AN ABSTRACT OF THE THESIS OF

Sushim Koshti for the degree of Master of Science in Mechanical Engineering presented on September 17, 2007.


Abstract approved:

_______________________________________________
Joseph R. Zaworski

Transportation plays such an important role in daily living that, without it, a person might be totally homebound. The nation’s air travel system for persons with disabilities is an area of substantial dissatisfaction, with both passengers and the airline industry recognizing the need for improvement. One of the major concerns of today’s practices is that of manual dependant transfers. These transfers are injurious to the airline staff, unsafe and undignified for the passengers, and are often a deterrent for potential wheelchair bound passengers. The need to facilitate these dependant transfers with a mechanical solution complies with human ethics and makes good business sense. This project was undertaken to investigate the performance of various design alternatives by means of 3D modeling and kinematic simulation. The various design iterations were simulated in a virtual environment and their performance was studied. The best design was the one with bent paddles, arms with 2 links having lengths 10” and 12”, and telescoping type base-supports. From the simulation standpoint, this project established and demonstrated the application of a procedure to aid in the evaluation of designs of the transfer device.
Designing a Passenger Lift and Transfer Device Using 3D Modeling and Kinematic Simulation Techniques

by

Sushim Koshti

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APPROVED

______________________________
Major Professor, representing Mechanical Engineering

______________________________
Head of the School of Mechanical, Industrial & Manufacturing Engineering

______________________________
Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes the release of my thesis to any reader upon request.

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Sushim Koshti, Author
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1. INTRODUCTION

1.1. Background on Disabilities and Challenges in Travel

Historically, society has tended to isolate and segregate individuals with disabilities. Despite some improvements, such forms of discrimination against individuals with disabilities continue to be a serious and pervasive social problem. Unlike individuals who have experienced discrimination on the basis of race, color, sex, national origin, religion, or age, individuals who have experienced discrimination on the basis of disability have often had no legal recourse to redress such discrimination (United States Department of Justice, 1990). The Americans with Disabilities Act (ADA) of 1990 includes a legal definition of disability, in part defining a person with a disability as one who has “a physical or mental impairment that substantially limits one or more major life activities”. The ADA provides guidelines that assure the provision of services to people with disabilities and the protection of their legal rights. It also prohibits discrimination on the basis of disability in employment, access to public services, public accommodations, and commercial facilities.

Transportation plays such an important role in daily living that, without it, a person might be totally homebound. A new Bureau of Transportation Statistics survey
found that nationally, almost 15 million people in this country have difficulties getting the transportation they need. Of these, about 6 million (40 percent) are people with disabilities. More than 3.5 million people in this country never leave their homes. Of these, 1.9 million (54 percent) are people with disabilities. About 560,000 disabled people indicate they never leave home because of transportation difficulties (Bureau of Transportation Statistics, 2003). The aging of national populations is another major factor in the increasing number of people who are transportation-disabled resulting in the growing demand for accessible transportation systems. It is estimated that worldwide there are now 472 million people over 65 years of age; by 2020 this number will increase by 50% to more than 707 million (International Center for Accessible Transportation: Background). These numbers are growing at a significantly higher rate than that of the general population and it represents an increasing segment of the travel market. Any intelligent transportation system must be universally accessible or it would fail to provide the level of service to meet this demand. Not only does striving for accessibility comply with human rights, safety, security and quality of life, but it also makes good business sense.

For years, access to the nation’s air travel system for persons with disabilities was an area of substantial dissatisfaction, with both passengers and the airline industry recognizing the need for major improvement. In 1986 Congress passed the Air Carrier Access Act, requiring the Department of Transportation (DOT) to develop new regulations which ensure that persons with disabilities will be treated without discrimination in a way consistent with the safe carriage of all passengers. These
regulations were published in March 1990 and represented a major stride forward in improving air travel for persons with disabilities. Despite such efforts to facilitate improved air travel for passengers with disabilities, transfers occurring between a wheelchair and an aircraft seat are still a major source of injury for both the passenger and the people assisting the transfer.

1.2 The Manual Transfer Process and Its Hazards

The term manual transfer process is applied to the relocation of a person with physical disabilities, to or from his or her mobility device, by another person. Typically, 2 people perform this transfer using a “front-and-rear” technique. The front agent grasps the person beneath the knees, and the rear agent through the arms and on the side of the chest. This technique is shown in Fig.1. The person is then lifted up by the agents and moved towards the seat or chair.

Fig.1. Manual Transfer Process
When a person in a wheelchair wants to board an airplane, a manual transfer process is indispensable. After arriving at the end of the jet bridge, the wheelchair bound person is transferred to an aisle chair. An aisle chair is basically a wheelchair narrow enough to move through the aisles of an airplane. The aisle chair, with the person in it, is then rolled into the aircraft to the appropriate seat and the person is transferred to the seat. This routine is repeated, in reverse, at the destination. Thus, it takes four manual transfers per person per journey. Apart from these, manual transfers are also required for a person with disabilities to use the onboard lavatory.

Not only do these transfers expose the traveler to the risk of being roughly handled, dropped and embarrassed, but also expose the transferors to the risk of developing a disabling lower-back injury. Amongst those who perform such transfers regularly, lower-back disorders caused due to lifting and transferring, are common (Harber et al., 1985).

It is evident from the above discussion that an alternative transfer technique is called for. A good technique would remove the risks associated with the transfer and also increase freedom of the persons with disabilities onboard an aircraft. It is expected that this will also increase the number of travelers with disabilities, thus promoting air travel for persons with disabilities and business for the airlines.
1.3 Overall Objectives of the Project

The Air Carrier Access Act clearly explains the responsibilities of the traveler, the carriers, the airport operators, and contractors, who collectively make up the system which moves over one million passengers per day. The Air Carrier Access rules are designed to minimize the special problems that travelers with disabilities face as they negotiate their way through the nation’s complex air travel system from origin to destination.

Listed below are the relevant rules from the Air Carrier Access Act (United States Department of Transportation, 1990):

“A carrier may not refuse transportation to a passenger solely on the basis of a disability.

Properly trained service personnel who are knowledgeable on how to assist individuals with a disability in boarding and exiting must be available if needed.

For aircraft with 30 or more passenger seats, at least one half of the armrests on aisle seats shall be movable to facilitate transferring passengers from on-board wheelchairs to the aisle seat.

Aircraft with more than 60 seats must have an operable on-board wheelchair if there is an accessible lavatory, or a passenger provides advance notice that he or she can use an inaccessible lavatory but needs an on-board chair to reach it.

Air carrier personnel shall assist a passenger with a disability to move to and from seats as a part of the boarding and exiting process.

Air carrier personnel shall assist a passenger use an on-board wheelchair when available to enable the passenger to move to and from the lavatory.

Air carrier personnel shall assist a passenger move to and from the lavatory, in the case of a semi-ambulatory person (as long as this does not require lifting or carrying by the airline employee).
If the plane has fewer than 30 seats, the carrier may refuse transportation if there are no lifts, boarding chairs or other devices available which can be adapted to the limitations of such small aircraft by which to enplane the passenger. Airline personnel are not required to carry a mobility-impaired person onto the aircraft by hand.

Carrier personnel are not required to provide assistance inside the lavatory.”

It can be observed that the rules of the Air Carrier Access Act are influenced by the current system of manual transfers. The guidelines protect the carrier personnel by not requiring them to provide assistance in many situations. Clearly, a better process will be beneficial to both the carrier and the passengers.

The overall objectives of this project at NCAT are to design a mechanical device to facilitate the transfer process by reducing the risks of injuries and increasing the safety and comfort of the passenger and airline personnel. This will benefit the airlines by reducing passenger complaints and law suits. This device will facilitate the transfer process without hurting the dignity of the passengers. The proposed solution will also be favorable to the airline personnel by being easy to operate and asking minimal physical effort. It is expected that this device will encourage persons with disabilities to travel more and hence benefit them as well as the industry.

1.4 Proposed Solution

The proposed mechanical solution is similar to the manual transfer process. The reason behind this is the shortcomings of the other devices already available in the
market. These devices are discussed in detail in section 2.1.3. As seen previously in section 1.2, in the manual transfer process one agent holds the passenger under the arms on the sides of the chest and the other supports the thighs. The proposed mechanical solution will also involve “arms” which hold the passenger on the sides of the chest and have leg-supports to support the thighs. The device will have a lifting mechanism to lift and lower the passenger, for example, from the chair to the seat and back.

The device will also have to take into account the limited space available in aircraft. The device in itself will not present a hazard to the passenger and airline agent. The device will be easy to operate and will demand little physical and intellectual effort from the agent. Human Factors guidelines will be applied to the device to facilitate the above.

