IDEA

Innovations Deserving
Exploratory Analysis Programs

Transit IDEA Program

TrainMate Robotic System
Making Public Transportation, Public!

Final Report for
Transit IDEA Project 100

Prepared by:
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Infratek Solutions, Inc.

April 2023

NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board

This IDEA project was funded by the Transit IDEA Program.

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- The NCHRP IDEA Program, which focuses on advances in the design, construction, and maintenance of highway systems, is funded by American Association of State Highway and Transportation Officials (AASHTO) as part of the National Cooperative Highway Research Program (NCHRP).
- The Rail Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
- The Transit IDEA Program, which supports development and testing of innovative concepts and methods for advancing transit practice, is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP).

Management of the three IDEA programs is coordinated to promote the development and testing of innovative concepts, methods, and technologies.

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TRANSIT IDEA PROJECT T-100

Prepared for

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Transportation Research Board
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ACKNOWLEDGMENTS

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GLOSSARY

ADA	American with Disabilities Act
AI	Artificial Intelligence
ANSI	American National Standards Institute
CAD	Computer Aided Design
FOS	Factor of Safety
ID	Internal Diameter
ISO	International Organization for Standardization
LiDAR	Light Detection and Ranging
ML	Machine Learning
MVP	Minimally Viable Product
OD	Outside Diameter
POC	Proof of Concept
ROS	Robotic Operating System
TMAC	Train Management and Control

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EXECUTIVE SUMMARY

The use of robotic assistance to help people with disabilities navigate public transportation has been a critical research topic for the past decade and has proven to be helpful in improving accessibility to transportation.
One example of this is the use of robotic guide dogs. These are robots that are designed to help visually impaired people navigate through public spaces, including public transportation stations and vehicles. These robots use sensors and cameras to detect the surrounding environment and provide guidance to the user using voice commands or tactile feedback. This can help visually impaired people travel more safely and independently.

Another example is the use of robotic assistants for people with physical disabilities. These robots can help people using mobility devices navigate through public transportation stations and onto trains or buses. The robot can be equipped with a manipulator arm or other tools that can help the user with tasks such as opening doors, pressing buttons, and maneuvering their wheelchair onto of off the vehicles.

In addition, robotic assistants can help people with cognitive disabilities navigate public transportation more easily. For example, a robot can be programmed to give clear and simple directions to someone with an intellectual disability or provide reminders for people with memory impairments.

Overall, the use of robotic assistance in public transportation can help people with disabilities travel more easily and independently, reducing the need for human assistance and improving their quality of life which is the primary focus of this work.

With the above in mind the IDEA product that the project team pursued in this project made it one step closer to “MAKE PUBLIC TRANSPORTATION, PUBLIC!”. The end results of this Transit IDEA endeavor demonstrated the feasibility of the TrainMate robotic system as a cost-effective, train station or public transportation assistant robot that helps passengers with disabilities using mobility devices to independently board and deboard trains at non-accessible, street level train stations in a manner that is smart, efficient, encouraging and does not cause embarrassment or unwanted attention for the disabled passenger. In New Jersey alone, 101 out of 162 train stations are street-level and non-accessible. The TrainMate system will not only facilitate the use of public transit for passengers with mobility disabilities but can also be used to provide service to passengers with other types of disability such as hearing or vision. While idle it can cater to other needs of the transit agency such as security and surveillance, cleansing and disinfection, public health monitoring, station asset inspection and providing announcements and general information to increase utilization and return on investment.

During the course of this project, the project team was able to conduct a thorough requirements analysis for a robotic system that is American Disability Act (ADA) compliant. As part of the project discovery phase, the team also visited more than 15 non-accessible train stations in New Jersey and New York to observe the limitations and unique station plans of such train stations. Using the requirement analysis documents, field information and priceless feedback and comments of our advisory panel, the project team was able to produce electromechanical computer-aided design (CAD) blueprints of a working prototype of the TrainMate robotic system. These blueprints were carefully modeled, tested and simulated in CAD software called SolidWorks.

The project team also focused on the robotic operating system, software components and artificial intelligence (AI) algorithms that shall be in place for such a system to be operational and developed proof of concept programs that prove the capability of such software components for the future prototyping phase.

Ultimately, all the designed hardware and software components were integrated in a software-based end to end simulation scenario and the feasibility and overall capabilities of the system were tested under varying scenarios and environmental test cases.

The results of the final simulation reinforced the sufficiency of the designed electromechanical components as well as the software system to meet the intended uses of the TrainMate robotic system. The final end to end tests also indicated that the TrainMate system only takes 2 minutes and 10 seconds to board or deboard a passenger using a mobility device on a railcar as opposed to average of 7 minutes that it takes the train station staff to do so which is a 350% increase in efficiency.

This research has resulted in several blueprints of hardware and software components that are tested in relevant CAD environments and are now ready to be prototyped and integrated to build the first physical working prototype of the TrainMate system. This system, once built, not only affords the disabled passengers with autonomy and independence in making their trips with public transportation but also enables the public transit agencies to have a modular and flexible technology platform to address the ever-changing needs and requirements of their passengers in efficient and practical manners using the advancements in technology.

