the car frame to allow for the proper motion of each piece. The bottom half of the door was easily

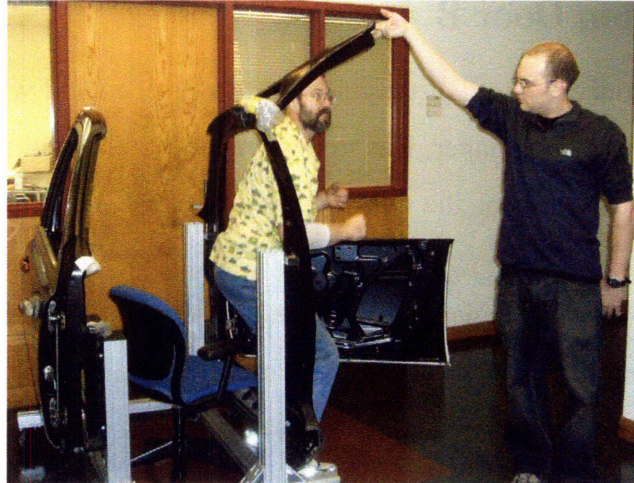
mounted to the “A” pillar of the frame with the existing door hinges. No modifications were necessary for this piece.

The top half of the door needed slightly more modification. While the top half of the door was still clamped to the frame, two standard hinges were welded to both the frame and the door by a member of the FSAE team, creating a permanent connection. The placement of these two hinges can be seen in Figure 3-3 circled in red.



**Figure 3-3: Top half of Door A**

One of the possible benefits of this door design would be to provide rain cover to the occupants of the car during a storm. This design, however, did not allow enough headroom for the occupant exiting the vehicle, as can be see in Figure 3.3. The door does not open high enough and an occupant could easily hit his or her head while exiting this door.



**Figure 3-4: Exiting Door A**

In addition to the height consideration for the top half of the door, there are at least two other design features which would need to be studied in further detail before this concept could be realistically brought to market. The first is to consider the window. The door we used in the prototype did not have the glass window installed. However, the window will pose a major design challenge. The door cannot split in half if the window is in any other position than fully open or fully closed. The fully closed window may still pose a significant challenge because of the mechanism used to hold the window in place and control its motion up and down. If the door is split, this mechanism would inevitably have to be split as well.

The second design feature which needs further analysis is how the two halves of the door will mate and lock together. Another important feature will be how the two halves will open and close. The bottom half of the door could easily use the current door handles since this part of the door is not changing significantly. Further study, however, of the top half of the door and the interface between the two halves is necessary.

As a result of some of these design challenges, it was decided to not pursue this concept any further at this time.

## 3.2. Multi-Motion Door B

The second concept posed at the onset of this project, and which will remain the focus of the remainder of this paper, was to design and build a multi-motion door which opens both towards the front of the car and towards the rear of the car, based on the user's choice.

The double hinged door would allow the user to enter the car from either side of car the door. The goal of this new design is twofold. On the one hand it is completely unique. There are no other car manufactures utilizing this design on their vehicles. It would give the manufacturer an edge over his competitors. On the other hand, this design would also allow the driver and passengers better access to entering and exiting the vehicle. For example, if a car was parked on the street such that a tree on the sidewalk was preventing the occupant from opening the door, the driver would have to move his or her car or the occupant would have to exit the car from another door, which for some people might not be possible. If, however, the door could be opened from the opposite side, it would allow the occupant to exit the car safely and without the possibility of damaging the car door by accidentally hitting the nearby tree.

The functional requirement for this door is that both sides of the door have the ability to open upon command of the user, without the door falling off of the car frame. In order to fulfill this requirement, the door must be hinged on both the "A" and "B" pillars of the car (Figure 3-5).

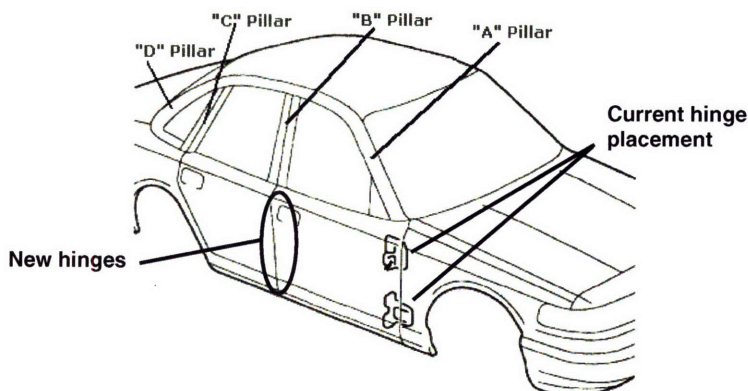


Figure 3-5: Automobile pillar locations and alphabetical naming<sup>6</sup>

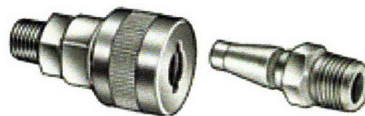
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<sup>6</sup> <http://autorepair.about.com/library/graphics/78390573.gif>



Since the door must open on either side of the door, the hinges on either side of the door have three functional requirements. The first is that when the door is closed, both sets of hinges are engaged and will not release unless commanded by the user. The second is that each set of hinges has the ability to disengage when the user wants to open that side of the door. The third requirement is that the hinges reengage smoothly and with little effort from the user upon closing the door.

With these considerations in mind, attention was focused on different models of quick-disconnect hose connectors to use in the hinge design. These couplings are used in a multitude of applications for quick and easy connection and disconnection of components. There are a large selection of different designs of these quick-disconnect couplings. However, after an extensive search, the Schrader-shaped hose coupling (Figure 3.5) was chosen to be used in the first prototype. The convenience of this style of coupling is that to connect the two pieces, the plug is pushed into the socket until it “clicks”. To disconnect, the sleeve of the socket can be twisted and the plug pulled out.



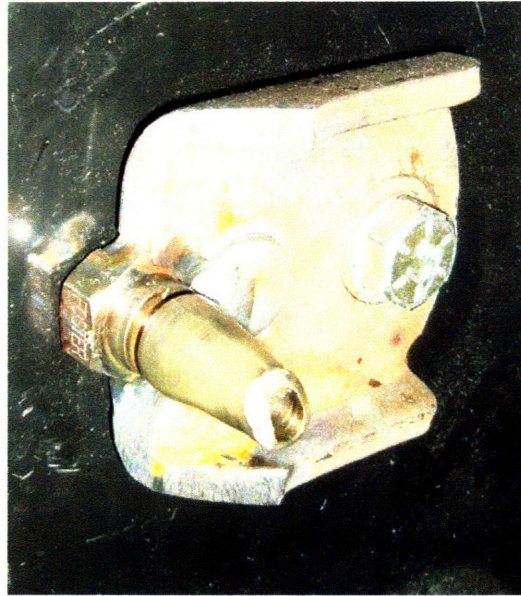
**Figure 3-6: Schrader coupling: socket and plug<sup>7</sup>**

For simplicity, the original hinges which were supplied with the car door were used in this design. In order to allow the door to be able to disengage and use the mounting features of the hinge to both the car frame and the door frame, the door hinge was cut along its vertical axis, as shown in Figure 3.5. The plug from the Schrader coupling was welded to the half of the hinge which is mounted to the car frame (Figure 3.7) while the socket of the coupling was welded to the second half of the hinge and mounted to the door frame (Figure 3.8). There were a total of four of these pairs made, two pair for the front of the door and two pair for the rear of the door. When these two

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<sup>7</sup> [www.mcmaster.com](http://www.mcmaster.com)

halves were connected by inserting the plug into the socket, the hinge was complete and functioned normally. All of the hinge work, including the welding, was done by Keith Durand.



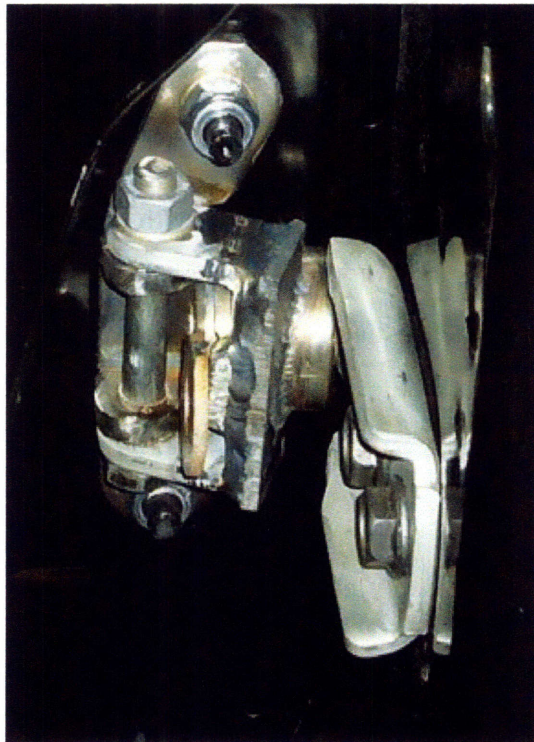
**Figure 3-7: Plug welded to hinge and bolted to car frame**



**Figure 3-8: Socket welded to hinge and bolted to door frame**



**Figure 3-9: Two sets of hinges and plugs bolted to car frame**



**Figure 3-10: Socket and plug engaged**

At this juncture in the design, two of the three functional requirements had been satisfied. By using the Schrader coupling, the hinge was easy to reengage. The door simply had to be closed, and if the plug and socket were aligned correctly, the door would shut and the hinge would be engaged. When both sides of the door were closed, the door was solidly mounted and could not be opened unless the user disengaged one of the hinges.

The final requirement left to fulfill was to design an opening mechanism which would release the plugs from the sockets and allow the door to be opened. As can be seen in Figure 3.9 above, there are two set of hinges mounted on each side of the door. Therefore, in order to open the door smoothly, both plugs must be released from the mating socket simultaneously.

In order to accomplish this, a linkage system was designed to connect the two couplings. A tab was welded to each of the coupling sockets to act as an actuator; by pulling on the tab, the shaft collar would turn, releasing the plug. A ball joint rod end was attached to both ends of a rigid rod and then secured to both tabs, creating a pivotal linkage joint, as shown in Figure 3.12. By connecting the two sockets with a rigid linkage allowed for both sockets to be actuated simultaneously when either one was actuated or when the rod itself was actuated.

Again, Keith Durand was very involved with this design. He was capable of doing all of the welding needed for this mechanism to function properly, as well as helping with the building of the linkage.