A 3D model of the proposed solution is illustrated in Fig.2.
1.5 3D Modeling and Kinematic Simulation

Engineering design is a creative activity, where the skills of the designer are used with the help of the engineering knowledge he/she has acquired to produce the design of an engineering system (Krishnamoorthy et al., 2005). The advances in computer science and technology have resulted in the emergence of very powerful hardware and software tools that offer scope for use in the entire design process resulting in improvement in the quality of the design.

1.5.1 Computer Aided Design (CAD)

Computer Aided Design (CAD) is a process where the designer and the computer work together to produce engineering designs. CAD is sometimes translated
as "computer-assisted drafting", "computer-aided drafting", or a similar phrase. Related acronyms are CADD, which stands for "computer-aided design and drafting", CAID for “computer-aided industrial design” and CAAD, for "computer-aided architectural design". All these terms are essentially synonymous, but there are a few subtle differences in meaning and application. CAD was originally the three letter acronym for "Computer Aided Drafting" as in the early days CAD was really a replacement for the tradition drafting board. But now the term is often interchanged with "Computer Aided Design" to reflect the fact that modern CAD tools do much more than just drafting.

Computer aided design has evolved from the simple replacement of traditional drafting equipment to a very sophisticated, highly visual design tool. The earlier CAD programs used the computer to generate lines for 2D drawings. As the software and hardware advanced, these 2D drawings could be converted into 3D objects that the computer recognized as having height, width, and depth. The software used to create these earlier 3D objects was still 2D based; they originated from and were primarily used to draw in two dimensions. Modern software used for solid modeling often functions in the reverse order; the three-dimensional object is drawn and then two-dimensional, orthographic drawings are generated from that model.

Advantages of wireframe 3D modeling over exclusively 2D methods include but are not limited to:
- **Flexibility**, ability to change angles or animate images with quicker rendering of the changes;
- **Ease of rendering**, automatic calculation and rendering photorealistic effects rather than mentally visualizing or estimating;
- **Accurate photorealism**, less chance of human error in misplacing, overdoing, or forgetting to include a visual effect.

### 1.5.2 Kinematic Simulation

A simulation is an imitation of the real thing. It refers to a broad collection of methods and applications to mimic the behavior of real systems, usually on the computer with appropriate software (Kelton et al., 2007). Kinematic simulation is the process of modeling kinematic systems and then simulating it in the suitable environment under the appropriate constraints.

Discussing below are features of the DMU Kinematics Simulator available with the software CATIA (Computer Aided Three-dimensional Interactive Application) as advertised on its website (IBM Software: CATIA).

**3D mechanisms:**

3D mechanisms based on 16 types of joints are available: Revolute, Prismatic, Cylindrical/Actuator, Planar, Rigid, Spherical, Universal, Point-Surface, Point-Curve, Roll-Curve, Slide-Curve, Screw, Gear, Rack, Cable and Constant Velocity joints. For most of joint types, the created mechanism can be associated to the joint type. It is
possible to define and verify joint limits (travel limits or joint stops) and thus guiding the design of the assembly.

*Automatically generates mechanism:*  
Constraints defined in CATIA Assembly Design product can be automatically interpreted as joints.

*Simulates mechanism motion:*  
Users can easily simulate motion using the mouse, and guide possible actions thanks to a co-pilot which pops up icons under the mouse. Users can also create a wide range of kinematics laws allowing time-based simulation. The laws can be graphically visualized.

*Analyzes mechanism motion dynamically:*  
During mock-up design review, the designer can not only view simulated kinematics motion but also analyze the mechanism's consistency with the functional specifications. DMU Kinematics Simulator 2 (KIN) performs interference and clearance checking as well as computing the minimum distance. A 'stop on collision' option freezes the motion for detailed analysis.

*Records motion analysis' results:*  
Users can replay a motion simulation, or save it as a video file.

*Generates useful information:*  
DMU Kinematics Simulator 2 (KIN) provides the ability to define a point in a moving
part and generate its trace in order to design cams. Users can also generate the swept volume of a moving part that is defined by a part moving through its entire range of motion. The swept volume can be reused in the clash analysis to check, during the digital mock-up evolution, that the mechanism can still be operated. During a simulation with laws, it is possible to plot sensors according to time but this functionality also offers the possibility to plot a sensor according to another sensor. This ability enhances the study of a mechanism offering a better way to qualify its behavior, or to improve its design. Users can run, for instance the simulation of an engine, and plot the position of an inlet valve according to the rotation of the crankshaft.

Allows automation of mechanism creation and simulation through Visual Basic macro programming:

Multiple combined simulations are possible for advanced digital product synthesis when using this product in conjunction with other DMU products. For example, users can simulate and synchronize un-mounting procedures with a kinematics motion when both the DMU Kinematics Simulator and DMU Fitting Simulator products are installed.

Simulates mechanisms:

The data used to create the full digital mock-up may come from any number of supported data formats, including: CATIA, STL, IGES, OBJ (from Wave front) or other multi-CAD environments. The kinematics simulation and associated kinematics analysis functions are identical whatever data format is used.
Looking at the above features, one can perceive the potential of 3D modeling and kinematic simulation. If made an integral part of the design process, it can be used effectively in the testing and evaluation stages. It has the ability to replace physical prototypes and make the design process not only cheaper but also faster and more flexible.

1.6 Summary

A significant number of people with disabilities never leave their home because of transportation difficulties. An even higher population is expected to face similar difficulties in the near future. Clearly the existing infrastructure does not promote air travel amongst persons in this population. There is a perceptible demand and need to improve air travel for persons with disabilities. Such a change can significantly improve the standard of living of this population and also increase business for the airlines. Techniques such as 3D modeling and kinematic simulation aid the design process by reducing the cycle time during the prototyping, testing and redesign stages.
2. BACKGROUND

2.1 Existing Transfer Methods

The various transfer methods practiced today in various scenarios are discussed in this section.

2.1.1 Manual Transfer

As discussed before, the term manual transfer process is applied to the relocation of a person with physical disabilities to or from his or her mobility device. These transfers require 2 people using the “front-and-rear” technique. The front agent grasps the person beneath the knees, and the rear agent, through the arms and on the side of the chest. The person is then lifted and moved towards the seat. There are many risks associated with such a transfer. A biomechanics study and computer survey discussed further, highlight a few of them.

2.1.1.1 Biomechanics Study

A biomechanics study, conducted by Dr. Michael Pavol at Oregon State University, looked at the risk factors for injury during manual transfers on an aircraft. The purpose of this study was to determine the influence of spatial constraints of an aircraft interior and the size of the traveler on the likelihood of injury to transferors and the traveler.
Two-person manual transfers were performed by healthy men and women who had no prior experience in conducting such transfers. The transfers were conducted in a laboratory simulation of an aircraft interior which included economy-class airplane seats mounted to the floor with armrests raised. Fig.3. shows the experimental setup of the transfer and Fig.4. shows the variations in techniques used.

Fig.3. Experimental Setup for Biomechanics Study.
The study observed consistent effects of spatial constraints, transfer direction and traveler size.

- The front transferor was placed at a higher risk of injury because of the constraints imposed by the seat in front of the traveler. This seat more than doubles the risk for the front transferor and thus represents a factor contributing towards the safety of a transfer.
- Similarly, the back seat imposes constraints on the back transferor, and is thus, another factor contributing towards the safety of a transfer.
- Traveler size had large effects on the lower-back loading of both the transferors.

Thus, the results strongly recommend elimination of the need to manually transfer a person.

2.1.1.2 NCAT Computer Survey

The National Center for Accessible Transportation conducted a computer survey in 2005 to probe the air-travel experience of passengers that must use an aisle
chair. The survey received more than 300 responses in addition to comments by many of the participants. The questionnaire asked users to rate both their experience during the routine of a manual transfer and the features of the aisle chairs used during the transfer. For the manual transfer routine, the responses varied from a 1 for ‘excellent’ to a 5 for ‘terrible’ and for the features of the aisle chair, they varied from a 1 for ‘very good’ to a 5 for ‘must be improved’.

Fig.5. shows the progression of the satisfaction with the various transfer processes. The horizontal axis represents the independence level of the passengers with 1 corresponding to fully independent and 5 to fully dependant. The trend clearly shows a need for improvement in the transfer process. The responses also indicated significant dissatisfaction with the aisle chair in terms of the straps used, footrest, chair size and seat cushion, amongst others.
2.1.2 Patient Transfers in Healthcare

Similar to the travel and tourism industry, manually lifting and transferring a patient with disabilities is a high-risk task in the healthcare industry as well. Nursing staffs have one of the highest incidences of work-related back problems of all occupations (Cust et al., 1972). Direct and indirect costs associated with back injuries are estimated to be between $24 billion and $64 billion annually, with $20 billion of that attributed to the health care industry (Safe Patient Handling and Movement, 2001). Over three quarters of a million working days are lost annually as a result of back injuries in nursing (Stubbs, Buckle, Hudson, & Rivers, 1983), with an estimated 40,000 nurses reporting illnesses from back pain each year (Garrett et al., 1992).
Transferring a patient can take place in various environments in the health care industry. These transfers include transferring a patient from a chair-to-toilet and back, chair-to-bed and back, and chair-to-bathtub and back, amongst others. In most of these cases, there is ample space available to facilitate the use of various lifting and transferring devices. Discussed below is one such device, SureHands. The next section, alternative transfer methods, includes a few more such devices.