IDEA PRODUCT

The product of this IDEA project is a feasibility study of the conceptual designs and software prototyping of electromechanical components for the robotic base and wheelchair lift modules, successfully passing all technical verification testing in CAD simulations with the following breakdown:

1. Blueprints and CAD designs for different electromechanical components of the base robotic and the lift modules.
2. Machine vision & AI control algorithms demonstrating high accuracy, generalization, and integration and applicability with public transit environments.
3. Field usability CAD simulations showing end to end operation and improved operation and cycle time for sample lift and passenger boarding/deboarding operations.

CONCEPT AND INNOVATION

Abundance of street-level train stations that require lifting of passengers on wheelchair to board or deboard railcars is a clear problem and missing link in disabled passengers' travel chain. While it may look simple and straightforward on the surface, upon further investigation and evaluation of the current solutions, it turns out that the problem has many more layers to it.

Figure 1 - Wheelchair boarding problem at street level train stations.

Consensus among us and our public transit partners is that to properly solve and address the challenge of lifting passengers with mobility impairment, one should not only take into account the mechanical act of lifting but also the nature and characteristics of the payload and how it is handled. In addition, impacts on other passengers as well as the business objective of the agency are other key factors. Matters such as safety, independence, not causing embarrassment, and dignity of the passengers as well as efficiency, practicality and cost-effectiveness should be prioritized as part of the solution.

The above considerations indicate a need for a custom, innovative solution. A solution that taps into the technological arena, applying the latest and greatest advancements in an innovative, modular, and multifunctional robotic platform that addresses the needs of passengers with disabilities at any location.

This platform, called TrainMate, can be the perfect fit to cater to the needs of passengers with different types of disabilities. It can also be utilized at times when a scalable technology platform is required to tackle unpredictable events or surprises to minimize adverse impacts on ridership.

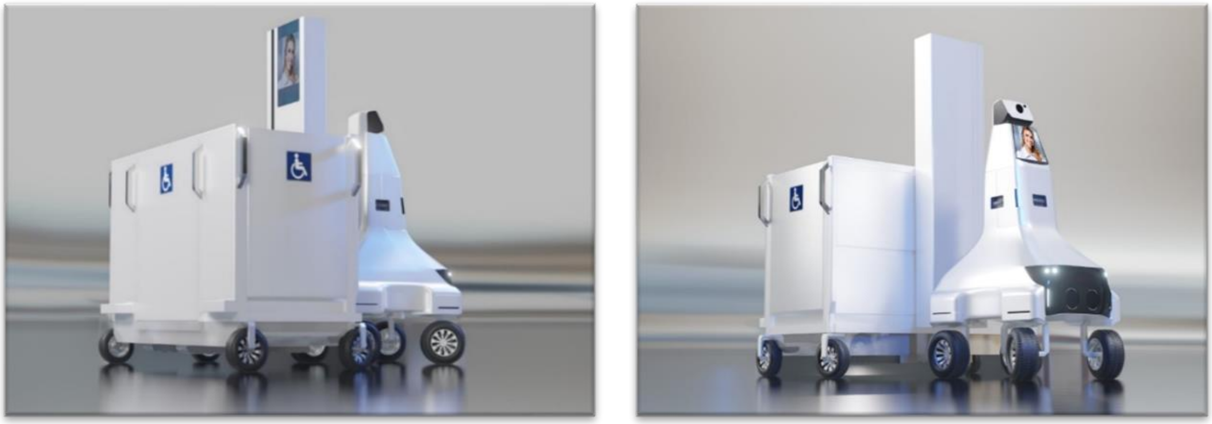

Figure 2 - 3D Conceptual design of the TrainMate system (base and wheelchair lift modules)

In other words, TrainMate can be defined as an autonomous, safe, practical, modular, efficient and cost-effective robotic system that delivers the independence and visibility that passengers with disability desire. The platform is also capable of providing side functionalities that are highly demanded by our transit agencies such as public announcement, security and surveillance, crime prevention, passenger escorting and facility inspection for timely repairs while in idle mode and not providing lift services. Such side services dramatically enhance the system's ROI and benefit the transit agency.

The base module is also capable of dynamically adapting to the demand by utilizing an intelligent architecture that pairs its robotic base module to several add-on side modules each specifically designed for a particular purpose. Sweeping and station cleansing, or snow plowing are a few of such ancillary add-ons that can further increase the ROI on the TrainMate system. Feasibility study and design of the side modules other than the wheelchair lift is not part of the current phase of this IDEA project.

According to the US Department of Transportation, Bureau of Statistics, of the nearly 2 million people with disabilities who never leave their homes, 560,000 never leave home because of transportation difficulties.[1] These difficulties can range from distance to public transportation, to lack of accessible features in stations or on transportation means and vary significantly between different modes of transportation.

Available data indicates that for two of the major northeast public transportation providers, the number of non-accessible train stations is more than 50% of the total train stations, most of which are street level train stations. This condition not only eliminates accessible, equitable transportation but also results in significant regulatory pressure and at times, hefty fines imposed by regulatory bodies on the public transit provider.