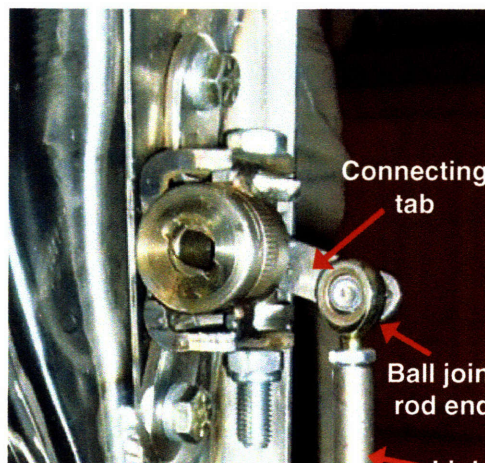
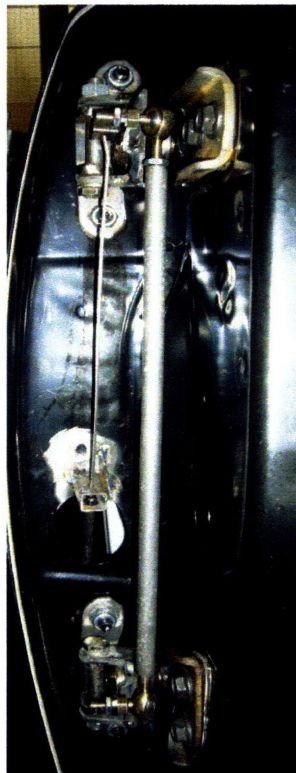


Figure 3-11: Close up of socket, tab, ball joint rod end, and link



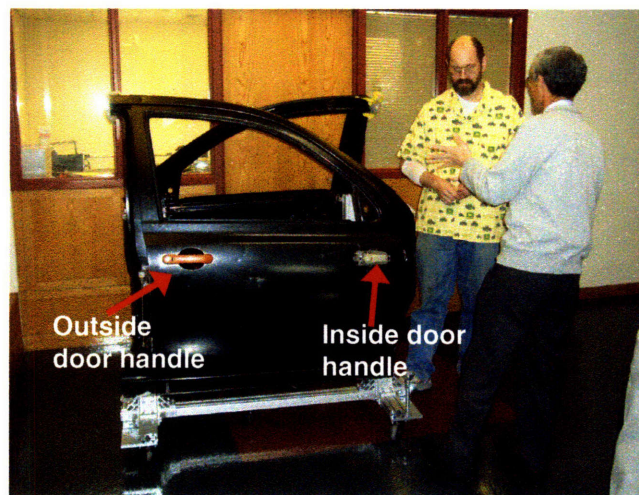
**Figure 3-12: Complete linkage mechanism connecting two hinges**

The final feature left to be designed was the user interface with the door. There needed to be a simple mechanism for the user to actuate the linkage and disengage the hinge in order to open the door. This was achieved with a system similar to what is used on most standard car models.

The standard system uses a steel cable attached between the latching mechanism and the door handle. When the handle is pulled by the user, a lever connected to the handle pulls the cable which in turn pulls and releases the latching mechanism. Both the inside and outside door handles function in this manner, although their appearance is slightly different from the outside of the door panel.

In order to actuate the linkage system by using a cable, a second tab had to be welded to one of the sockets. A cable was connected to this new tab and then run through the door panel and connected to a door handle mounted to the outside of the door frame. For simplicity, the original door handles were used. There was one outside door handle and one inside door handle available. The way the door frame was manufactured,

there is an indentation in the outside door panel where the handle mounts and allows room for the user's hand to fit in order to grab the handle. The outside door handle was mounted in this position. In order to actuate the other side of the door (near the front of the car), the inside door handle was used. Holes were cut in the door panel to accommodate the mounting features of this handle and it was then bolted to the door panel. The door now had two handles on this outside door panel, as seen in Figure 3.13 below. When one of the handles was pulled to open the door, the cable inside the door was pulled outwards with the handle, which pulled on the tab on the socket. The socket collar then turned and the plug was released and the door could be opened.



**Figure 3-13: Outside view of final prototype**

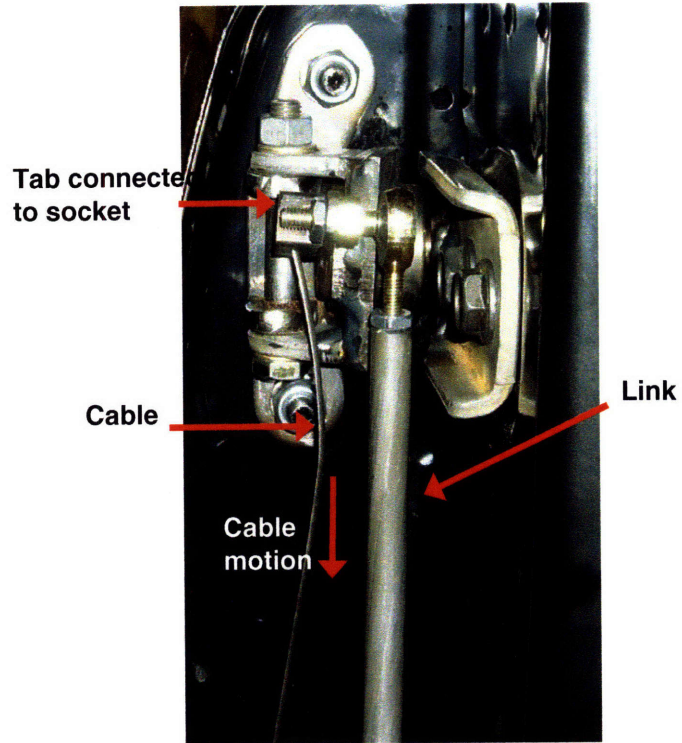


Figure 3-14: Close up of link mechanism

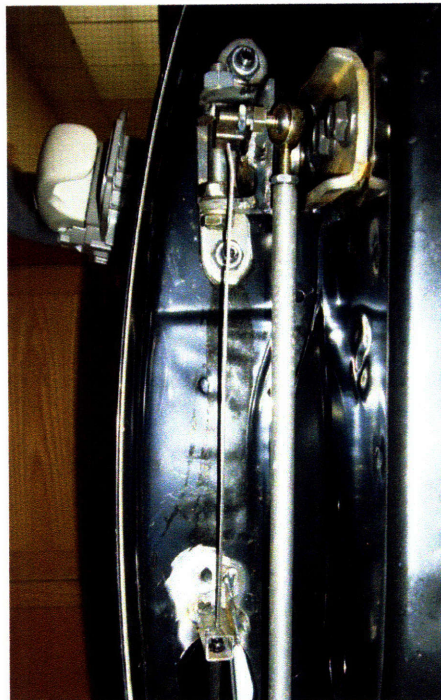


Figure 3-15: Cable routed through door

One significant problem with this design was misalignment due to sagging of the door. When the door is opened, it tends to sag downwards due to its weight. This could be compensated for on at least one side of the door. The hinges could be adjusted to account for this inherent sag by adding a pre-load to the door. However, it is not possible to pre-load both sides of the door with this adjustment because then the side that was opened would not engage properly. Therefore, one side of the door always sagged more than the other.

By sagging, the alignment of the plug and socket on either half of the hinge would be skewed and the plug and socket would no longer meet upon closing the door. This could be compensated for by lifting the door slightly when closing is, however, this action was undesirable. As a countermeasure instead, Delrin stoppers were added to the bottom of the car frame to help “lift” the door into place during closing.

The next steps that came out of this prototype was to design and build a mechanism which would provide some amount of preloading to the system to prevent some of the sagging which was occurring. The sagging not only caused misalignment of the system during closing, but it also made the door difficult to open. Having a preloading system would provide both a smoother opening and closing function of the door. This led to the concept of using the principle of self help to create a mechanism that was inherently preloaded.

Also of interest was designing an electrical system for opening the car door to provide keyless entry for the user. This would eliminate the need for a door handle on the front of the door, providing an aesthetically pleasing door and reducing aerodynamic drag.



# Chapter 4

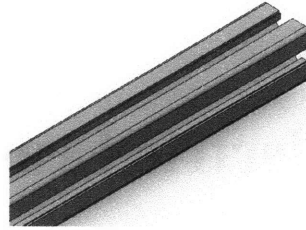
## Prototype II – Electric Lead Screw Design

Based on what was learned through Prototype I, two new design parameters were required in Prototype II. The first was the ability to control the engagement and disengagement of the hinge and latch electronically to eliminate the second door handle and allow for keyless entry. The second requirement was to introduce preloading to the door in order to prevent the inherent sagging of the door.

In order to accomplish this, the concept of using a lefthand/right hand lead screw to control a latching mechanism was introduced. This design was first used by Professor Alexander Slocum in the design of a robot gripper (Slocum 1998). He suggested that a lead screw driving a nut into a tapered hole could function as both a hinge and a latch, and the lead screw forces that could be generated meant that preload could also be achieved; furthermore, a lead screw is not backdriveable so the latch would also be inherently safe in the case of an accident.

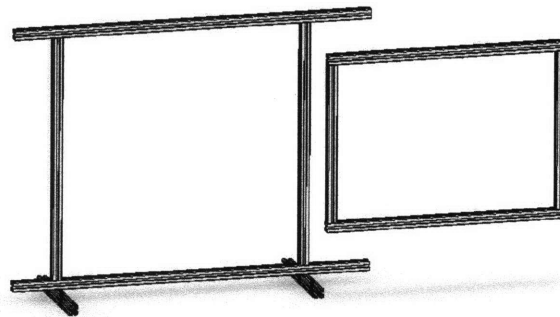
### 4.1. Aluminum Framing

Two car doors and frames had been sent from Japan for use in building the prototypes for these doors. Both doors, however, had already been used to build the first two prototypes in Phase I. Ordering another door from Japan would have taken weeks to arrive and it was decided not to strip down either of the first two prototypes. Making a model of the door would be the easiest way to demonstrate proof-of-concept for this new design. Aluminum T-slot framing was used to make a rough approximation of a car door and the mounting frame. Aluminum framing is convenient because it is lightweight, easily accessible, and easy to use. A close-up of the framing is shown in Figure 4-1. Sliding nuts fit in the slots, which allows for easy adjustability of parts and was a huge convenience during the building of this prototype.



**Figure 4-1: Aluminum T-slot framing**

Based on dimensions taken from one of the original doors from the first prototype, a rectangular car frame was modeled with T-slot framing 1.5 meters long by 1 meter tall. A second rectangle, 1 meter long by 0.65 meters tall was constructed, also with T-slot framing, to approximate the car door. Both models are shown in Figure 4-2.



**Figure 4-2: Solid model of aluminum car and door frames**

## **4.2. Hinge Design**

The new hinge design consists of two parts. The majority of the hinge design features are located on the car door frame, while only the mating brackets are located on the car frame. The hinges and mating brackets on both sides (front and back) of the door are identical. This made manufacturing significantly easier.

The main hinge components are located on the car door frame. Since the hinge design of both the front and rear (or left and right) sides of the door are the same, only one side will be considered during this discussion, but it can be assumed that the other side is identical.

The main components of the hinge consist of a small DC motor, a left-hand threaded rod, a right-hand threaded rod, two hexagonal nuts, and retaining brackets. The two threaded rods are connected by the motor and have a hexagonal nut on the opposite end. By holding the nuts in a bracket, rotational motion of the nut is restricted and the nuts can be driven up and down in a linear motion by the motor. Each nut has a mating bracket located on the car frame such that when the door is closed and the motor is actuated, the nuts are driven into the mating bracket and the door is then rigidly locked. The nuts and mating bracket not only act as the locking point, but also as the hinge point. When the opposite side of the door is opened, the door pivots about the point of contact between the nut and mating bracket.

Before any construction was begun, the design was modeled in Solid Works. Building a 3-D model before building was imperative to the overall design. Dimensions could be easily modeled and changed before any machine time was wasted. Figures 4-3 through 4-8 below show the completed Solid Works model of the hinge and mating components. Each component will be discussed in further detail throughout the remainder of this section.