**SureHands**

This lifting-device (Fig.6) developed by the SureHands company (SureHands) is used at diverse places for lifting and transferring people with disabilities, e.g. wheelchair, bedroom, restroom or even at pools. The product design is very simple. It consists of two arms of bent steel pipe, pivoted directly above the person. At the lower end of the arms, two cushions of solid synthetic foam are fixed, holding the person. Two steel hooks are located on the upper end. These rather long hooks lead back to the center, where they can be linked to any kind of hoist. The user’s legs are supported by two curved pieces that are flat and have been coated with a soft plastic. These coated supports are fixed to the pipes through adjustable belts. In that way the vertical distance between supports and pipes can be adjusted. In addition, the belts can be moved on the horizontal part of the pipes, making the SureHands device adjustable to people of different sizes.
The SureHands device has to be used with a lifting device such as a hydraulic jack or an overhead track which allows transfer between rooms and over flights of stairs. This prohibits its use in confined spaces such as those in aircraft.

2.1.3 Alternative Transfer Methods

Apart from the manual transfer process, there exist many devices which provide an alternate method of performing a transfer. These devices have been designed for performing transfers in various settings, such as hospitals, swimming pools, cars, and public modes of transportation such as buses and airplanes. Discussed further are a few such devices.
2.1.3.1 Haycomp

The Haycomp Eagle 2 is an aircraft passenger hoist for passengers requiring full assistance. This device has been designed to transfer passengers to and from wheelchairs and starboard side aisle seats of an aircraft. It can be used on a B717 and larger Boeing and Airbus aircrafts (Haycomp Products: Eagle 2). The transfer process starts outside the aircraft, where the person in the wheelchair wheels into place inside the frame of the lift. A sling is placed underneath the passenger and then attached to the arms on the Eagle 2. The passenger is then lifted off of the wheelchair with the help of an electrical lift. The device, with the passenger in the sling, is rolled into the aircraft and positioned such that the passenger in the sling is above a starboard side aisle seat. The passenger is then lowered onto the seat and the sling is removed from underneath the passenger. This process is repeated in reverse while de-boarding the aircraft.

Fig. 7. Haycomp Eagle 2 Passenger Hoist
This device has a few limitations. Due to its inherent design, it can be used only on the starboard side aisle seats in an aircraft. The other, more important, limitation is that it uses a sling to lift and carry a person. While a sling is an effective way of carrying a person, it invades the personal space of the passenger because of its need to be positioned underneath the passenger and then similarly removed.

2.1.3.2 Xpiration (XP Equipment: XP Boarding Chair)

The XP BoardingChair combines a hoist and an aisle chair. The hoist utilizes a sling to lift the passenger of the wheelchair and place him/her onto the seat of the XP BoardingChair. The chair is the rolled into the aircraft and the passenger is lifted off of the seat of the XP BoardingChair to the seat of the aircraft. While this device is a simple and safe alternative to the manual transfer process, the sling necessitates the invasion of the personal space of the passenger.

Fig.8. Xpiration Boarding Chair
2.1.3.3 Existing Patents

There exist many devices which make an effort at facilitating the transfer process. Though a few of these show some potential, most of the devices still neglect important factors like comfort and physical limitations of the persons with disabilities. In this section, a few such devices are discussed.

The existing devices can be divided according to the basic principle used in achieving the

➢ Chair/Seat
➢ Sling
➢ Sliding Surface
➢ Hoist
➢ Transfer stand
Travel Insert Chair and method of transporting the physically handicapped.

US Patent 4,113,307

This apparatus aims at being used as a transportation device for moving the persons with disabilities at public transport facilities from the terminal to the bus/airplane and between buses/airplanes. Though it will require an initial and final transfer, this device significantly reduces the number of transfers that would be carried out otherwise. But it cannot be used in places which do not have a large enough space in front of the seat to be able to maneuver the chair in place. As a result it cannot be used effectively in airplanes.
Easy Transport Chair.

US Patent 5,769,360

This device is similar to the previous one. It uses a seat already a part of the bus/airplane. This seat is modified by making it detachable from the other seats in the row and adding wheels to it. This seat can then be rolled out of the bus/airplane, be occupied by the passenger and be rolled in again. It can then be reattached in its original place. Though this removes the requirement of a transfer in the bus/airplane, it still requires an initial and final transfer into and out of the seat. Also, the aisles in the airplanes being very narrow will not accommodate movement of a seat.
Device for moving a disabled person.

US Patent 5,579,546

This device utilizes a canvas rectangular-shaped sling for lifting a person. It includes 2 pairs of hand grips, one on each side for holding and lifting the sling. These hand grips can be removed and the sling can be attached to a conventional patient lift sling. This device is simple and inexpensive to manufacture. But it does not address the issue of intimacy in that the agents will have to put the sling under the person. This is a common problem with all sling-type devices.
Wheelchair and platform device for movement of a disabled person from a wheelchair to a chair seat support in a vehicle or aircraft.

US Patent 5,669,620

This transfer mechanism permits the person on the seat and the seat to move laterally. The seat is on a platform that has a base and 2 laterally movable platforms. The bottom of the seat has 2 tracks that are matched to and engage a track on a fixed seat frame such as a seat on an aircraft. This would require at least a few seats to be modified on all airplanes.
Method and means for assisting a person to, into and out of a seat in a confined space.

US Patent 2006/0082210 A1

This apparatus comprises inflatable structures for positioning on seats and a rigid transfer means supported on top of the structures. It has primarily been made to overcome difficulties experienced by disabled passengers on an aircraft while transferring to a seat not easily accessible from the aisle, such as the window seat.
Lift and transfer apparatus for a disabled person.

US Patent 6,119,287

This device includes a motor actuated rotatable platform on which is mounted a frame for pivotally supporting a pair of motor actuated lift arms which carry forearm support pads and hand grips. The arms pivot to pick up a person either seated or lying down, and the person may stand on the platform. The platform is rotated to transfer the person after which the arms lower the person to the desired position. Though this device is collapsible making it easier to transfer and store, it does raise questions on the required strength of the persons, forearms, biceps and shoulders.
This transfer apparatus is comprised of a wheeled base having a vertical column mounted on it. The column is vertically slideable and has a pair of arms extending from it. A third arm extends upwards and then outwards in a position between the pair of arms. These 3 arms support a chair for transferring the person. This chair has 4 flaps which fold out to be positioned flat on a bed, and fold in to take the shape of a chair. To use this device, the seat portion of the chair is positioned below the person and the other flaps are then sequentially folded in during the transfer. To place the person, the chair is positioned in the required spot and the flaps are then folded out and the chair is slid from underneath the person. This mechanism is similar
to a flexible sling used to transfer a person and hence has the drawback of invading the personal space of the passenger.

### 2.2 Previous NCAT Work

#### 2.2.1 Mr. Wörz’s Work

Ulrich Wörz, a graduate student working with the National Center for Accessible Transportation started the process of developing a mechanical aid to facilitate the transfer process. In the two years he spent at OSU in this pursuit, he developed and investigated the performance of a few prototypes. The first device held a person under the arm pits and had supports for the feet. The second device was a more complex scissor-like mechanism which grasped the person on the sides of the chest by using the weight of the person being lifted up.

The first prototype is as shown in Fig.17. It consists of 2 rigid arms extending from a vertical column. The horizontal arms had a curve at the end which was padded with a cushioning material. This curved region was placed under the arm pits of the person being lifted up. The vertical column had supports at the bottom to support the feet of the person. The device was lifted up using an overhead hoist. The overhead hoist could be replaced by another lifting mechanism like a hydraulic jack or a telescoping actuator by making a few changes to the device. The device thus had the capability to be used in an aircraft where overhead space is limited.
Fig.17. Mr. Wörz with His First Prototype

After conducting several trials Ulrich observed that 80%-90% of the body-weight was being supported by the arms of the device. This exerted a great force on the person’s arms and raised issues concerning dislocation of the shoulder joint. Studies of the manual transfer process revealed that about 70% of the body-weight was supported under the arms and the rest under the thighs. The first prototype did not lift the thighs of the person during the transfer process. Also, the person carrying out the transfer not only lifted under the arms, but also exerted a lateral force on the sides of the person’s chest. Fig.18. shows some conceptual designs that were developed to more closely replicate the manual transfer.
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Fig. 18. Conceptual Drawings of Designs Similar to SureHands
A second prototype was built following the idea of concept 1. To exert the lateral force, a scissor-like mechanism was explored. This mechanism exerted a lateral force on the arm-end proportional to the weight supported on the leg-end. It had the potential to eliminate the need of an external energy source for the lateral force. The second prototype was developed using this mechanism and paddles and leg hooks to support the chest and thighs of the person being lifted up (Fig.19).