Figure 3 uses dimensions from the Rapid Assessment of Product Usability & Universal Design (RAPUUD) that is a simple tool for rapid assessment of product usability and universal design for equipment used by people with disabilities. The chart below (derived from surveys conducted among 23 passengers with physical disability) compares the TrainMate system with the other alternatives to assist passengers using mobility devices to board and deboard the train. The results clearly show that the TrainMate system outperforms the other methods in most to all of the dimensions thus providing lots of benefits to the passengers and the agencies.

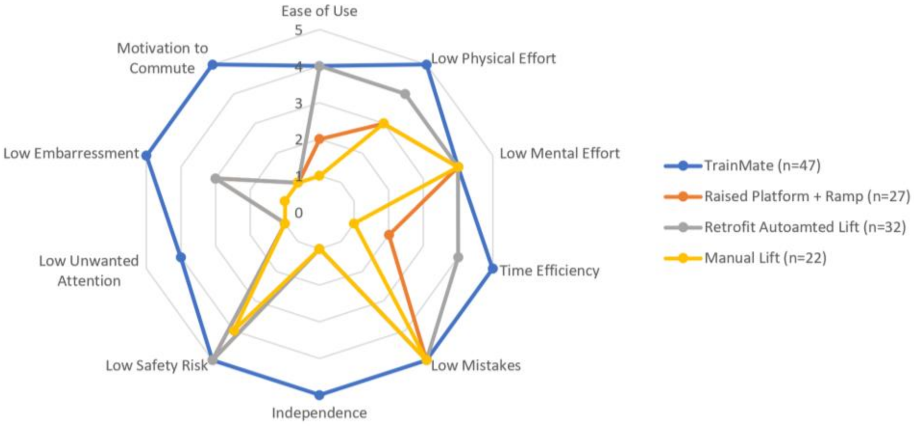

Figure 3 - Comparison of TrainMate with alternative solutions using a method derived from RAPUUD. (5=Best, 1= Worst, Dimensions are assigned to the best of our knowledge)

Dimension	Description
Ease of Use	Simplicity of the entire process inclusive of asking for help to boarding and deboarding the train

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[1] Https://www.bts.gov/archive/publications/special_reports_and_issue_briefs/issue_briefs/number_03/entire#:~:text=A%20new%20Bureau%20of%20Transportation,country%20never%20leave%20their%20homes.

Low Physical Effort	Amount of physical effort made by the passenger with disability
Low Mental Effort	Amount of effort to figure out and learn the process to use any of the methods
Time Efficiency	Time efficiency from the perspective of both passenger with disability as well as the agency
Low Mistakes	susceptibility to operational mistakes by the passenger with disability or agency's staff
Independence	Degree of independence and autonomy of the passenger with disability (level of dependence on others)
Low Safety Risk	Level of safety of the process for the passenger with disability
Low Unwanted Attention	Level of unwanted attention from other passengers
Low Embarrassment	Degree of embarrassment caused to the passenger with disability as a result of using any of the methods to board or deboard the train
Motivation to Commute	Level of motivation and encouragement from sophistication of the method that will result in the passenger with disability's use of public transportation.

Table 1 - Description of dimensions used to make figure 3.

As seen in table 1, the TrainMate robotic platform enables the transit organization to properly address its mission of providing accessible, equitable transportation for all while providing a suite of ancillary services that can encourage more passengers to use rail transit thus increasing ridership and passenger satisfaction. Services such as public announcement, station cleansing, snow plowing, public health monitoring and remote inspection can dramatically increase ROI for the transit agencies.

There are several ways that transit agencies can adopt the TrainMate system:

Robotics as a Service: Under this scenario that does not require any purchase of the equipment, the agency will only pay a monthly service charge (subscription fee) that will include the use of equipment, operation, and maintenance. Operation and maintenance can be transferred to the agency at the later stages of the adoption.

Purchase of Equipment: Under this scenario, the agency will acquire the TrainMate systems while the operation and maintenance of the systems can take place using trained agency staff or Infratek Solutions' team.

SAMPLE OPERATION SCENARIO

The following steps depict how our transit agency partner can benefit from a typical scenario of the autonomous operation of the system to lift a passenger on a wheelchair and assist with the boarding process at a street level train station.

1. TrainMate service can be called for, using many different options including but not limited to the following methods. It can be generally linked and called from any and all available means to purchase a ticket in addition to other accessible options.