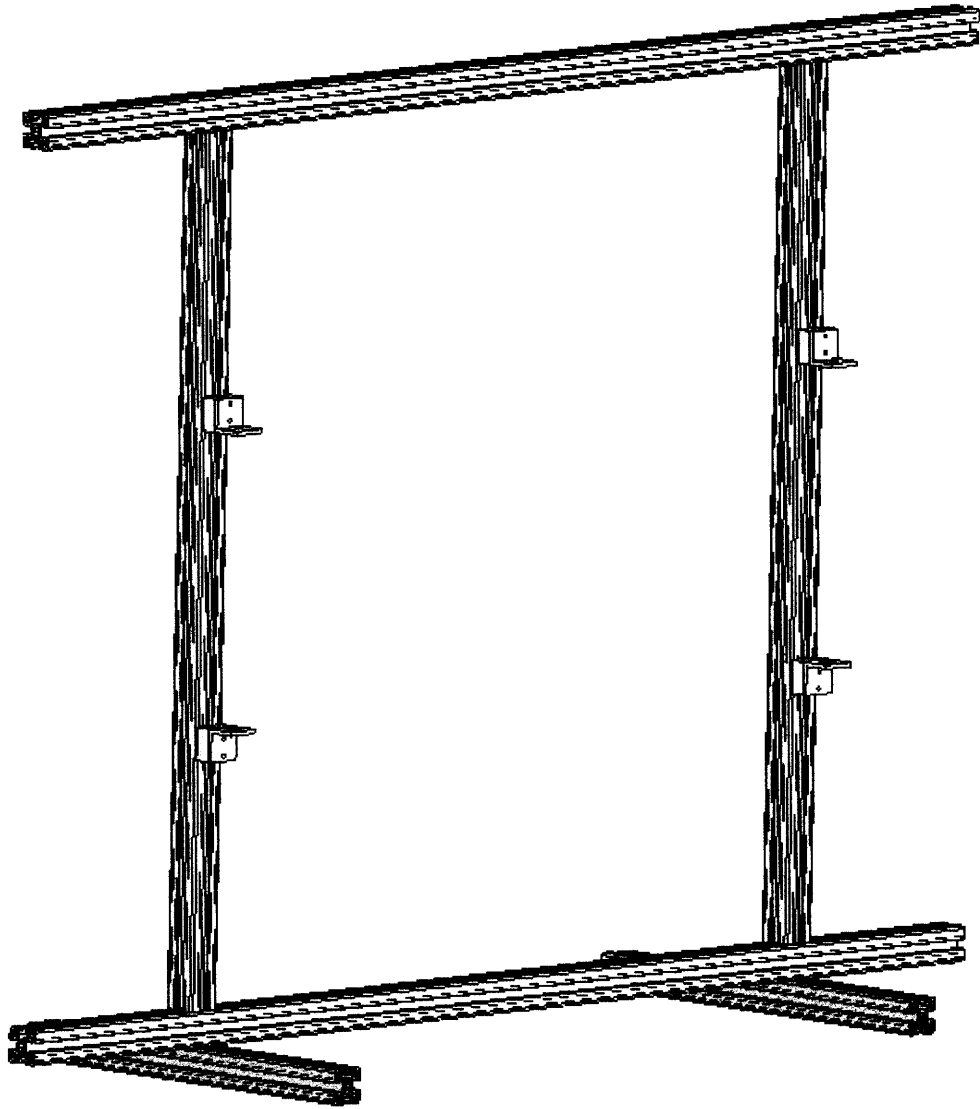
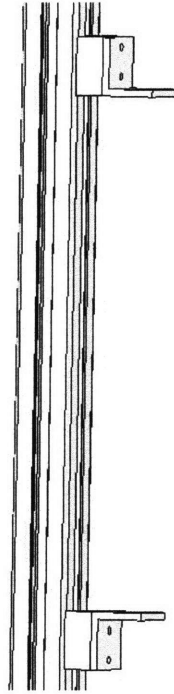
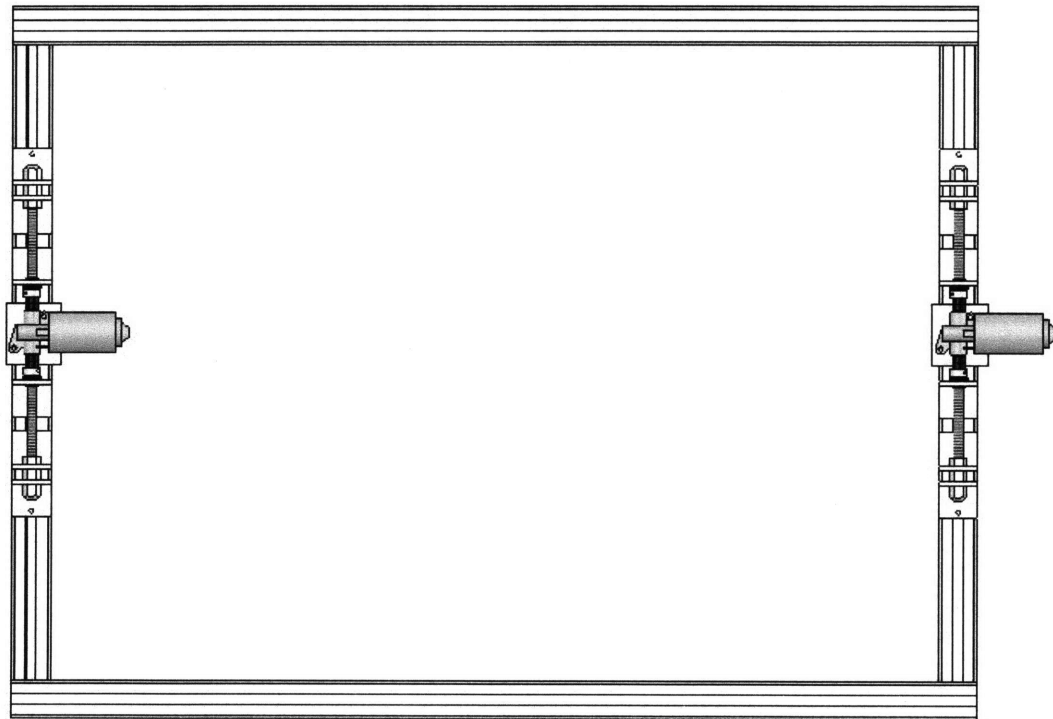


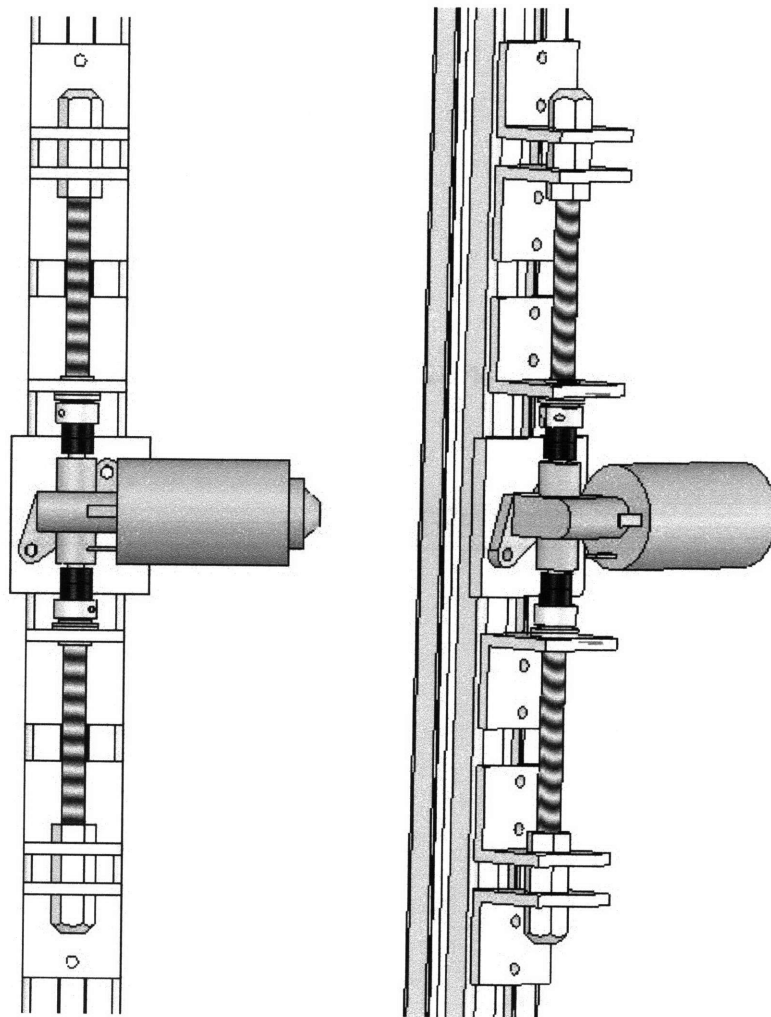
Figure 4-3: Car frame model with mating brackets



**Figure 4-4: Close up of mating brackets mounted to car frame model**



**Figure 4-5: Door frame model with hinge assembly**



**Figure 4-6: Hinge assembly mounted to door frame**

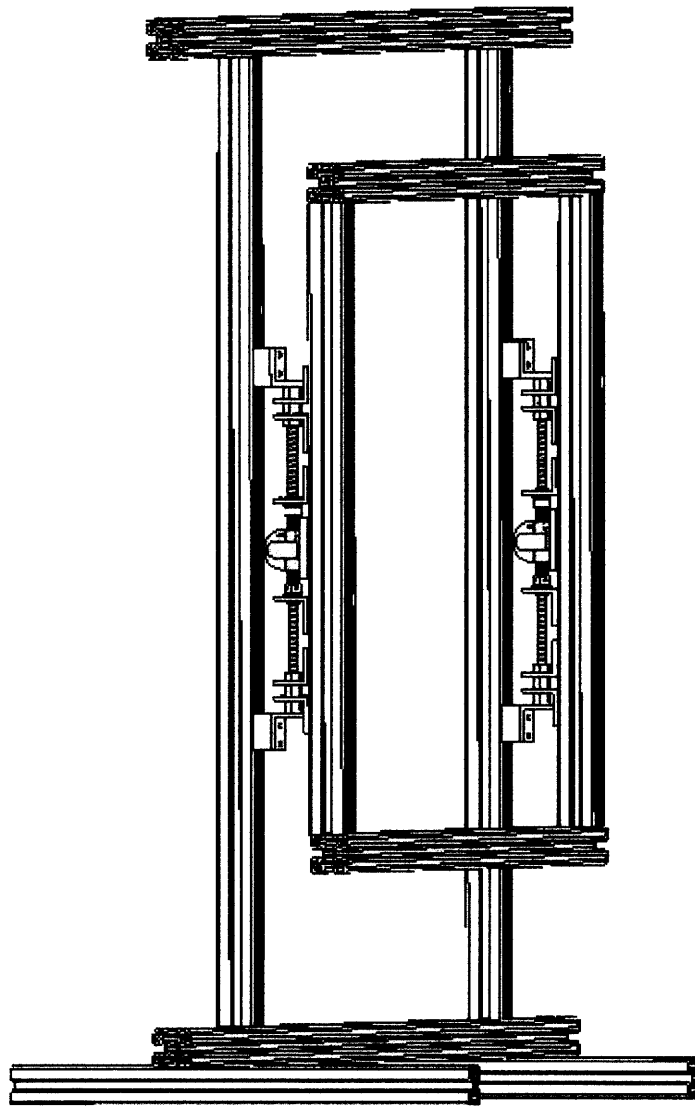
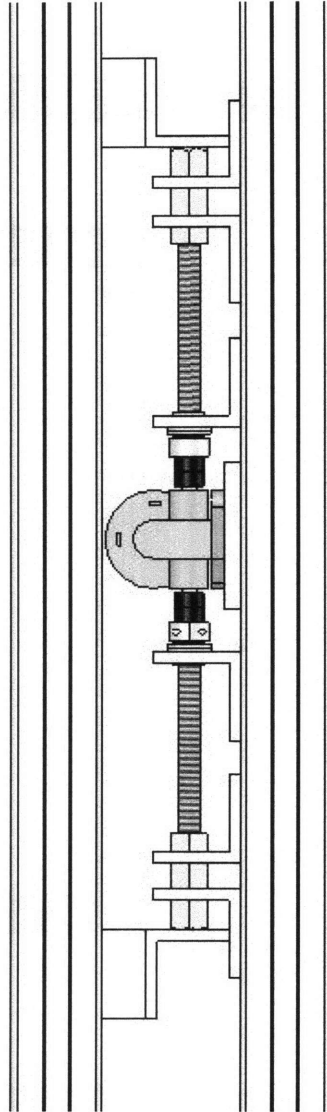


Figure 4-7: Fully assembled car door model



**Figure 4-8: Side view close up of hinge and mating components**



## 4.2.1 Bosch Motor

The motors used in this design are manufactured by Bosch Automotive (Figure 4-9). They run at a nominal voltage of 8 Volts at a no load speed of 50 revolutions per meter and have a stall torque of 0.7 Newton-meters. The motor requires a 4 millimeter by 4 millimeter square shaft.