![Fig.19. Mr. Wörz with His Second Prototype](image-url)
Tests on this device showed that the device worked well without inducing any pain on the arms of the person. Thus, an acceptable grasping technique, that of applying a lateral force on the sides of the chest and supporting the thighs, was determined. But this mechanism does not take account of the horizontal motion required to transfer a person from the chair to seat. The prototypes developed by Mr. Wörz used an overhead hoist for lifting purposes. Due to the inadequate overhead space available in airplanes, a mechanism which could lift the device from below is desired. Further development has since been done to design a solution for these challenges.

### 2.2.2 Current Design

After the encouraging results obtained by Mr. Wörz through his work on the transfer process, additional work has been done in the grasping, lifting and moving mechanisms. Since the grasping technique used by Mr. Wörz in his second prototype worked well, it was decided to use a similar technique. A new design for the grasping mechanism which consisted of 2 arms which, when placed under the arm pits of a person held the person on the sides of the chest, was developed. These arms are horizontal and have paddles at the ends to maximize the comfort of the person being transferred. To aid the horizontal motion of the person, these arms are connected to a vertical column through a 2-link mechanism. The vertical column supports a sleeve which is free to move along the column. The sleeve can be moved up and down with a hydraulic jack.
A wooden prototype was made to investigate the operation of the 2-link mechanism of this device (Fig.18). This prototype was then positioned adjacent to airplane seats, as it would be when used during a transfer. It appeared viable to transfer a person to the aisle seat in an airplane. The results were promising and it was decided to make a working prototype which would be able to lift and transfer a person.
Since this prototype was to be used in the NCAT laboratory for study purposes only, weight and space were not a constraint. Fig.21 shows the finished version of this working prototype.

The arms are similar to the wooden prototype and have ergonomic paddles to maximize the comfort of the person being transferred. The 2 arms are connected by a horizontal crossbar at the other end. The arms support 2 leg hooks to lift underneath a person’s thighs. These leg hooks hang from the arms using nylon straps. The crossbar
is connected to a 3-link mechanism. The 2-link mechanism was replaced by a 3-link mechanism to attempt a transfer to the middle seat of the airplane. This 3-link mechanism is connected to a sleeve on the vertical column. This sleeve is connected to a hydraulic jack that provides the lifting ability.

To provide the lateral force for holding the person, a few designs were tried out. The first was a simple but clever arrangement of the nylon straps used to support the leg hooks. This arrangement can be seen below in Fig.22.

Fig.22. Nylon Strap Arrangement
The 2 leg hooks were connected to each other through a small aluminum plate. This plate was then connected to another strap on both ends to form a closed loop. This loop went around the arms of the device. A buckle was provided to change the length of this loop and also the length of the straps connecting the leg hooks. When the leg hooks support a person’s thighs, a lateral force proportional to the weight of the person is exerted through the paddles on the arms on the person’s chest. This eliminates the need for an external energy source to do the same. The lateral force can be varied by changing the length of the loop and the length of the aluminum plate. Changing the position of the straps on the arms, i.e. moving them closer or away from the person also changes the lateral force. Investigating the force required to hold a person will help design this arrangement effectively.

The lateral force can also be changed independently of the person’s weight. This is done by using a pneumatic cylinder instead of the nylon straps in another variation of the arm design. This arrangement can be seen in Fig.23. A single-acting pneumatic cylinder is connected between the 2 arms. This cylinder is normally closed, and opens when subjected to pneumatic pressure. The circuit is controlled by including devices such as flow control valves and pressure regulators.
The first prototype confirmed that the design, based on the manual transfer technique, works as expected. This encouraged the development of the device along the same concept. The next challenge was to confirm that such a design would work well even in the constraints of an aircraft. The first prototype had an awkward lifting mechanism. It was bulky and heavy. Even the arms used to hold the person were fairly long. The most significant challenge though, was to design a base which could provide not only support but also mobility to the whole device.

The hydraulic jack, the vertical column and the sleeve on the column, were all replaced by a single, electrically actuated telescoping mechanism. It is a D-M13 type
telescoping column from X2 Technology in Sweden. The ability of this column to lift a load of 300 lbs. at an offset of 40 inches makes it an appropriate match for our needs. It runs on 24 Volts DC and has a variable speed control to adjust vertical motion. This column is a more compact, aesthetically pleasing, easy-to-operate and light in weight solution to the special requirements for functioning in an aircraft. The length of the arms was reduced by 4 inches to 14 inches instead of the previous 18 inches.

Next, the telescoping column along with the arms supported to it, and an aisle chair were mounted on a base. This base had wheels which provided mobility. Also, the vertical column was mounted on a pair of tracks on the base, such that it could be moved close to and farther away from the chair. This accommodates various sizes of persons using this device. This arrangement, without the arms, can be seen in Fig.24.
The integration of the chair and the vertical through a common base makes it even simpler to perform a transfer. Instead of moving the person on a chair and the transfer mechanism separately, it can be done together. This also assists in placing the lifting mechanism relative to the person in the chair and the intended transfer seat in the aircraft. In simple terms, the transfer procedure is as follows. At the end of the jetbridge an attendant will operate the transfer device to transfer the passenger from his/her wheelchair to the seat in the transfer device. The transfer device will then be rolled into the aircraft on the wheels mounted on the base. The device will be placed such that the chair is in line with the intended transfer seat. An attendant will then operate the transfer device to move the passenger to the aircraft seat.
The mechanism of the arms is still to be added to the second prototype. It will include either the pneumatic setup or the arrangement of the straps to hold a person. The nylon straps do not require any external energy, but rely on the person's weight transmitted through the legs. The pneumatic arrangement requires an external supply of compressed air but accommodates passengers with disabilities caused by lost legs. The design of the articulating arms which help maneuver and position the passenger during the transfer requires analysis of the geometric constraints existing in an aircraft. The number of links used and the length of each link are the factors that govern the functionality of the mechanism.

### 2.3 Project Objectives

The space constraints presented by the interiors of an aircraft, and the significance of weight of the device, are the major concerns in designing equipment to be used in aircraft. The weight is a significant factor if the device is to be used for inflight applications such as for lavatory use. Weight can be reduced by using materials like carbon fiber which are light in weight and have high strength. Weight can also be reduced by reducing the volume of material used, that is, a smaller device will have lesser weight compared to a bigger device of the same material. Thus, a small device not only satisfies the space constraints but it also helps reduce the overall weight of the device. On the other hand, a smaller device can reduce functionality. Thus, the device has upper limit constraints imposed by the interiors of the aircraft and lower limit constraints imposed by its functionality.
The complex 3 dimensional designs and arrangement of an aircraft’s interiors make it difficult to envision its interaction with the transfer device with a person in it. This challenge prompted the development of the first 2 prototypes. The prototypes allowed us to investigate the physical interaction between the device and its environment, the interior of an aircraft. But, the interior of an aircraft is limited to 2 rows of seats. Key elements such as the overhead bins were missing. Also, because of the limited number of seats, it was not possible to create an aisle having seats on both sides. Also, creating physical prototypes is expensive and time consuming. It slows down the entire design process because of the time required to manufacture and test the prototypes manually.

This encouraged the use of the latest developments in the field of Computer Aided Design and Kinematic Simulation. The aim of the project is to find the best design by investigating the interaction of the different designs of the transfer device with the interiors of an aircraft using 3D Modeling and Kinematic Simulation techniques.
3. MATERIALS AND METHODS

3.1 CATIA

CATIA (Computer Aided Three dimensional Interactive Application) is a multi-platform PLM/CAD/CAM/CAE commercial software suite developed by Dassault Systemes and marketed world-wide by IBM. Commonly referred to as 3D Product Lifecycle Management software suite, CATIA supports multiple stages of product development (CAx). The stages range from conceptualization, through design (CAD), analysis (CAE), until manufacturing (CAM). CATIA provides open development architecture through the use of interfaces, which can be used to customize or develop applications.