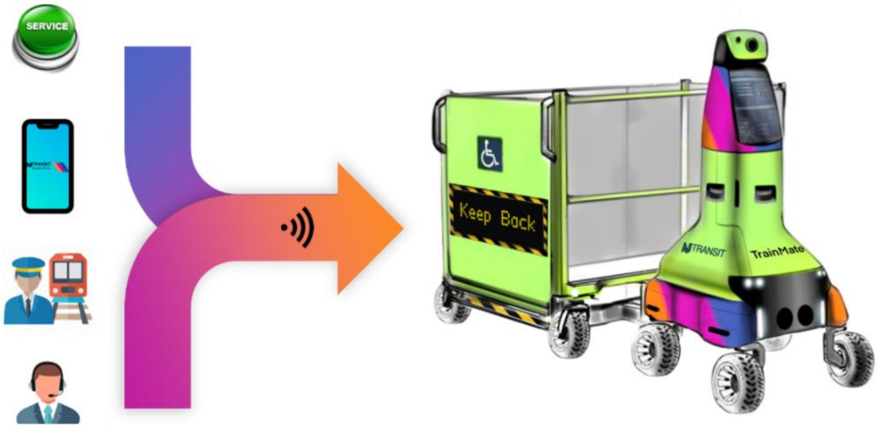


Figure 4 - Several modes of requesting service form TrainMate

2. Upon receiving the service call, TrainMate will station itself at the designated, marked area in the station to meet and greet the passenger some time prior to the train's arrival. The time is long enough to ensure safe and proper placement of the lift and the passenger using the mobility device within a safe distance in the vicinity of the railcar with accessible entrance.
3. Once the passenger confirms the service request at the meeting point, the TrainMate system requests the passenger to follow it towards its next station in the vicinity of the accessible rail car of the upcoming train (figure 5). Through integration with transit agency's TMAC system, TrainMate can approximate an optimized waiting location before train's arrival.
4. TrainMate navigates the station autonomously and reaches the waiting area before the train's arrival, while requesting the passenger to wait at the area behind the lift within a safety distance.
5. Once the train arrives and makes a full stop, TrainMate identifies the accessible door on the accessible railcar and conducts its final alignment with the entrance.
6. TrainMate then conducts the final safety checks for the lift operation, deploys the stabilizers, fully engages all the breaks, deploys the entrance ramp, and signals the passenger to board the lift. (Figure 7)
7. Once the passenger boards the lift, the entrance ramp is closed, passenger is notified, the lift moves up to the proper height to facilitate a safe deployment of the exit ramp. (Figure 8)

Figure 5 - Passenger following TrainMate to designated wait area

Figure 7 - Passenger waiting for indication from TrainMate

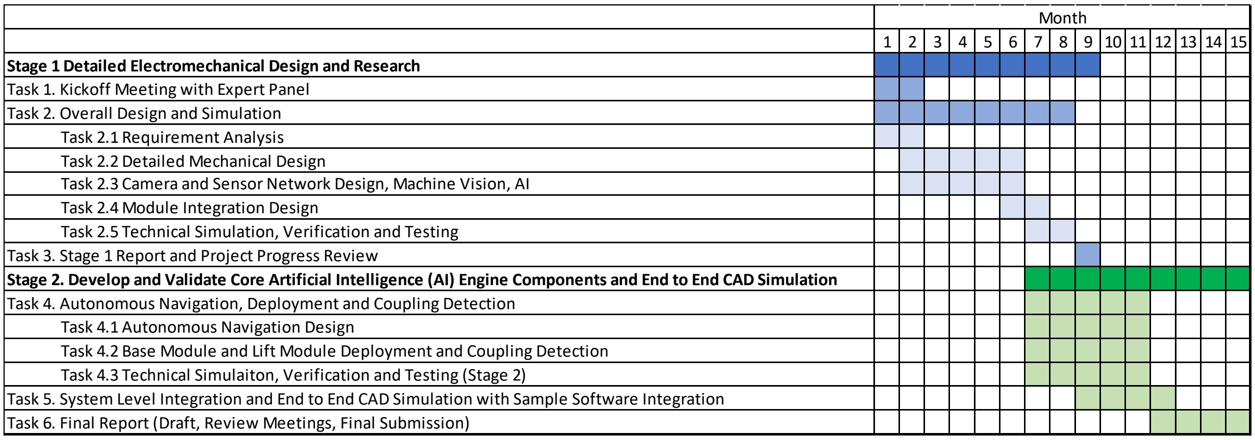
Figure 6 - Passenger boarding

8. The exit ramp is deployed, and proper audio and visual signals are given to the passenger to announce that it is safe to enter the train.
9. Once the passenger enters the train, the exit ramp is closed, lift moves down. Breaks and stabilizers are disengaged.
10. If there are other passengers, the same process takes place for all passengers from step 6.
11. TrainMate moves away from the train and navigates back to its docking (charging) station awaiting the next service request.

Figure 8 - Passenger boarding

INVESTIGATION

Our investigative approach includes several tasks integrated within three main stages to demonstrate technical and business feasibility of the TrainMate system. These three objectives in addition to their associated technical tasks, success metrics, and alternative strategies for each objective are explained below. Figure 9 provides the investigative approach stages and associated tasks.