This motor was chosen for firstly because it was readily available within the lab. Secondly, it provided adequate power and torque for the application. Lastly, due to its configuration and shaft mounting, it was easy to install directly in line with the lead screws.



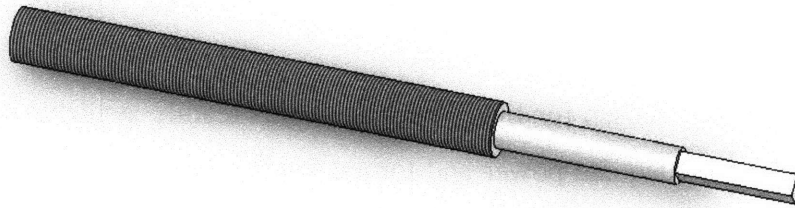
Figure 4-9: Bosch motor<sup>8</sup>

## 4.2.2 Lead Screws

Both a right-hand and left-hand screw was necessary in this design. Three foot lengths of 3/8" – 16 threaded rod was purchased. Each rod was cut to a length of 7 3/4 inches. One end of each rod was machined on the lathe such that a length of 2.1375 inches was tuned down with a round cross-section 0.25 inches in diameter. Finally a 0.8375 inch length of the very end of this section was squared off in the mill to a square cross-section 4 millimeters by 4 millimeters. The shaft-way length on the motor is 1.675 inches long. Each threaded rod was machined such that the square section was half of this length. This allowed each rod to fit halfway into the motor shaft-way and eliminated the need to connect the two rods with a shaft coupling (Figure 4-10).

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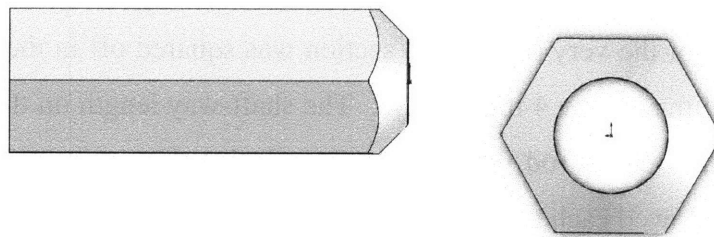
<sup>8</sup> <http://pergatory.mit.edu/2.007/kit/actuator/boschmtr/boschmtr.html>



**Figure 4-10: Solid model of threaded rod**

### **4.2.3 Hexagonal Coupling Nuts**

One right-hand threaded hexagonal coupling nut and one left-hand threaded hexagonal coupling nut were used. Each nut is  $1 \frac{3}{4}$  inches long,  $\frac{5}{8}$  inch wide and screw size  $\frac{3}{8}$ " - 16. One end of each nut was turned on the lathe with a  $45^\circ$  angled tool to produce a conical end (Figure 4-11).



**Figure 4-11: Solid model of hexagonal coupling nut with conical end**

## 4.2.4 Bearing Brackets

Two bearing housing brackets were produced per side of the door. The brackets were made from 3/16 inch thick aluminum angle stock with 1 ½ inch by 1 ½ inch legs. Pieces 40mm in width were cut. Two holes were drilled in one face to fit 10-32 bolts for mounting. The other face was drilled with a 0.25 inch diameter hole to fit a 0.25 inch diameter flanged ball bearing (Figure 4-12). This bearing fits on the rounded section of each lead screw.

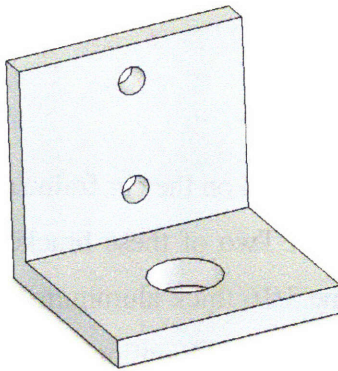
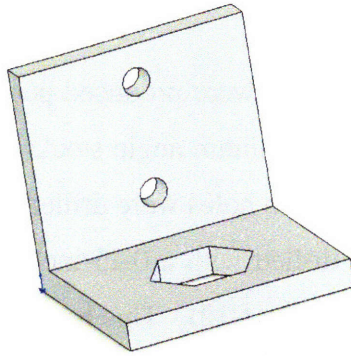


Figure 4-12: Solid model of bearing bracket

## 4.2.5. Hexagonal Brackets

Retaining brackets were necessary for each of the hexagonal nuts. The design required that the nuts be driven up and down in a linear motion. In order to accomplish that, the nuts had to be prevented from rotating. By forcing them to travel through a hexagonal shaped hole, rotational motion was eliminated.

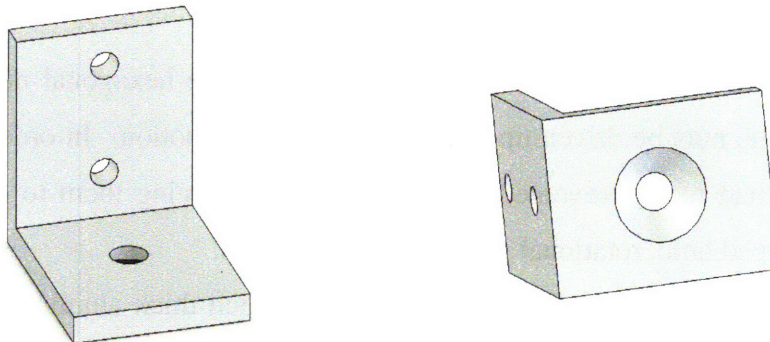
Each bracket was made from the same 3/16 inch thick aluminum angle stock as the bearing brackets and was cut to a width of 40mm. Similar mounting holes were drilled in one face. On the second face, a 5/8 inch wide hexagonal hole was machined on the mill (Figure 4-13).



**Figure 4-13: Solid model of hexagonal bracket**

### **4.2.6. Mating Brackets**

The mating brackets are located on the car frame and provide the locating, locking and pivoting points for the hinge. Two of these brackets are necessary per side of the door. They are made of the same 3/16 thick aluminum angle stock material. Each piece was cut to a width of 30 millimeters. Mounting holes 0.191 inches in diameter were drilled on one face. The second face was first drilled to a diameter of 0.25 inches and then countersunk with a 45 degree angled tool. This countersink matches the conical surface machined on the hexagonal nuts (Figure 4-14).



**Figure 4-14: Solid model of mating bracket: top and bottom views**

### 4.3. Hinge Assembly

The motor was the first thing mounted on each side of the model door. Each motor was mounted on an aluminum plate 0.28 inches thick. The thickness of the plate was determined by the height of the lead screws when mounted through the bearing bracket and the hexagonal bracket. The plate was then fastened to the aluminum framing at the center of each side of the door.

Each lead screw was fit through the bearing in the bearing bracket and then a second flanged bearing was placed on the shaft and held in place by 0.25 inch diameter washers. A shaft coupling with a 5/16 inch bore and a 5/8 inch outer diameter was then placed on the shaft, as well as several washers and a 1/4 inch long, black-finish aluminum spacer. Both lead screws were fit into the shaft-way on the motor and the bearing brackets were secured to the frame with 10-32 screws. Figures 4-15 and 4-16 show a close-up of the motor assembly and bearing brackets mounted to the aluminum framing.

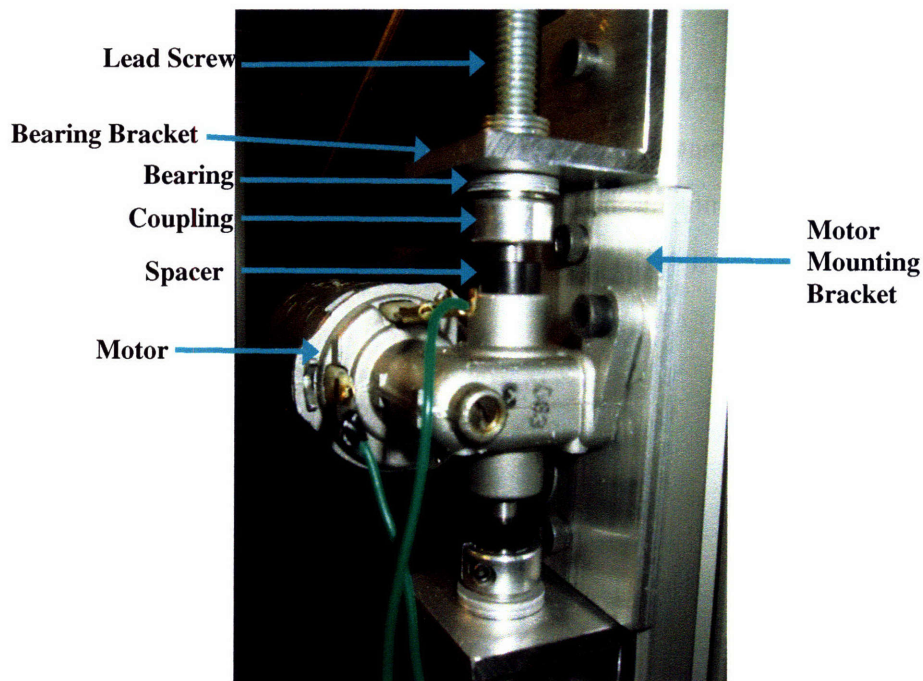
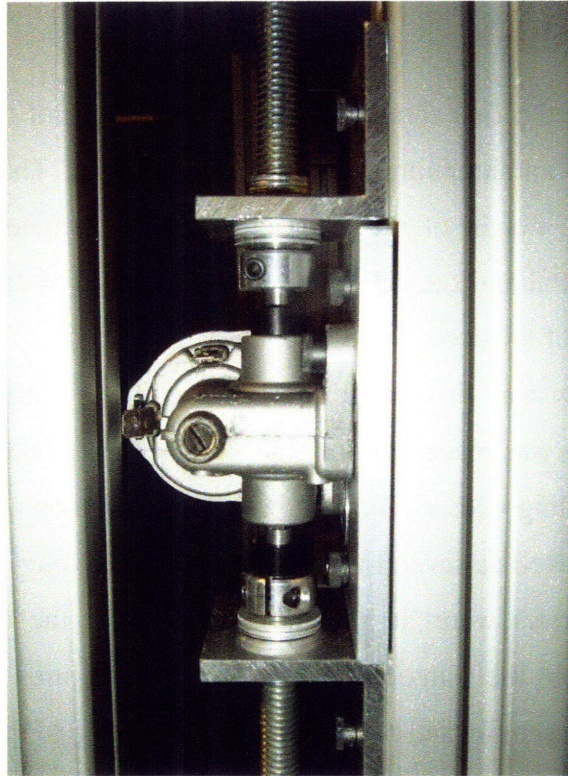
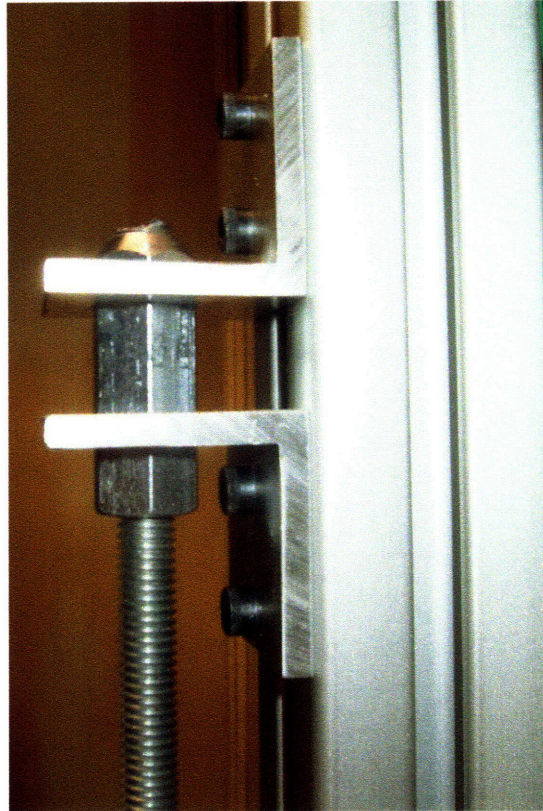