The 2005 CATIA V5 release 16 was used in this study. The capabilities of this version allows CATIA V5 to be applied in a wide variety of industries, such as aerospace, automotive, industrial machinery, electrical, electronics, shipbuilding, plant design, and consumer goods, including design for such diverse products as jewelry and clothing. The Boeing Company used CATIA V3 to develop its 777 airliner, and is currently using CATIA V5 for the 787 series aircraft. They have employed the full range of Dassault Systemes' 3D PLM products, comprised of CATIA, DELMIA, and ENOVIA, supplemented by Boeing developed applications (Boeing: 777 family).
CATIA V5 supports the following disciplines:

**Mechanical Design:**

The CATIA Mechanical Design discipline helps accelerate core activities of development from concept to detailed design and sheet creation. Dedicated applications for sheet metal and mold design enhance productivity and strongly reduce time-to-market (CATIA V5: Mechanical Design).

**Shape Design and Styling:**

The CATIA Shape Design and Styling discipline allows design of innovative products by creating, controlling and modifying engineered and free form surfaces (CATIA V5: Shape Design and Styling).

**Product Synthesis:**

The extensive range of tools provided by the CATIA Product Synthesis discipline allows automation and validation of the design and manufacturing data (CATIA V5: Product Synthesis).

**Equipment and Systems Engineering:**

The CATIA Equipment and Systems Engineering discipline enables not only design, but also integration of electrical, fluid and mechanical systems within a 3 dimensional mock-up (CATIA V5: Equipment and Systems Engineering).
**Analysis:**

The CATIA Analysis discipline provides fast design and analysis iterations and allows easy product optimization based on product analysis specifications and results (CATIA V5: Analysis).

**Machining:**

The CATIA NC Manufacturing discipline is a 3D PLM knowledge-based product portfolio based on an infrastructure that covers all the specialized CAM applications (CATIA V5: Machining).

**Infrastructure:**

The CATIA Infrastructure discipline provides a uniquely scalable and open platform for collaborative product development (CATIA V5: Infrastructure).

**Human Builder:**

The Human Builder creates and manipulates accurate standard digital humans in the digital mock-up environment for early human-product interaction analysis (CATIA V5: Human Builder). Mannequin generation, gender and percentile specification, mannequin manipulation techniques, animation generation, and advanced vision simulation are a few of the tools available. The software allows non human factors specialists to conduct simple human factors studies. In this study, we used this discipline to create a mannequin and then incorporate it in the virtual simulation environment.
3.2 Modeling Data:

For the purpose of investigating the performance of the transfer device in the aircraft, it was important to model the environment accurately. The environment consisted of appropriately arranged aircraft seats, the aircraft body, and a manikin to replicate the transfer process.

3.2.1 Seats

The NCAT laboratory has airplane seats provided by Boeing. The various dimensions of these seats were measured and used to make a 3D model in CATIA. 3 of these seats connected together form a typical row of seats as seen in Fig.25. The seats when arranged correctly, form the most important part of the virtual environment. The manikin will be transferred from a position in the aisle to the aisle-seat in the row of seats.

Fig.25. Aircraft Seats
3.2.2. Aircraft body

The dimensions of the aircraft body are that of a Boeing 737 and were obtained from a drawing available on Boeing’s website. A small section of the body, enough to occupy 3 rows of seats was used in this study (Fig.26). The body was useful in investigating the distance of the manikin from the overhead baggage bins during a transfer.
3.2.3 Virtual Aircraft

Rows of seats were then arranged in the body. For this study, “six-abreast seating”, the type of seating most commonly found in the economy class of regional jets was chosen because it has one of the smallest aisle sizes of 21 inches. The pitch of the seats in the virtual aircraft is set at 32 inches, again one of the smallest amongst its variants. Fig.27. shows the virtual airplane environment.
3.2.4 Tony the Passenger:

Tony, the virtual manikin, is a 90th percentile American male and was created using the Human Builder module in CATIA. The module allows easy creation and manipulation of the manikin. Tony, when created, is in the standing position (Fig. 28) and is then made to be in a sitting position for the purpose of this study. Tony is attached to the arms of the transfer device similar to a person being held from the sides of the chest. Tony will be transferred by the device from a position in the aisle to the aisle-seat in one of the rows of seats in the virtual airplane. Tony will help investigate the clearance between an actual person and the seats and overhead baggage bins during a transfer.

Fig.28. Tony the Passenger
3.2.5 Path-of-Transfer

The path-of-transfer is the path along which the passenger is moved during a transfer from the aisle chair to the aircraft seat. The path used in this investigation was 2-dimensional and placed perpendicular to the axis of the aisle. The path was made of 3 sections as seen in Fig.29. The first section was vertical and accounted for the passenger being lifted up from the chair such that the arm rest would not obstruct the transfer. The second section was horizontal and represented the motion from the center of the aisle to the center of the seat. The third section was vertical again, and corresponded to the passenger being lowered to the aircraft seat.

Fig.29. Path-of-Transfer
3.3 Kinematic Model

A Kinematic model was created to simulate the movements of the physical prototype. The components of the prototype have a definite relationship with each other. Replicating these relationships makes it possible to reproduce the movements of the prototype. The Kinematic model can be analyzed as discussed below.

*Joint 1: Prismatic Joint – 2 links of the vertical column*

The electrically actuated telescoping mechanism used to lift up the passenger, consists of 2 square links. The telescoping mechanism is replicated by creating a Prismatic joint between the 2 links and has a range of 26”.

![Fig.30. Prismatic Joint in Kinematic Model](image)
**Joint 2: Revolute Joint 1 – Top link of Vertical Column and Arm Link 1**

The relationship between the vertical column and Link 1 of the Arms was replicated by creating a Revolute joint between the top link of the column and Link 1 of the arms. The range of this joint is 180 degrees.

This joint is illustrated in Fig.31.

![Fig.31. Revolute Joint 1 in Kinematic Model](image-url)
Joint 3: Revolute Joint 2 – Arm Link 1 and Arm Link 2.

The relationship between Link 1 and Link 2 of the Arms was replicated by creating a Revolute joint between them. The range of this joint is 360 degrees.

This joint is illustrated in Fig.32.
**Joint 4: Revolute Joint 3 –Arm Link 2 and Cross-Arm of Paddles.**

The relationship between Link 2 of the Arms and the Cross-Arm of the Paddles was replicated by creating a Revolute joint between them. The range of this joint is 360 degrees.

This joint is illustrated in Fig.33.

![Fig.33. Revolute Joint 3 of Kinematic Model](image)

The prismatic and 3 revolute joints together form the Kinematic Model. This model accurately reproduces the movements of the physical prototype and its simulation allows easy control and analysis of its performance.
3.4 Experimental Procedure

The experimental procedure was standardized across the various design iterations to ensure accurate and consistent results. The 3 components of the transfer device that were tested are the paddles, arms and the base-supports. Fig.34 shows these and other components of the transfer device. The procedures used to investigate the designs are discussed further.

Fig.34. Components of the Transfer Device.
3.4.1 Paddles.

*Design Requirements:*

The best design of the Paddles will –

1. Satisfactorily complete the transfer from the initial to the final position.
2. Not generate any interference between the critical components.
3. Utilize the smallest lengths for the Paddles.

*Constraints:*

1. The space available between the seats of an aircraft creates a constraint on the maximum length of the paddles.
2. The paddles are the only components of the device which come in contact with the passenger. If the length is too small, there is a possibility of the cross-arm of the paddles hurting the passengers’ chest. This introduces a constraint on the minimum length of the paddles.
3. The requirement of a good moment-arm for the strap mechanism to work effectively generates a constraint on the minimum length of the paddles.

*Materials Used:*

Arms with both Link 1 and Link 2 being 12” long, vertical column, Base, Virtual aircraft, Tony, Path-of-Transfer.
Procedure:

1. Starting Position: Tony was seated in the aisle chair (not shown) with the Paddles positioned on the sides of his chest. The Arms were positioned such that the Vertical Column did not interfere with Tony’s knees.

2. Transfer: Tony was then transferred from the aisle chair to the aircraft seat. It was made sure that there was no interference between Tony and the front seat, and the device and the front seat.

3. Final Position: Tony was seated in the center of the aisle seat of the aircraft. This ensured that Tony would not have to be pushed any further after the transfer by the device was completed.

4. Data recorded: The following data was recorded during the transfer:
   a. Interference-check between Tony and front seats.
   b. Interference-check between Tony and overhead bins.
   c. Interference-check between arms of device and front seats.

Fig.35. CATIA Reporting Interference
In CATIA, interference between components is shown by highlighting the interfering components. The picture on the previous page shows that the seat is interfering with link 2 of the arms on device.