	Month														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Stage 1 Detailed Electromechanical Design and Research	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦						
Task 1. Kickoff Meeting with Expert Panel	🟦	🟦													
Task 2. Overall Design and Simulation	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦							
Task 2.1 Requirement Analysis	🟦	🟦													
Task 2.2 Detailed Mechanical Design		🟦	🟦	🟦	🟦	🟦									
Task 2.3 Camera and Sensor Network Design, Machine Vision, AI		🟦	🟦	🟦	🟦	🟦									
Task 2.4 Module Integration Design						🟦	🟦								
Task 2.5 Technical Simulation, Verification and Testing							🟦	🟦							
Task 3. Stage 1 Report and Project Progress Review									🟦						
Stage 2. Develop and Validate Core Artificial Intelligence (AI) Engine Components and End to End CAD Simulation							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Task 4. Autonomous Navigation, Deployment and Coupling Detection							🟩	🟩	🟩	🟩	🟩				
Task 4.1 Autonomous Navigation Design							🟩	🟩	🟩	🟩	🟩				
Task 4.2 Base Module and Lift Module Deployment and Coupling Detection							🟩	🟩	🟩	🟩	🟩				
Task 4.3 Technical Simulaiton, Verification and Testing (Stage 2)							🟩	🟩	🟩	🟩	🟩				
Task 5. System Level Integration and End to End CAD Simulation with Sample Software Integration									🟩	🟩	🟩	🟩			
Task 6. Final Report (Draft, Review Meetings, Final Submission)												🟩	🟩	🟩	🟩

Figure 9 - Project Plan

STAGE 1. DETAILED ELECTROMECHANICAL DESIGN AND RESEARCH

Through a prior comprehensive literature review effort and a strong working relationship with our public transit partners, Infratek Solutions team gathered a collection of important, high-level business and technical requirements for the system. Our expert robotic engineers designed conceptual drawings and 3D models that have received good reception from the stakeholders and have given us a strong head start in advancing the project's stage one.

Requirements Analysis

One of the first and most important tasks in starting the project was conducting a comprehensive requirement analysis to understand the needs and expectations of all the stakeholders of the TrainMate system. Figure 2 shows how we dissected the research needs statement to create the building blocks of our comprehensive requirement analysis phase to lead the system's electromechanical design.

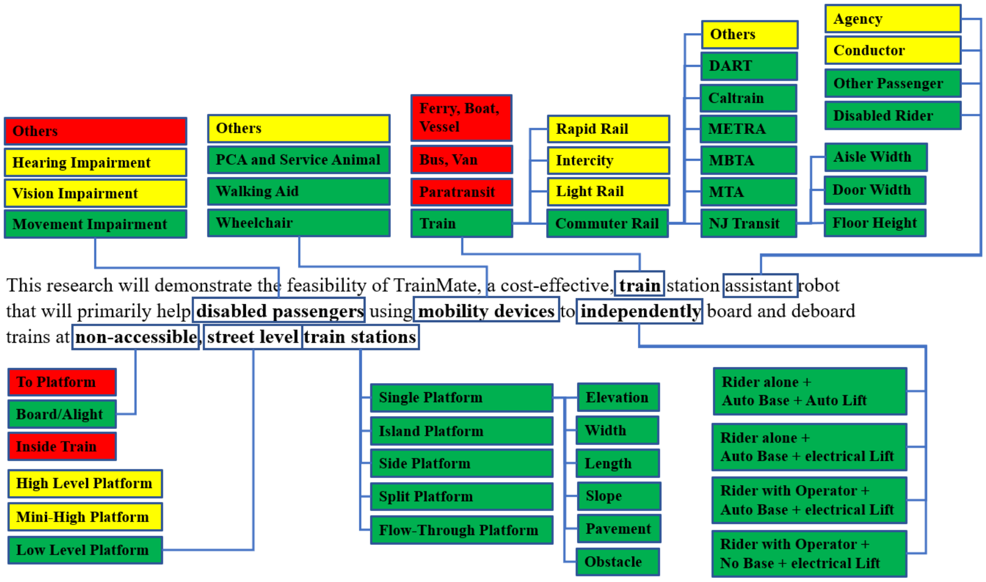


Figure 10- Requirement analysis break down

The following items are some of the several topics the team reviewed to develop the list of requirements:

- FTA standards and Federal Codes
    - Reviewed the following codes and translated them into functional requirements for the system: Title 49, Subtitle A, Part 27, Part 37, Part 38, and Part 39 Code of Federal Regulations. FTA C 4710.1 Circular, ADA 2010 Standards for Accessible Design and ASME 18.1 -2005 Safety Standard for Platform Lifts and Stairway Chairlifts as Supplement.
- Types of disability
    - Reviewed the definitions and types of disability defined by the Americans with Disabilities Act (ADA) and transit agencies such as NJ Transit to clarify the types of disabilities the TrainMate system can serve.
- Existing accessibility and common practices
    - Conducted online research to understand the current practices and existing accessibility methods of transit agencies such as NJ Transit, Amtrak, and SEPTA to provide accessible service to their passengers. Disabled passengers' feedback and experiences were reviewed online to learn the general workflow, difficulties, and challenges they face to board or alight trains. The existing lift systems available on the market were also studied and key features, pros, and cons of each were recorded.
- Types of existing mobility devices
    - Researched online to become familiarized with common wheelchairs, including both manual and motorized, and other mobility devices, including walker, cane, crutch, brace,

as well as personal care attendants and service animals to ensure we have fully understood the types of mobility devices the TrainMate system shall accommodate.