Figure 4-15: Motor and bearing bracket



**Figure 4-16: Side view of motor and bearing brackets**

Each hexagonal nut was fastened onto the appropriately threaded lead screw until it was threaded approximately halfway onto the lead screw. Then, the hexagonal brackets were finally fit onto the hexagonal nuts and secured to the frame, also with 10-32 screws (Figures 4-17 and 4-18).



**Figure 4-17: Hexagonal coupling nut and brackets mounted to aluminum frame**



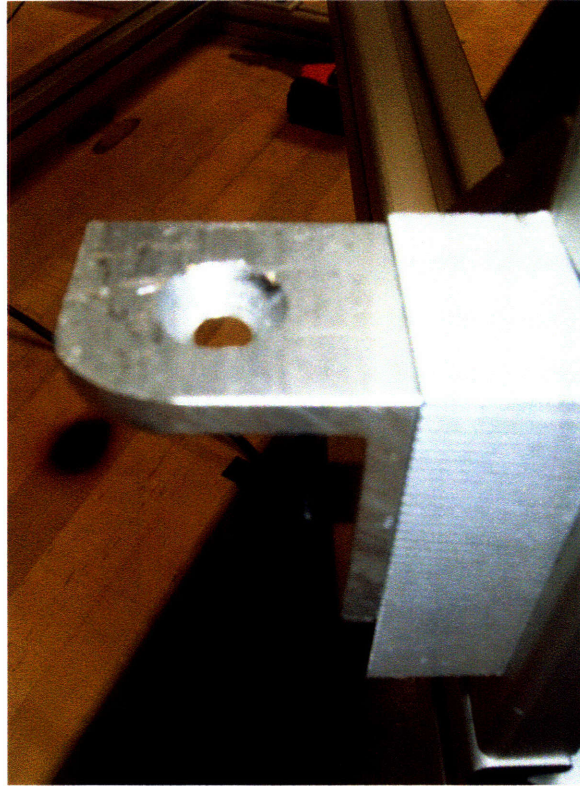
**Figure 4-18: Top half of hinge assembly**

It was imperative that this system be adjusted during assembly such that the entire system, from one hexagonal nut to the other, was completely parallel to the frame. If the system was misaligned, the door would sag when one side of the door was opened. This would cause the door to get stuck and not open smoothly because the door would not be level. Great care was taken to ensure that the door was level with respect to the frame when it was initially mounted.

The final components to be mounted were the mating brackets. These pieces were mounted to the model car frame with  $\frac{3}{4}$  inch aluminum spacers (Figure 4-19). The



spacers were necessary to allow enough room for the door to swing open without interfering with the frame.

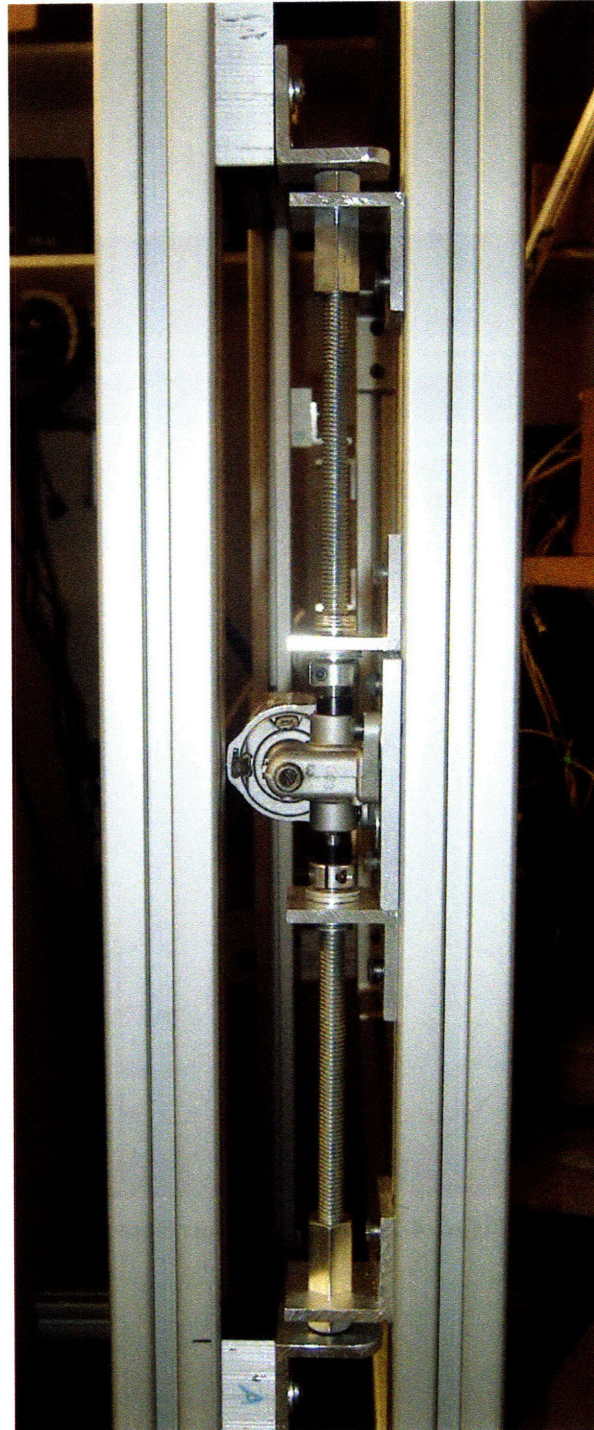


**Figure 4-19: Mating bracket and spacer mounted to car frame**

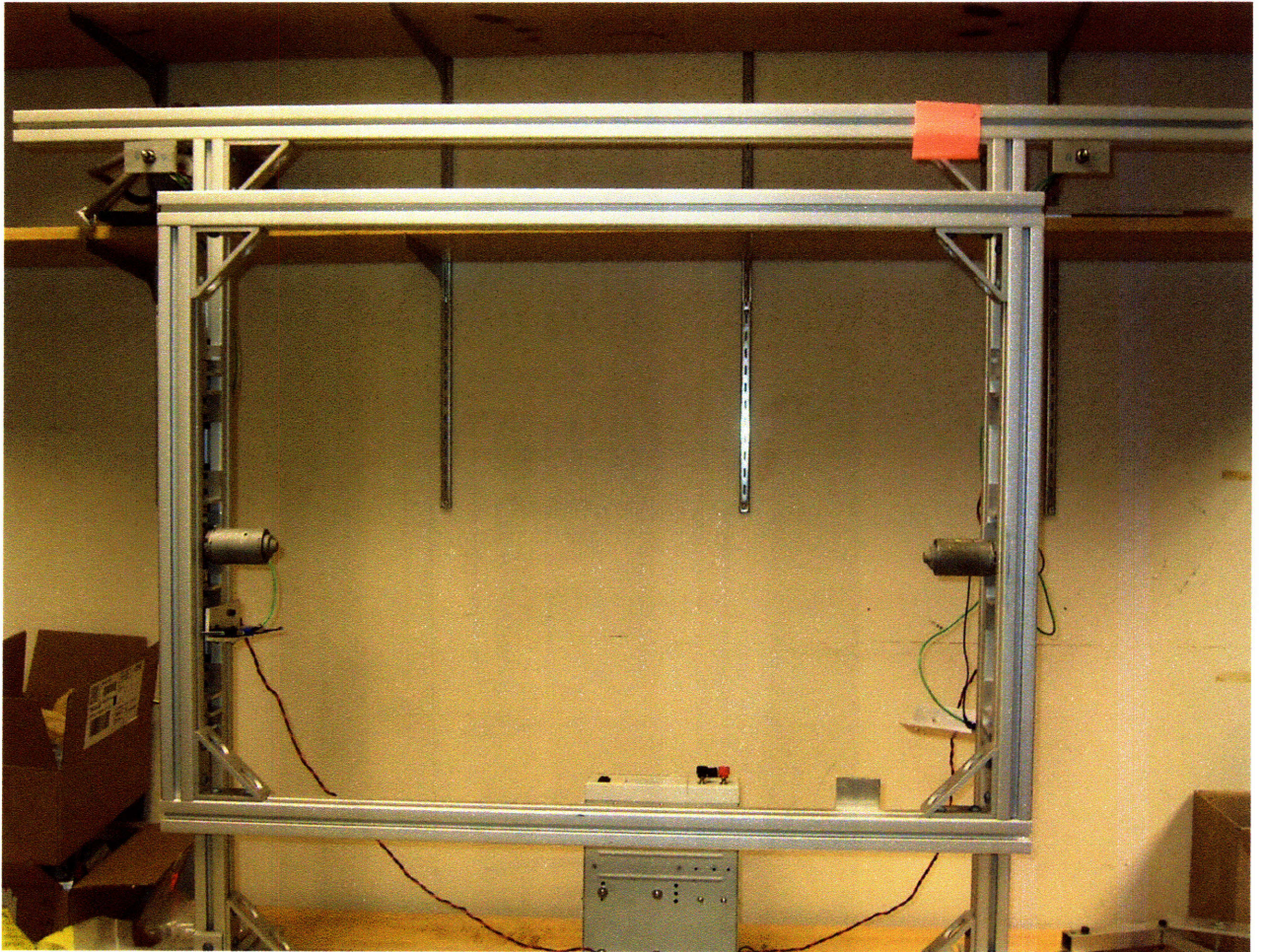
Once the hinges were mounted on both sides of the door, the bottom mating brackets were mounted to each side of the car frame. The door was then hung on these brackets, with the hexagonal nuts in the “closed” position. The top brackets were brought into the correct position, mating with the top hexagonal nuts, and the brackets were then secured in place to the frame with 10-32 screws. The following Figures 4-20 through 4-24 illustrate the completed door and hinge assembly.