Fig.36. Sequence of transfer from aisle chair to aircraft seat.
3.4.2 Arms

*Design Requirements:*

The best design of the Arms will-

1. Satisfactorily complete the transfer from the initial to the final positioning
2. Not generate any interference between the critical components
3. Have an adequate range of operation

*Constraints:*

1. The space available within the aisle and the arrangement of the seats in an aircraft creates a constraint on the maximum length of the links.
2. The requirement of satisfactorily completing the transfer introduces a constraint on the minimum length of the links.

*Materials Used:*

Bent-Paddles, vertical column, Base, Virtual aircraft, Tony, Path-of-Transfer.

*Procedure:*

A design requirement for the Arms was to have an adequate range of operation. This would make the device robust from the users’ point of view. To get the range of operation, the procedure was repeated at least at 2 positions, and more if required, along the aisle of the aircraft. It was ensured that the device satisfies the design requirements at both the aisle-positions. The procedure followed at the aisle-positions was as follows -
1. Starting Position: Tony was seated in the aisle chair (not shown) with the Paddles positioned on the sides of his chest. The Arms were positioned such that the Vertical Column did not interfere with Tony’s knees.

2. Transfer: Tony was then transferred from the aisle chair to the aircraft seat. It was made sure that there was no interference between Tony and the front seat, and the device and the front seat.

3. Final Position: Tony was seated in the center of the aisle seat of the aircraft. This ensured that Tony would not have to be pushed any further after the transfer by the device was completed.

4. Data recorded: The following data was recorded during the transfer:
   a. Interference-check between Tony and front seats.
   b. Distance between Tony and front seats.
   c. Interference-check between Tony and overhead bins.
   d. Distance between Tony and overhead bins.
   e. Interference-check between Arms of device and front seats.
   f. Position of base along the aisle of the aircraft.

5. The range of operation was calculated using the position of the base recorded in both the aisle-positions.
3.4.3 Base-Supports

*Design Requirements:*

The best design of the Base-Supports will-

1. Not obstruct the motion of the device in the aisle of the aircraft when it is moved in and out of the aircraft.

2. Not generate any interference between the critical components during its operation.

3. Have a large range of operation

4. The supports may allow transfer of passenger towards any 1, or both directions from the aisle to the seat.

*Constraints:*

1. The space available within the aisle and the arrangement of the seats in an aircraft creates a constraint on the maximum length of the links.

2. The ability to support the device during a transfer generates a constraint on the minimum length of the supports. This minimum length was considered to be 20", the distance from the center of the aisle to the center of the seat, also the maximum overhang generated during the transfer.

*Materials Used:*

Vertical column, Base, Virtual aircraft.
Procedure:

One of the design requirements for the Base-Supports was to have a large range of operation. This would make the device robust from the users’ point of view. To get the range of operation, the procedure was repeated at least at 2 positions, and more if required, along the aisle of the aircraft. It was ensured that the device satisfies the design requirements at both the aisle-positions. The procedure followed at the aisle-positions was as follows -

1. The base, with the supports, was appropriately positioned in the aisle and the supports-mechanism was activated.
2. The supports were extended and retracted and the operation was checked for interference.
3. Data recorded: The following data was recorded during the transfer:
   a. Interference-check between supports and seats
   b. Position of the base along the aisle of the aircraft.
4. The range of operation was calculated using the position of the base recorded in both the aisle-positions.
4. RESULTS

This section presents the results of the performance of the various designs tested for the paddles, arms and base-supports. 3 designs for the paddles, 6 designs for the arms and 4 designs for the base-supports were tested.

4.1 Paddles

3 design variations were tested for the Paddles. The designs and their results are discussed further.

4.1.1 Paddles Design 1

The Cross Arm length was selected as 14 inches to accommodate the chest-width of Tony, a 90\textsuperscript{th} percentile American Male. The Paddle length was chosen as 18 inches to have a sufficient gap between the Cross Arm and Tony’s chest.

**Design Configuration:**

Cross Arm Length: 14”

Paddle Length: 18”

Fig.37. Paddles Design 1
Results:

a. Interference-check between Tony and front seats: \textit{No Interference}

b. Interference-check between Tony and overhead bins: \textit{No Interference}

c. Interference-check between arms of device and front seats: \textit{Interference}

4.1.2 Paddles Design 2

During the investigation of the Design 1, it was noticed that the length of the paddles caused interference between the paddles and the aircraft seat. To avoid this, the length was reduced to 14 inches. This length also generated a sufficient gap between the Cross Arm and Tony’s chest.

Design Configuration:

Cross Arm Length: 14”

Paddle Length: 14”

![Fig. 38. Paddles Design 2](Image)

Results:

a. Interference-check between Tony and front seats: \textit{No Interference}
b. Interference-check between Tony and overhead bins: \textit{No Interference}

c. Interference-check between arms of device and front seats: \textit{No Interference}

\subsection*{4.1.3 Paddles Design 3}

The investigation of design 2 revealed no interference. The gap created between the Cross Arm and Tony’s chest was also sufficient. For Design 3, the corners generated at the Paddle-Cross Arm joints were eliminated.

\textbf{Design Configuration:}

Cross Arm Length: 10”

Paddle Length: 14” \textit{(Bent Design)}

![Fig.39. Paddles Design 3](image)

\textbf{Results:}

a. Interference-check between Tony and front seats: \textit{No Interference}

b. Interference-check between Tony and overhead bins: \textit{No Interference}

c. Interference-check between arms of device and front seats: \textit{No Interference}
4.2 Arms

Following are the 6 designs tested for the Arms.

<table>
<thead>
<tr>
<th>Design Configuration</th>
<th>Link 1 length</th>
<th>Link 2 length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12”</td>
<td>12”</td>
</tr>
<tr>
<td>2</td>
<td>12”</td>
<td>10”</td>
</tr>
<tr>
<td>3</td>
<td>12”</td>
<td>8”</td>
</tr>
<tr>
<td>4</td>
<td>12”</td>
<td>6”</td>
</tr>
<tr>
<td>5</td>
<td>20”</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>18”</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Design Configurations for Arms

To get the range of operation these designs were tested at various points and the extremes were located. These extreme positions are called as “Closest-to-Passenger” and “Farthest-from-passenger”. Tony, in the aisle chair, is kept in-line with a row of seats, and the vertical column is moved closer or further away from him. The “Closest-to-Passenger” position is restricted by the interference between Tony’s knees and the vertical column of the transfer device, if the vertical column gets too close to him. The “Farthest-from-Passenger” position is constrained by the reduced “reach” capability required to transfer Tony to the aircraft seat.

The first 4 configurations employ designs in which the vertical column is fixed on the base. The next 2 configurations have an added prismatic joint between the bottom link of the vertical column, and the base. This allows the column to slide
relative to the base. This joint was added as an attempt to maintain the reach of the device after the Arms were reduced to one link.

4.2.1 Arms Design 1

The prototype made at NCAT had 3 links which were 12”, 6” and 6” in length, adding up to 24”. Since that configuration worked well, a device with 2 links was investigated. The total length of the links was maintained at 24”.

This design is illustrated in Fig.40.

Design Configuration:

Link 1: 12”

Link 2: 12”
Results: “Closest-to-Passenger” position

a. Interference-check between Tony and front seats: No Interference

b. Minimum distance between Tony and front seats: 0.805 inches

Fig. 41. Result Window from CATIA Showing Minimum Distance Between Tony and the Front Seats.
c. Interference-check between Tony and overhead bins:  \textit{No Interference} \\

d. Minimum distance between Tony and overhead bins:  \textit{1.4 inches}
e. Interference-check between Arms of device and front seats: No Interference

f. Position of base along the aisle of the aircraft: 11.998 inches from front seat

Fig. 43. Distance of Base from Front Face of Front Seat.