- Train stations and railcars
    - Researched online to understand the types of rail services, including rapid rail, light rail, commuter rail, and intercity rail. Searched for the most common and standard dimensions of train doors (width, height, floor height, etc.)
    - Conducted research online and read through Train Station Platform Design Guide from major commuter rail service providers such as NJ Transit, METRA, MBTA, and Caltrain to understand the conditions of train stations as it pertains to station types, station dimension, platform dimension, including platform height, etc. so that the project team has a clear understanding of the working environment of the TrainMate System. Also visited more than 12 street-level train stations in New Jersey to check platform size, ground condition, common obstacles, and the general station design.
- Defined detailed technical stories resulting from the business requirements
    - Conducted detailed analysis of Part 38 Subpart E 38.95 Mobility Aid Accessibility for TrainMate technical requirements. Gathered all requirements into a 20-pagefile and added Infratek-defined requirements as well.

01. Passengers with Disability

From the viewpoint of the passengers with disabilities, an ideal solution to bridge the gap in the travel chain shall -at least- provide the following:

- Promote independence, autonomy, and control.
- Provide assurance and awareness about the availability of the service ahead of time with confidence.
- Preserve passengers' dignity and instigate a sense of self-sufficiency.
- Increase safety, practicality and comfort.
- Cause encouragement and motivation to use public transportation.

02. Other Passengers

From the viewpoint of the other passengers (passengers without disability) the lift shall have the following characteristics:

- Have minimal burden on the other passengers (e.g., not cause long delays or service disruption).
- Be pleasant, practical and safe (e.g., not an eye-sore or dysfunctional).

03. Transit Agency

From the viewpoint of the transit agency which is responsible for ensuring fair, accessible, and equitable transportation to all, an ideal wheelchair lift solution shall at least provide the following:

- Provide efficiency and speed of service.
- Be safe for disabled passengers and other riders.
- Cause no delay to NJ Transit's train schedule or burden on the traveling public.
- Be cost-effective and easily maintainable.
- Cause minimal to no change to the infrastructure.
- Leave positive effects on agency's public image.

Module Break Down and Design

Once the first version of the requirements analysis document was finalized, we defined different modules of the TrainMate Robotic System as a modular design prompts simpler upgrades and scalability of the system. We completed the detailed mechanical design for all crucial components of the lift, coupler, and base module with the following outcomes:

- **Lift Module**
  - Conducted cost-benefit analysis (modifying an existing lift vs. building our own from scratch). Decided to build our own lift mechanism from scratch and custom tailor it to the needs of the TrainMate Robotic System need, being safe, smart, precise, cost efficient, reliable, automated, and mobile. This would also give us independence in case we would like to make changes in the future.
  - Researched and compared existing lifts in the marketplace. Reached out to different vendors and used their insights to calculate, compare, and select the components.
  - Designed the lift mechanism.
    - Conducted comparison between different lift mechanisms from electrical cylinder to wire drum, leads screw, rack and pinion, and scissor Jack. Decided to use lead screw mechanism because of its small footprint, good lift height, self-locking capability, manual-operation capability, design simplicity and reliability as well as cost efficiency.
    - Calculated and ensured the design meets speed, load, size, weight, power, ADA factor of safety, self-locking capability, manual-operation capability, and braking requirements. Cooperated with part manufacturers for part selection. Checked component availability, pricing, and compatibility.
    - Final selection is to use the Nook Industrial PowerAC 1 1/2"-4 LS w/Bronze Nut as the lead screw shaft, a GAM V-090-6:1-K0-3000 gearbox, a GAM 1:1 right angle gearbox, and the Kollmorgen AKM2G-32 PL 48VDC servo brushless DC motor.
  - Designed the frame, body, and cover.
    - Designed the lift module frame, track, lift car and body cover.

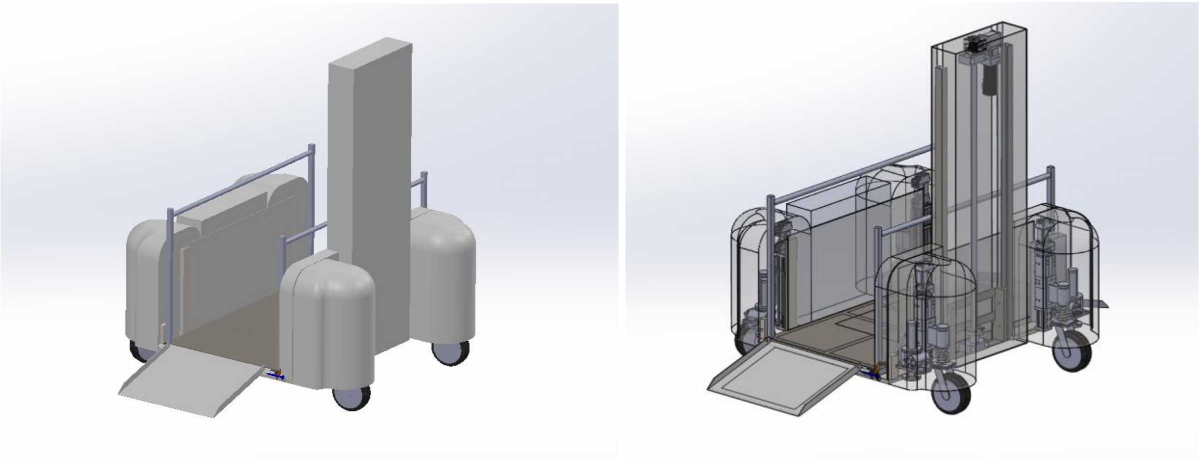


Figure 11 - Lift Module cover design (Left); Lift Module design with internal components