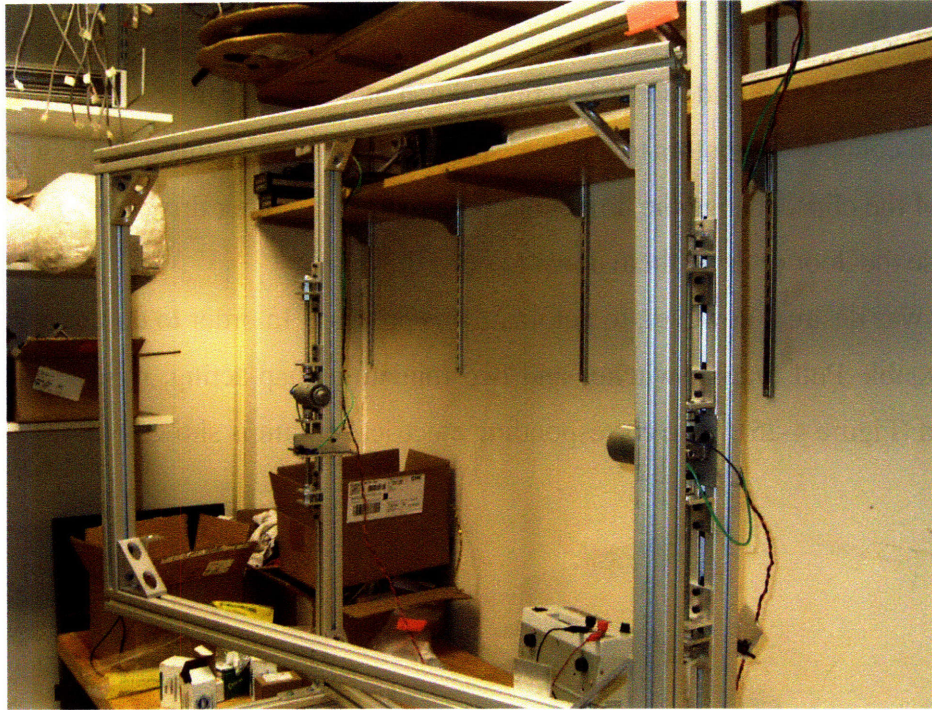
**Figure 4-20: Close-up of top hexagonal nut engaged with mating bracket**



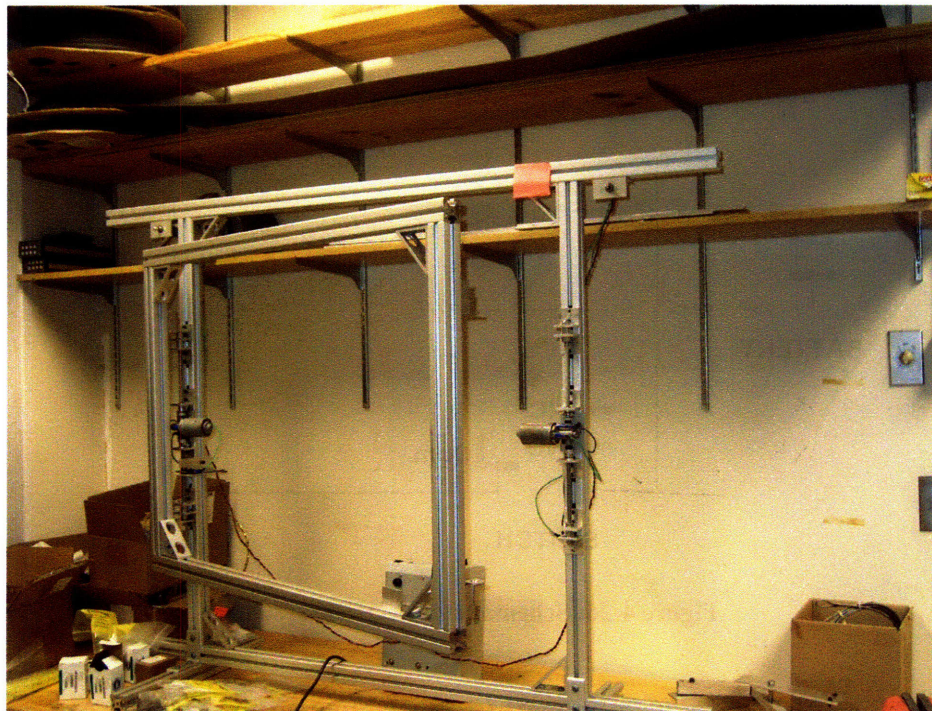
**Figure 4-21: Engaged hinge assembly**



**Figure 4-22: Complete door: closed**



**Figure 4-23: Completed door: left side open**



**Figure 4-24: Completed door: right side open**

## 4.4. Electronics

In order for this door to function, the motors needed to be actuated. It was possible to connect the motors to a power supply with alligator clips and by switching the polarity of the clips, change the direction of the motor and either drive the hexagonal nuts up to close the door or drive them down to open the door.

It was desired, however, to automate this process. In order to do this, two Double Throw Double Pull toggle switches and two miniature snap-acting, rigid lever switches were used (Figure 4-25). The corresponding electrical circuit is shown below (4-26).

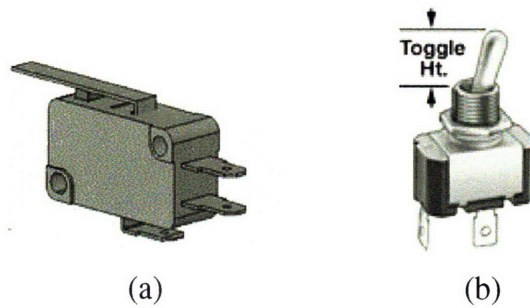


Figure 4-25: Switches (a) miniature switch; (b) toggle switch

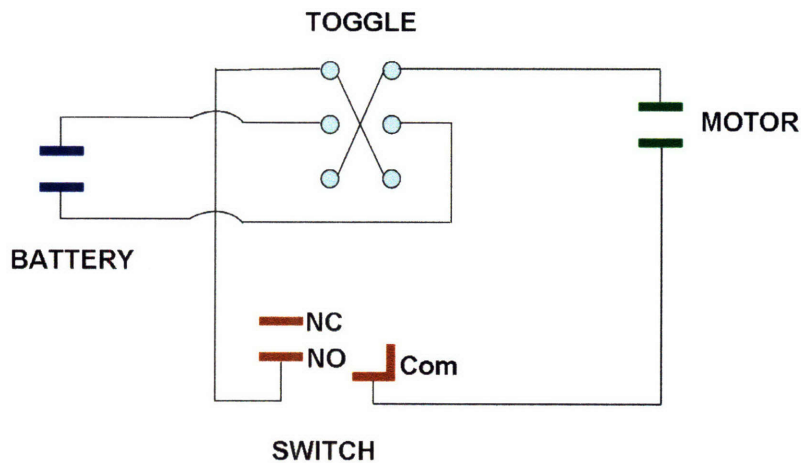


Figure 4-26: Schematic of electrical systems

The toggle switches were mounted to the frame so they were easily accessible. The miniature switches were mounted to the car frame, such that when the door was closed, the switches would be triggered and the motors would turn on and when the door was opened, the switch remained triggered until the user pulled the door open.

The procedure to open the door is:

1. Flip toggle switch to the “**OPEN**” position
2. When the door is fully disengaged, flip the switch to the “**NEUTRAL**” position
3. Open the door

The procedure to close the door is:

1. While the door is open, flip the toggle switch to the “**CLOSE**” position
2. Close the door – this will trigger the miniature switch and activate the motor
3. When the hinge is fully engaged, flip the switch back to the “**NEUTRAL**” position

This process could be easily automated in an automobile. Step 2 in the open procedure and Step 3 in the close procedure could be automated by using limit and current switches respectively or alternatively, either could be automated with timing. Step 2 in the close procedure would be the most challenging and would require some logic function, but could be accomplished through micro-controllers or through the car’s computer, for example.

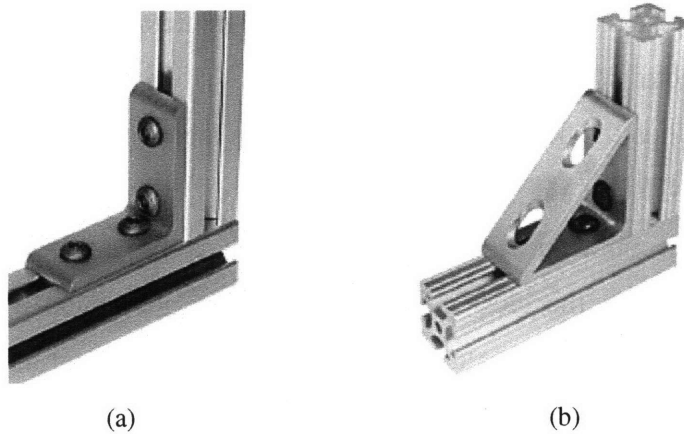
A DC power supply was used to power the motors. The voltage was set to 11.2 Volts and the current was limited to 2.8 Amps. The current limit allowed the hexagonal nuts to be driven into the mating brackets until it hit this current limit. Once the limit is hit, the power supply cuts the power so that the motors cannot burn themselves out.

## **4.5. Structural Considerations**

Several structural changes were made to this system after it was initially built. Originally, the mounting brackets, the hexagonal bracket, the bearing bracket, and the mating bracket, each had only one hole drilled to be used to mount the bracket to the aluminum framing. The brackets experience large amounts of torsion when the door is open and mounted on only one side. Because of this torsion, the screws securing the brackets to the frame, especially those on the mating brackets, were becoming loose and the brackets could no longer support the weight of the system. In order to account for

this, a second mounting hole was machined in each bracket. This prevented the brackets from loosening and created a much more stable system.

One other feature modified in the system was the aluminum framing mounting brackets. Initially, the individual pieces of the each frame were joined together with simple joining plates (Figure 4-27a). These joining plates did not provide enough stiffness to the rectangular frames they were supporting and were replaced with corner gussets (Figure 4-27b).



**Figure 4-27: Aluminum framing mounting brackets: (a) Joining plate; (b) Corner gusset**



# Chapter 5

## Prototype III – Mechanical Override System

Prototype II was extremely successful, especially once the structural and alignment issues were resolved. One remaining design concern before this concept could be ready for the production department, however, was a safety issue. The purely electric door could pose a potential safety risk in the case of an accident that resulted in the loss of the vehicle's electrical system. In either case, an occupant would need to be able to override the electrical system in order to exit the vehicle. As a result, the third, and final, prototype includes a mechanical override system to the electrically controlled door.

### 5.1. Override Design Selection

In order to mechanically disengage at least one set of hinges so the door could swing open, there are essentially two components which need to be considered. The first is the hexagonal coupling nuts. In the electrical system, it is these nuts which are controlled to either engage or disengage the system. The other critical components in the engagement of the hinge are the mating brackets. The mating brackets accept the hexagonal coupling nuts and create the stopping and locking point for the coupling nuts.

In order to design a mechanical override of this system, both the travel of the coupling nuts and the mating brackets were considered. Each design will be further described in the following sections.

#### 5.1.1. Motor Override System

The first design considered was a system which would mechanically override the motor. This design would incorporate a handle which would be able to turn the lead screws and therefore drive the hexagonal coupling nuts down, disengaging them from the

mating brackets. In order for this design to work, the motor used would have to be backdrivable in order to be overridden. The Bosch motor used in the initial design cannot be backdriven and a new motor would have to be chosen.

Another consideration in this design is the amount of travel the handle would have to go through in order to turn the lead screw enough times to drive the hexagonal nut far enough away from the mating bracket to allow for smooth opening. If the hexagonal nuts need to travel approximately  $\frac{1}{2}$  inch to allow the door to fully disengage, and the lead screw is  $\frac{3}{8}$ "-16 thread, then the lead screw needs to turn approximately eight turns for the door to be able to open. The handle would ideally travel through 180 degrees. At 180 degrees the handle would hit the vehicle door and be prevented from opening any further.