The result windows shown for Design 1 were recorded for all the designs. For the remaining design configurations for the Arms, only the numerical values are shown.
Results: “Farthest-from-Passenger” position

a. Interference-check between Tony and front seats: \textit{No Interference}

c. Minimum distance between Tony and front seats: 0.779 inches

b. Interference-check between Tony and overhead bins: \textit{No Interference}

c. Minimum distance between Tony and overhead bins: 1.141 inches

d. Interference-check between Arms of device and front seats: \textit{No Interference}

e. Position of base along the aisle of the aircraft: 3.756 inches from front seat

\textit{The range of operation for this configuration is } 11.998 – 3.756 = 8.242 inches.
4.2.2 Arms Design 2

Design Configuration:

Link 1: 10”
Link 2: 12”

Results: “Closest-to-Passenger” position

a. Interference-check between Tony and front seats: No Interference
b. Minimum distance between Tony and front seats: 0.795 inches
c. Interference-check between Tony and overhead bins: No Interference
d. Minimum distance between Tony and overhead bins: 2.076 inches
e. Interference-check between Arms of device and front seats: No Interference
f. Position of base along the aisle of the aircraft: 13.11 inches from front seat

Results: “Farthest-from-Passenger” position

a. Interference-check between Tony and front seats: No Interference
b. Minimum distance between Tony and front seats: 0.778 inches
c. Interference-check between Tony and overhead bins: No Interference
d. Minimum distance between Tony and overhead bins: 1.22 inches
e. Interference-check between Arms of device and front seats: No Interference
f. Position of base along the aisle of the aircraft: 6.476 inches from front seat

The range of operation for this configuration is 13.11 – 6.476 = 6.634 inches.
4.2.3 Arms Design 3

Design Configuration:

Link 1: 8”
Link 2: 12”

Results: “Closest-to-Passenger” position

a. Interference-check between Tony and front seats: No Interference
b. Minimum distance between Tony and front seats: 0.776 inches
c. Interference-check between Tony and overhead bins: No Interference
d. Minimum distance between Tony and overhead bins: 1.999 inches
e. Interference-check between Arms of device and front seats: No Interference
f. Position of base along the aisle of the aircraft: 13.197 inches from front seat

Results: “Farthest-from-Passenger” position

a. Interference-check between Tony and front seats: No Interference
b. Minimum distance between Tony and front seats: 0.78 inches
c. Interference-check between Tony and overhead bins: No Interference
d. Minimum distance between Tony and overhead bins: 1.183 inches
e. Interference-check between Arms of device and front seats: No Interference
f. Position of base along the aisle of the aircraft: 8.343 inches from front seat

The range of this configuration is 13.197 – 8.343 = 4.854 inches.
4.2.4 Arms Design 4

Design Configuration:

Link 1: 6”

Link 2: 12”

Results: “Closest-to-Passenger” position

a. Interference-check between Tony and front seats: No Interference

b. Minimum distance between Tony and front seats: 4.71 inches

c. Interference-check between Tony and overhead bins: No Interference

d. Minimum distance between Tony and overhead bins: 1.078 inches

e. Interference-check between Arms of device and front seats: No Interference

f. Position of base along the aisle of the aircraft: 11.749 inches from front seat

Results: “Farthest-from-Passenger” position

a. Interference-check between Tony and front seats: No Interference

b. Minimum distance between Tony and front seats: 3.105 inches

c. Interference-check between Tony and overhead bins: No Interference

d. Minimum distance between Tony and overhead bins: 1.753 inches

e. Interference-check between Arms of device and front seats: No Interference

f. Position of base along the aisle of the aircraft: 10.768 inches from front seat

The range of this configuration is 11.749 – 10.768 = 0.981 inches.
4.2.5 Arms Design 5

The 2-links Arms designs showed great potential during the investigation. The design configurations 4 and 5 employ a different Kinematic model. There is an extra prismatic joint between the vertical column and the base. This allows the column to slide relative to the base. These designs have only one position they can be suitably operated from and the data is recorded at that position.

Design Configuration:

Link 1: 20”

Fig.44. Arms Design 5
Results:

a. Interference-check between Tony and front seats: *No Interference*

b. Minimum distance between Tony and front seats: *2.634 inches*

c. Interference-check between Tony and overhead bins: *No Interference*

d. Minimum distance between Tony and overhead bins: *1.173 inches*

e. Interference-check between Arms of device and front seats: *No Interference*

4.2.6 Arms Design 6

Design Configuration:

Link 1 = 18”

Results:

a. Interference-check between Tony and front seats: *No Interference*

b. Minimum distance between Tony and front seats: *0.779 inches*

c. Interference-check between Tony and overhead bins: *No Interference*

d. Minimum distance between Tony and overhead bins: *1.26 inches*

e. Interference-check between Arms of device and front seats: *No Interference*
4.3 Base-Supports

4 designs were tested for the Base-Supports. Unlike the Paddles and Arms, these designs are not derived from each other. These designs were tested at various points along the aisle and the range of operation was calculated by using the positions at which the operation was successfully carried out without generating any interference. During a transfer, when the passenger is moved towards the aircraft seat, a moment is generated which tends to tip the device on its sides. The function of the base-supports is to support the device during the transfer and prevent it from tipping over.

*Nomenclature:*

![Diagram of seats with labeled parts including backrest, back seat, front seat, back leg, front leg, and front face.]

Fig.45. Nomenclature for the Seats
4.3.1 4-Bar Mechanism

This mechanism utilizes the base as one of the links along with the leg which extends out. The leg is retracted in the initial position and extended out between the seats in the final position. Fig.46. illustrates the mechanism in top view and represents the retracted position. The design configuration and its results are discussed below.

**Design Configuration:**
- Link 1: Fixed Link: Base
- Link 2: Crank
- Link 3: Rocker: Leg
- Link 4: Slider

Fig.46. 4-Bar Mechanism for Supports

Fig.47. 4-Bar Mechanism in Extended position
Results:

This design required a wide space to swing-open. The range of operation was 2 inches.

4.3.2 Wing Mechanism

This mechanism has 2 links which appear like wings when they open during operation. In the retracted position, these links fold up along the vertical column and in the extended position, spread out under the seats. Fig.48. shows the basic dimensions of the Wing Mechanism and Fig.49. illustrates the mechanism’s operating and extended positions.

Fig.48. Basic dimensions of the Wing mechanism
Results:

The mechanism operated between the back leg of the front seat and the front face of the back seat. This space is 6 inches wide and the supports are 2 inches wide. Thus, the range of operation was 4 inches.

4.3.3 Horizontal-Wing Mechanism

This design was derived from the previous wing design. It uses a similar wing-mechanism which operated in the horizontal instead of vertical plane. Fig.50. shows the basic dimensions of the Horizontal Wing Mechanism and Fig.51. illustrates the mechanism’s operating and extended positions.
Fig. 50. Basic Dimensions of the Horizontal-Wing mechanism

Fig. 51. Horizontal-Wing mechanism in Operating and Extended Positions
Results:

This mechanism operated between the back legs of the front seat and the front legs of the back seat. This space was 8 inches wide and the range of operation for this device was 5.7 inches.

4.3.4 Telescoping Mechanism

This design used a telescoping mechanism which extended out between the seats. The telescoping mechanism consists of 2 links which extend out when required. In the retracted position, these links are stowed in the base itself. Fig.52. shows the basic dimensions of the Horizontal Wing Mechanism and Fig.53. illustrates the mechanism’s retracted and extended positions.

Fig.52. Basic Dimensions of the Telescoping mechanism
Results:

This mechanism operated between the back legs of the front seat and the front legs of the back seat. This space is 8 inches wide and the supports are 2 inches wide. Thus, the range of operation is 6 inches.
5. DISCUSSION

This section evaluates the performance of the results presented in the previous section. After considering the various design options available, the best for the paddles, arms and base-supports are identified.

5.1 Paddles

The design requirements for the paddles called for the smallest paddles which could satisfactorily complete the transfer. Constraints that affected the design included those produced by the space available in the aircraft, the interference between the paddles and the passenger and the moment-arm required to operate the strap mechanism.

Design 1

Design 1 was the design of the paddles used on the prototype at NCAT. The prototype made at NCAT utilizes paddles which are 18” in length. The cross-arm is 14” in length, the chest-width of Tony. The results show that Design 1 generated interference between the paddles and the aircraft seats. It was observed that the length of the paddles was causing this interference. Hence, this length was reduced and Design 2 was created.

Design 2

Design 2 utilized a length of 14” for the paddles. The cross-arm specifications were not changed. This design worked well and no interference was produced. Also,
these paddles generate a sufficient gap between the cross-arm and Tony’s chest, and a functional moment-arm. Although this design satisfied all the requirements and the length of the paddles could no longer be reduced, a third design was created.

**Design 3**

Design 3 eliminated the corner by the paddles and cross-arm. It was observed that this design produced a greater clearance between the paddles and seats during a transfer.

**Best Design**

Design 3 was thus the best design amongst the three and is recommended for use in the final design of the transfer device. This design will also be used in all further analysis in this project.

### 5.2 Arms

The design requirements for the arms called for a design with a sufficiently large range of operation which could satisfactorily complete a transfer. Constraints that affected the design included those produced by the space available in an aircraft, the interference between the arms and the aircraft seats and the “reach” required for completing the transfer.

**Design 1**

The prototype at NCAT utilizes a design with 3 links. Since this design worked well in the lab, it was decided to test a smaller design. Thus, design 1 had 2 links
instead of 3. Results show that this design worked very well with a large range of operation of 8.2”.

**Design 2**

Since design 1 worked well, design 2 was generated by reducing the length of link 1. The length of link 1 was reduced to 10” and that of link 2 was maintained at 12”. Link 2 was kept at 12” to aid the ability to “reach” up to the center of the aisle seat. Investigating the effects of changing link 2 instead of 1, or both, is a recommendation for future research. It can be seen from the results that design 2 performed well too and had a range of operation of 6.6”.