    - Conducted comprehensive simulation of the lift track by running stress simulation in the CAD software (SolidWorks) to study their performance under load, assess Factor of Safety (FOS) requirements, and optimized their dimension, geometry, and material selection.

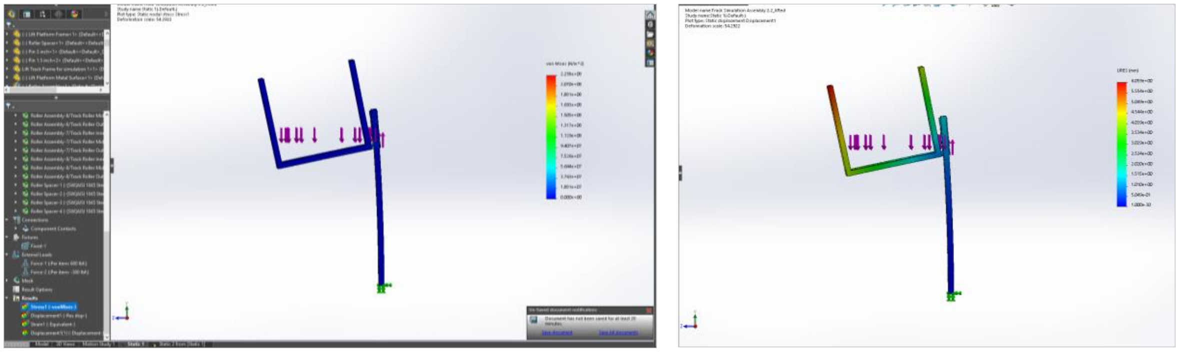


Figure 12- Simulation Scenario - Lift car, rolling bearing, and track under 600lbs. of load; Von Mises Stress to test parts' integrity and strength (Left); Displacement to check lift car's deflection under load (Right)

- Designed the modular suspended caster with lift/deploy mechanism
    - Researched and compared different suspension and wheel designs for the robotic platform. Studied the caster size and tire material.
    - Compared and designed caster lift/deploy mechanism. Selected parts. Designed and created 3D models accordingly.
- Designed the modular lift stabilizer
    - Conducted conceptual design for the lift stabilizer, which is an optional add-on feature for the TrainMate Robotic System for certain train stations with rougher or sloped grounds. Calculated the stabilizer requirements and conducted initial component selection.
- Designed and modeled the automated ramp system
    - Designed the ramp so that it can be opened/closed automatically and slide sideways automatically to align itself with the railcar's accessible door.

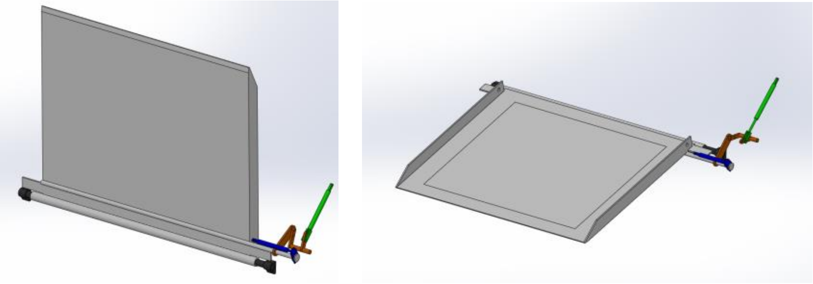


Figure 13-Automated ramp, closed position (Left); Opened position (Right)

    - Conducted simulation of the ramp by running stress simulation for designed parts in SolidWorks to study their performance under load, assess Factor of Safety (FOS) requirements and optimize their dimension, geometry, and material selection.

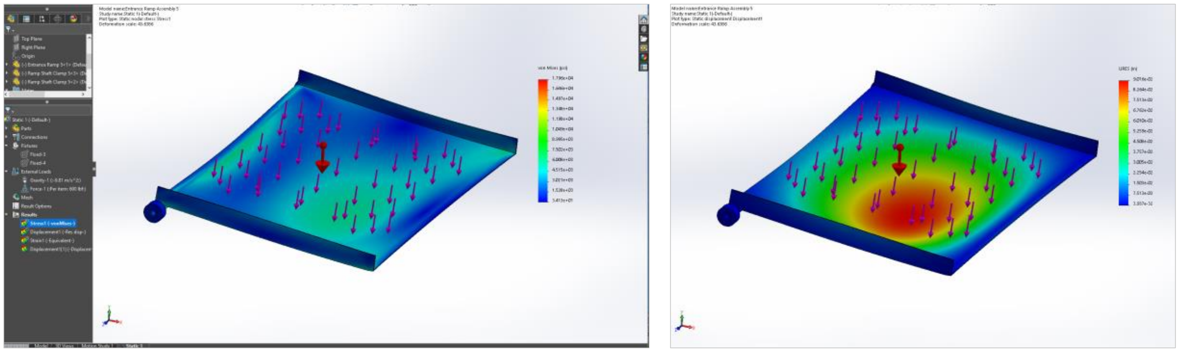


Figure 14 - Simulation Scenario - Entrance Ramp under 600 lbs. of load; Von Mises Stress to check shaft diameter and material selection (Left); Displacement to optimize ramp thickness (Right)