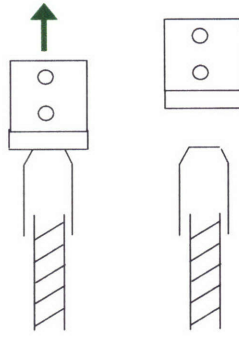
In order to control the lead screws by a lever handle, the screws and the handle must be connected with a series of gears. However, with such a limited amount of travel by the handle and such a large motion required by the screws, a huge gear reduction and a very large force would be required.

Another factor in this design which would have to be addressed is the backdrivability of the motor. If the motor has the ability to be driven by hand, then it would be possible that a brake system would have to be introduced to this design in order to prevent the lead screws from accidentally being turned and accidentally disengaging the hinge.

### **5.1.2. Mating Bracket Override System**

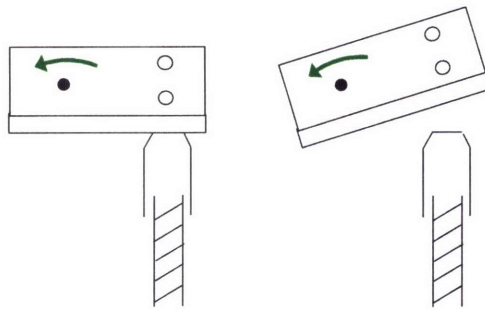
The second design considered was an override to the mating brackets. The engagement of the hinge occurs when the coupling nuts encounter the mating brackets and can travel no more. If the mating brackets could be controlled and removed from the coupling nuts, then the door would be disengaged and could be opened. Several configurations of this idea were considered.

Two options for removing the mating brackets were considered. The brackets could be removed by moving them linearly away from the coupling nuts, either moving the bracket up for the top nut or moving it down for the bottom nut. A schematic of this is shown in Figure 5.1.



**Figure 5-1: Linear system to remove mating brackets**

The second option would be to pivot the bracket about a point and rotate the bracket away from the coupling nuts (Figure 5.2).



**Figure 5-2: Rotational system to remove mating brackets**

The second option, the rotating bracket, provides greater control of the bracket as well as greater ease in controlling both the top and bottom brackets simultaneously. A linkage mechanism was designed which would connect the top and bottom bracket allowing them to be actuated at the same time.

The last consideration was the location of the mating brackets. If the system remained identical to Prototype II, the mating brackets would be located on the “car” frame and the main hinge components would be on the “door” frame. In doing this, the handle to actuate the mating brackets would have to be located on the door frame. This is not standard in the car industry and could pose confusion to the eventual end user. The alternative was to switch the location of the mating brackets and the main hinge components. This would allow the door handle to remain located on the door. Based on

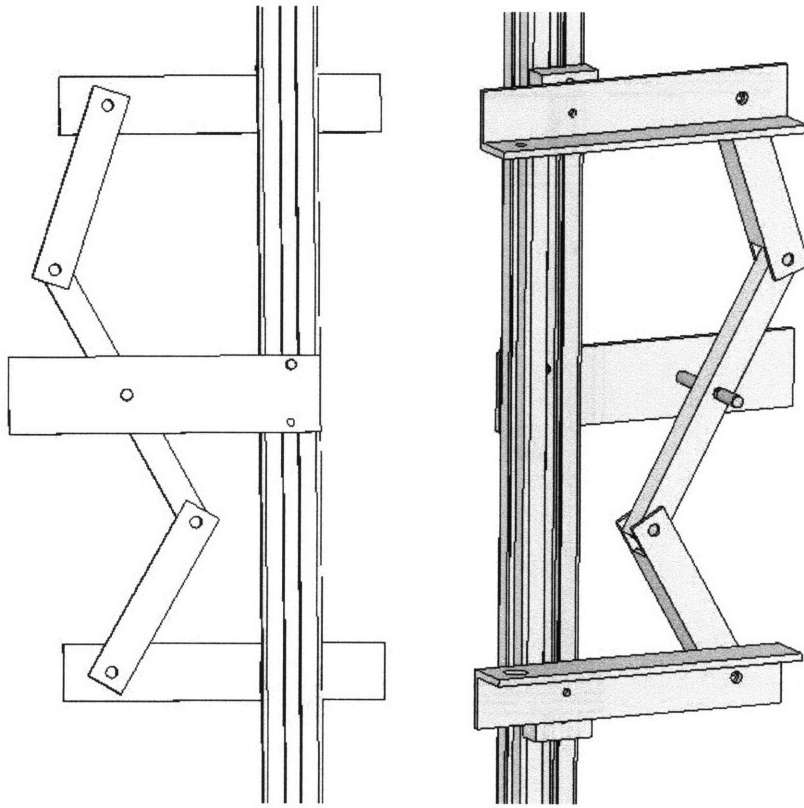
direction from the manufacturer, the later choice was settled upon. In Prototype III, the location of the mating brackets would be swapped with the main hinge components.

## **5.2. Linkage Design**

The final component of the mechanical override system left to be designed was the linkage mechanism to control the actuation of the mating brackets. This design was kept simple and modeled after a garage door opening device. Each bracket is controlled with a rigid link which in turn is controlled by a central link which pivots about a fixed point.

When the linkage system is such that the three bars are in a perfectly straight line, the system is highly unstable and, with very little input energy, will tend to transition to a more stable state. In the closed door system, the linkage is just beyond this point and is prevented from opening further by a stopper. In this position, the mating brackets are engaged with the coupling nuts and the hinge is engaged.

This system was modeled in Solid Works similar to Prototype II. Figure 5-3 below illustrates a close-up of the system in its closed position without the hinge components, from the outside and the inside of the vehicle. Figure 5-4 shows the whole system engaged and the door in the closed position.



**Figure 5-3: Override linkage system**

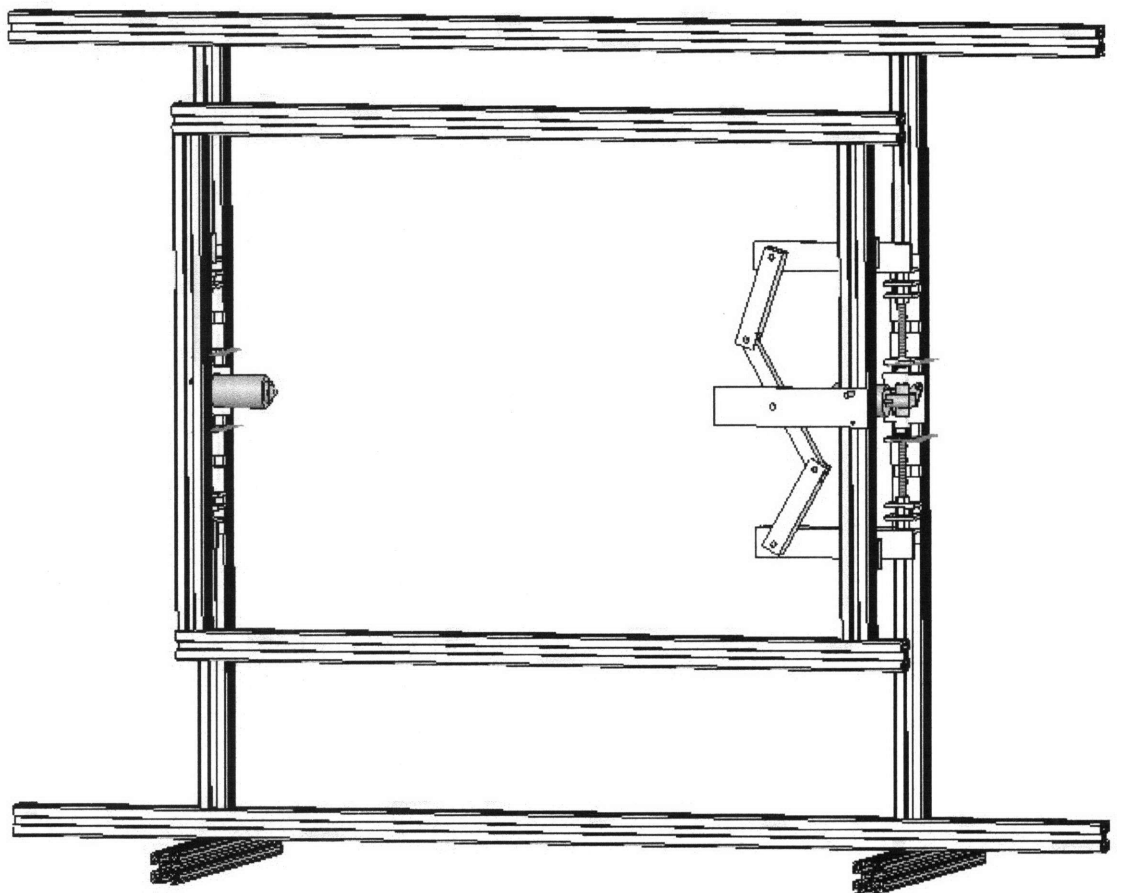
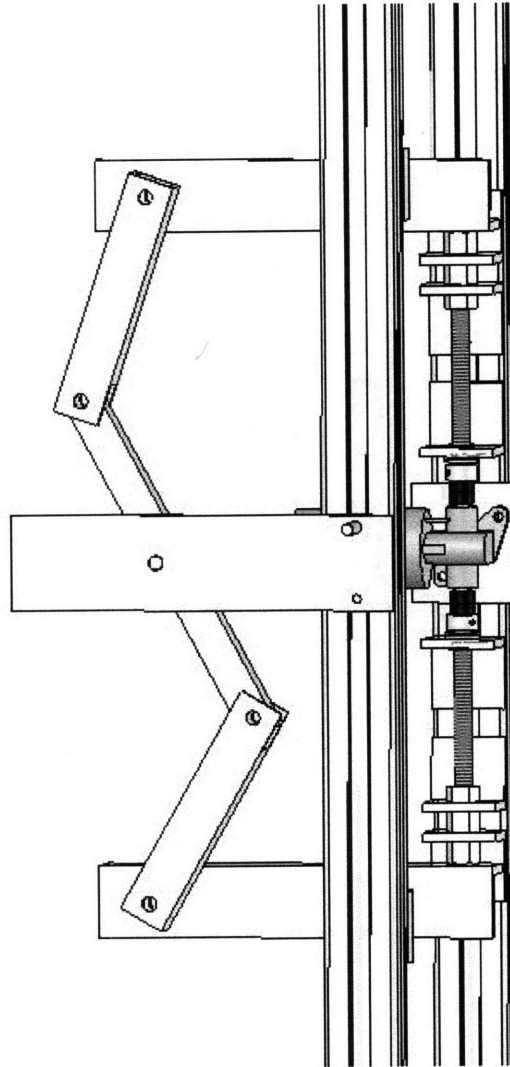