**Design 3**

As design 2 performed suitably, the length of link 1 was further reduced to 8”. Thus, design 3 had link with a length of 8” and link 2 was again maintained at 12”. This design also satisfactorily performed the transfer without generating any interference. The range of operation dropped down to 4.8”.

**Design 4**

Once again, the length of link 2 was reduced by 2”. Design 4, thus, had link 1 with a length of 6” and link 2 with a length of 12”. The investigation showed that even though the transfer was performed satisfactorily, the range of operation declined to a little less than 1”. Due to this drop in the range, no further alterations were made to the 2-link design.
Design 5

Link 1 was eliminated and a 1-link design was introduced. To make up for the lost reach, an extra joint was added to the Kinematic model. This joint, a prismatic one between the vertical column and the base, allows the column to slide relative to the base. This permits the column to move closer towards the passenger during the transfer and as a result, increase the “reach” of the arms. Design 5 was thus created using one link with a length of 20” and an extra prismatic joint. Investigation proved that this design concept worked very well. The transfer was satisfactorily completed without generating any interference. But, due to the inherent nature of the design of having only one link, there is no range of operation for this design. The device has to be positioned at a particular location along the aisle to complete the transfer.

Design 6

The performance of the previous design encouraged the generation of design 6. This design had a link with a length of 18” instead of 20. Results show that this design too, performed well without producing any interference. No further alterations were made to this design because a length of 18” is essential to satisfactorily transfer the person through the distance from the aisle to the seat, which is 20”.

Best Design

Designs 5 and 6 showed great potential in-spite using only one link. The factor that comes into play, though, is the fact that this design requires simultaneous movements of the arms and the vertical column. If these movements are not in-sync,
the transfer of the passenger will be hindered. It can also cause interference between the critical components and collision between the passenger and aircraft seats.

The 2-link designs performed well without showing such problems. These designs were simple to operate and easier to control. Designs 3 & 4 used a link 1 having lengths of only 6” and 8”, and performed well. But these designs had a range of operation which was less than 5”. Design 1, which used a length of 12” for link 1 also performed well and had a range of 8.2”. But design 2 which had a smaller link length of 10” also had an adequate range of 6.6”. Hence, for having small links and an adequate range of operation, Design 2 is judged as the best design for the arms.

5.3 Base-Supports

The design requirements for the base-supports asked for a design which provided sufficient support for the transfer device without causing it any hindrance during the transfer device’s passage through the aisle of an aircraft. A good design also required a large range of operation. Constraints that influenced the design included those generated by the space available in an aircraft and the ability to sufficiently support the transfer device during a transfer.

*Design 1: 4-Bar Mechanism*

The 4-bar mechanism utilizes a swinging motion of the arm which requires a large space. The legs of the aircraft seats obstructed the operation of this mechanism causing the range of operation to be a mere 2”. The vertical column can be attached to either end of the base.
Design 2: Wing Mechanism

The previous investigation showed that the modest space available on the floor of an aircraft is not favorable to a design utilizing a horizontal-swing motion. Hence, the wing mechanism looked at utilizing the available space in the vertical plane. The results show that the wing mechanism performed better than the 4-bar mechanism and had a range of operation of 4 inches. Also, the lengths of the supports were 30”, and could be increased further without affecting the range of operation by a significant amount.

Design 3: Horizontal Wing

The performance of the previous wing mechanism encouraged the investigation of a similar design which operated in the horizontal plane. Unlike the 4-bar mechanism which also operated in the horizontal plane, the horizontal wing mechanism worked well in avoiding any interference with the seats. The results show that this device had a range of operation of 5.7”, almost 2” more than the previous wing mechanism. The vertical column can be attached to either end of the base.

Design 4: Telescoping Mechanism

The previous designs have shown that a mechanism with any kind of swinging motion generates interference with the seats negatively affecting the range of operation. The telescoping mechanism attempts to evade this problem by operating in a straight line. The results show that it this idea was largely successful providing it
with a range of operation of 6”, the highest amongst the 4 designs. The vertical column can be attached to either end of the base.

**Best Design**

The 4-bar mechanism had a range of operation of 2” which is practically insignificant. The vertical wing mechanism showed a modest range of 4” which is still not adequate. The horizontal wing mechanism performed well too, but even its range of 5.7” could not match that of the telescoping mechanism. Hence, the telescoping mechanism with a range of operation of 6” is the best design for the base-supports.

**5.4 Transfer Device**

In the previous sections we have discussed the results of the paddles, arms and base supports. After testing various designs, the best designs for these 3 components have been selected. The best design for the completer transfer device will be the combination of these 3 designs. The transfer device will thus have the following configuration:

_Paddles:_ Bent paddles design with arm length as 14”

_Arms:_ 2-link arms design with Link 1 having a length of 10”, Link 2 having a length of 12”, and a range of operation of 6.6”.

_Base-Supports:_ Telescoping mechanism with a range of operation of 6”.

The range of operation for this combination will be 6”, the range of the supports.
6. CONCLUSION

6.1 Limitations of this project

Though this project succeeded in achieving its purpose, it has a few limitations which should be taken note of. First, the dimensional data used to model the aircraft seats and body is not very accurate. These dimensions were measured off of existing seats and limited data available through Boeing. Though this affects the numerical values of the results, the performance of the designs relative to each other remains the same. Also, for the purpose of establishing a procedure for testing performance, only a modest number of designs were investigated. This project only demonstrates the performance of the tested designs and does not necessarily conclude their superiority to new ideas. Only a few aspects of the design were investigated in this project. The length of the base and its ability to through turn through aisles in multi aisle aircrafts was not considered in this project. The designs were investigated more from the geometrical point of view and not the mechanical design and strength. Satisfactory attention was given to not test designs which are not feasible to manufacture.

Limited simulation resources were utilized in this project. Only CATIA was used for the simulations and its capabilities were not compared to other similar resources available, if any. Tools such as “Band Analysis” can increase the validity of the results by giving a detailed analysis of the distance between the components at each point during a transfer.
6.2 Suggestions for Future Studies

The Virtual Environment used in this project which was comprised of the aircraft seats and aircraft body can be dimensionally more accurate than this study. These components affect the performance of all the designs and their accuracy is necessary in predicting the effectiveness of the designs. The 3D models of these components could be obtained directly from their manufacturers for best precision.

The Virtual Environment in this study was modeled after that of the Boeing 737 series aircrafts. Though this aircraft is one of the most common ones used for domestic travel, it is not the smallest. Smaller aircraft have smaller aisles and also smaller seat pitch in some cases. The designs can be tested in these environments too.

Multi-aisle aircrafts sometimes have aisles which have turns and bends. The length of the base should be checked against the ability to satisfactorily move along these turns and bends. Also, the need and advantages of testing more number of designs is evident.
6.3 Suggestions for Future Designs

The mechanism for operating the paddles can be as simple as the nylon straps arrangement or can employ a pneumatic cylinder. The operating mechanism affects the length of the paddles and when its design is finalized, the design of the paddles can be refined by carrying out an investigation of its performance in the Virtual Environment.

In this project the design of the Arms was varied by changing the length of Link 1 only. The length of Link 2 can also be changed and its effect can be investigated. Only 4 designs were tested for the base-supports.

More designs can be tested and a finite element analysis can be done to verify their ability to support the device during a transfer. The combination of the base and supports should be able to move through turns and bends in aircraft aisles. Another study can be conducted where these turns in aircraft aisles are included in the virtual environment and the base with the supports is moved along the aisle to check for maneuverability.
6.4 Overall Project Summary

The biomechanics study and the computer survey identify the need for the development of an alternative for the manual transfer process which is an integral part of air travel for a large population. The current practice is unsafe, uncomfortable, and undignified. It is also a deterrent for people who want to travel and is thus harming the air industry. With the predicted increase in number of wheelchair bound passengers in the near future, developing an alternate solution is not only ethical, but also makes good business sense.

The research at the National Center for Accessible Transportation has made significant development towards this goal. The next prototype can utilize the results of this project and a study conducted to investigate the effects of lateral force on passenger comfort during a mechanically assisted dependant transfer. This prototype will be another significant step towards the end product that NCAT is striving for.

This project investigated many design variations and outlined the best design for each of the components of the transfer device. Another significant achievement of this project was that is demonstrated the potential of 3D modeling and kinematic simulation as a design aid in machine design. It established and showed the application of a meticulous procedure for investigating the performance of the various designs. The Virtual Environment created for this project can be used for future studies. By creating similar environments and following a slightly modified procedure, virtually any scenario can be investigated.
BIBLIOGRAPHY