Figure 5-4: Complete door system with override system

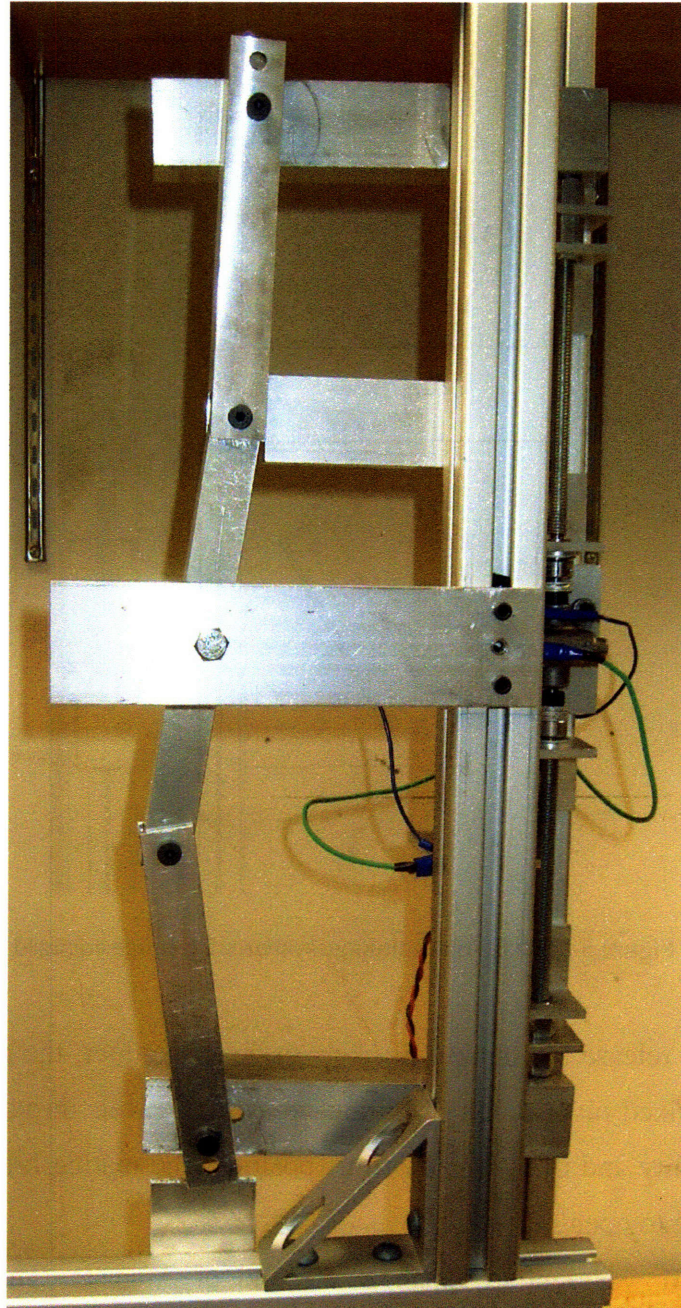


**Figure 5-5: Close-up of linkage system with hinge engaged**

In order to release the mating brackets to open the door, the central link can be rotated about the fixed pivot point. The linkage system travels through the dead center position of instability and once it is past this position, the mating brackets are released and the door is free to open.

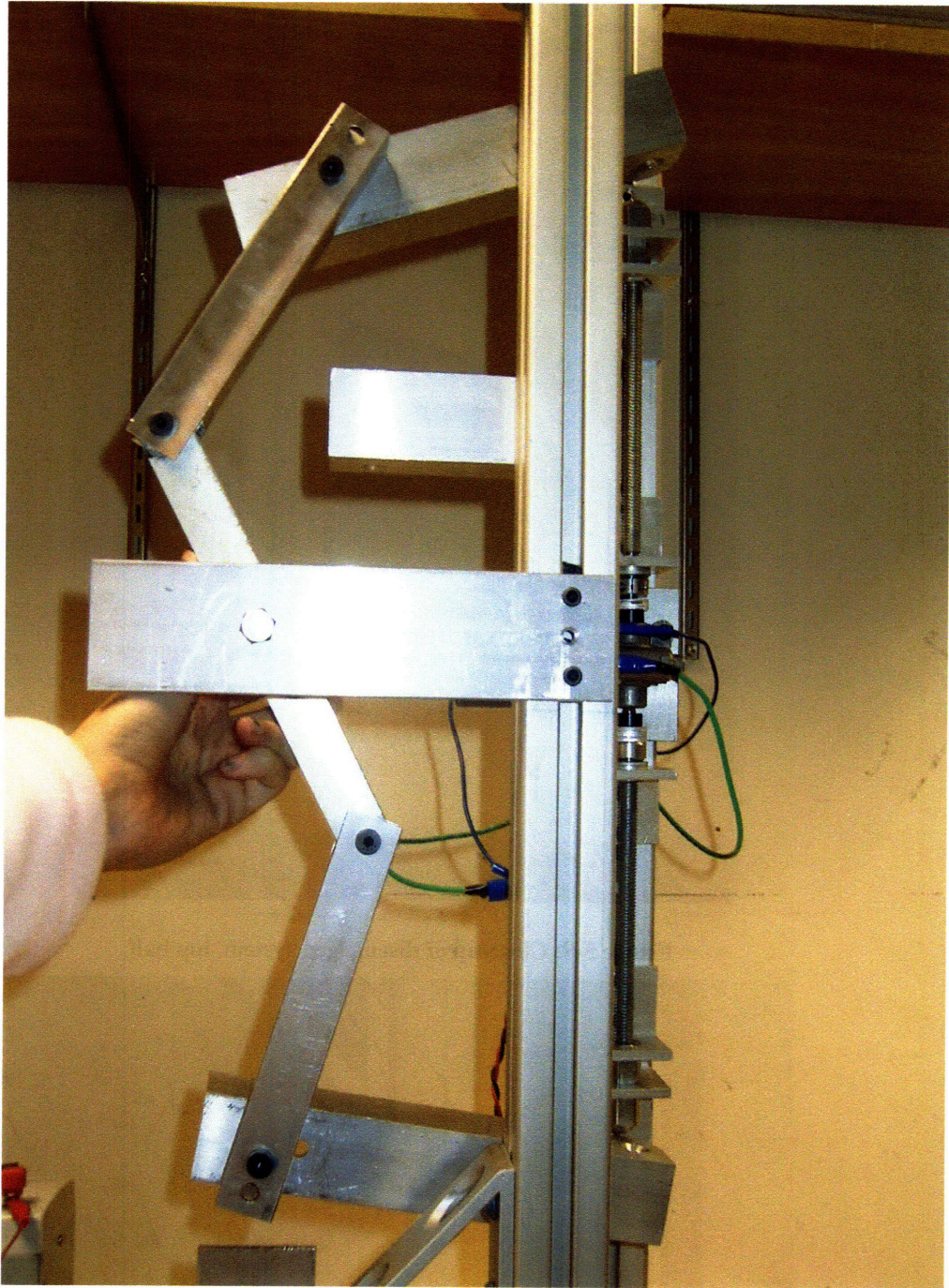
Prototype II was sent to Japan at the end of August. Therefore, additional aluminum framing was purchased and a new system was built with the new linkage system. All components of the system were remade for the new prototype. The linkage system was built out of 1 inch by 1 inch aluminum box extrusion and  $\frac{3}{4}$  inch by  $\frac{3}{4}$  inch solid aluminum extrusion. The mating brackets are identical to the original mating

brackets expect instead of being only 40mm long, they are now 8.5 inches long. Figures below illustrate the completed mechanical override system.

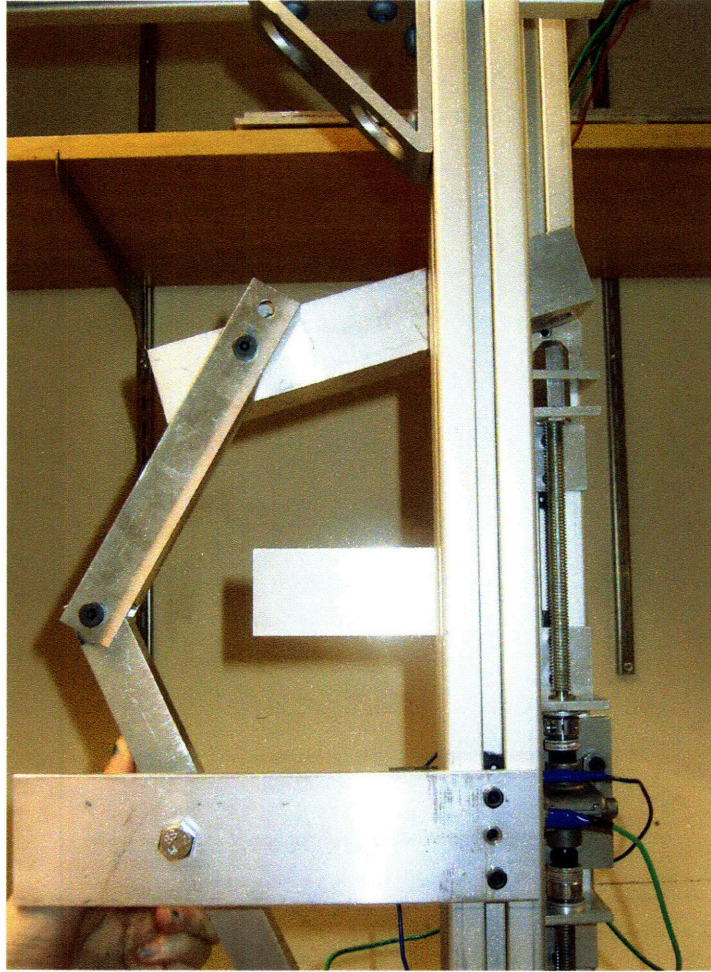


**Figure 5-6: Linkage system installed on prototype**





**Figure 5-7: Linkage system in open position and door disengaged**



**Figure 5-8: Close-up of disengaged system, top half**



**Figure 5-9: "Inside" view of linkage; mating bracket pivot**

The current system opens smoothly, but needs some strength to get the linkage system to toggle through its dead center position. By adjusting the length of the linkage bars, this motion could become much easier and smoother for the user.

This override system was only installed on one side of the door. The design of the other side remains identical to Prototype II. In case of an emergency, an override system would only be necessary on one side of the door.

# Chapter 6

## Conclusions and Future Work

Prototype I was a mechanical system which was based upon a component which is commercially available. This component, the Schrader coupling, is easy to use and provided the main design feature in Prototype I. Prototype I was the proof-of-concept model which allowed the multi-motion door concept to be validated.

An important lesson was learned through Prototype I; the door sags under its own weight and because of the flexibility of the car frame as well as compliance and clearances in the coupling. When the door is hinged about the rear part of the door, the front of the door tends to sag and misalignment in the system occurs, preventing the door from closing smoothly.

In order to account for this, Prototype II strove to eliminate this problem by demonstrating a new design that used left hand/right hand leadscrews to drive tapered-end leadscrew nuts into tapered sockets to act as a combination hinge/latch on the front and rear of the door so the door could open in either mode. This prototype was built out of aluminum framing for simplicity and provided an excellent model for the new design. This design was selected in order to account for the sagging of the door in the first prototype and eliminate it. By controlling the mating juncture electrically, the amount of initial pre-load introduced to the system could be adjusted based on the current limit set on the power supply. With a more powerful motor, more force can be applied and the door can be pre-loaded.

Prototype III had the design requirement that a mechanical override system be added to the system. In case of a loss of power in the vehicle, the door needs to have the ability to be opened mechanically to prevent the entrapment of the occupants. This was accomplished with a simple design similar to that found in a garage door. A linkage system, featuring a toggle mechanism, enables the mating brackets to be rotated away from the hexagonal coupling nuts and allowing the door to be opened. The electrical system is still enabled on both sides of the door.

Three proof-of-concept models were successfully built, each building on lessons learned from the previous model. Now that the concept of a multi-motion door has been proven, the remaining work should be focused on production design, as the lead screw based design proved to very robust and functional, as well as simple, thus most likely very cost effective. A thorough ergonomic and economic analysis should be performed on the entire door.

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