- **Coupler module design**
    - Conducted coupler requirement analysis.
        - Ensured the coupling between the base module and sub-modules is flexible but at the same time secured and rigid under different operational conditions including omnidirectional movement, turning, spinning, going on/off inclined surfaces, and going over bumpy or rough roads.

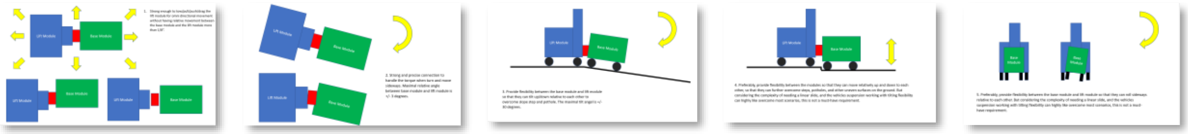


Figure 15 - Coupler requirement analysis document

    - Designed and created 3D models accordingly and ran static analysis in the simulation engine and optimized the design according to the simulation results.
        - Ran static analysis to study the design's performance under all diverse kinds of load that will occur in the conditions mentioned above.
        - Checked the design's weak spots and redundancies in the simulation. Optimized the design accordingly.
- **Base module design**
    - Investigated and studied existing outdoor omni-directional mobile robotic platforms.
        - Searched online and reached out to vendors looking for potential robotic rover platforms that can be adapted to the needs of the TrainMate System. No suitable robotic platforms were found.
    - Studied and compared unique designs and configurations for modular robotic driving and steering wheel as well as the drivetrain.
        - Searched and compared different robotic platforms such as NASA's modular robotic vehicle, ClearPath Robotics, Adept Robotics, and different agricultural robots.
    - Studied the base module drivetrain requirements and conducted calculation, detailed CAD design, and component selection for motors and gearboxes.
        - Conducted detailed requirement analysis for the base module drivetrain.
        - Calculated linear and angular velocity and acceleration requirements under different scenarios.

        - Calculated output force, speed, and power requirements for the drivetrain components and logged them all in a report.

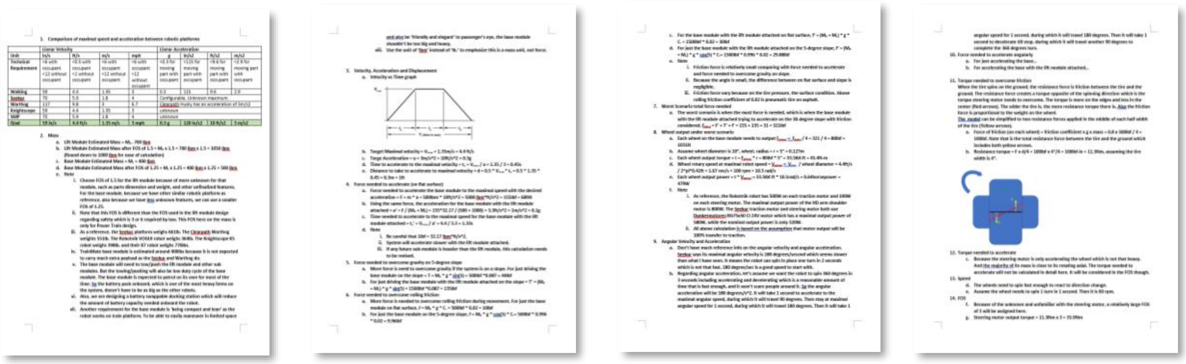


Figure 16 - Drivetrain Calculation Report screenshots.

    - Modular Drive/Steer Wheels
        - Defined the requirements for the Modular Drive/Steer Wheels.
        - Searched and studied hub motors also known as in-wheel motors, drive-integrated motors, hub gearing and steering gearing solutions.
        - Reached out to vendors and compared various products.
        - Found out that a custom designed modular wheel is needed for the TrainMate Robotic System to meet the intended requirements.
        - Collaborated with gearbox manufacturer GAM Enterprises, to custom designed steering gearbox for the base module modular drive/steer wheels to minimize footprint and cost and maximize parts’ strength and efficiency,
        - Searched, studied, and compared different configurations and types of suspension systems from different existing robotic platforms, such as NASA Modular Robotic Vehicle, Hyundai robotic vehicle, Adept Robotics, and some agricultural robots. Conducted requirement analysis. Compared linear suspension design vs. rotary suspension design. Designed the modular drive/steer wheel suspension.

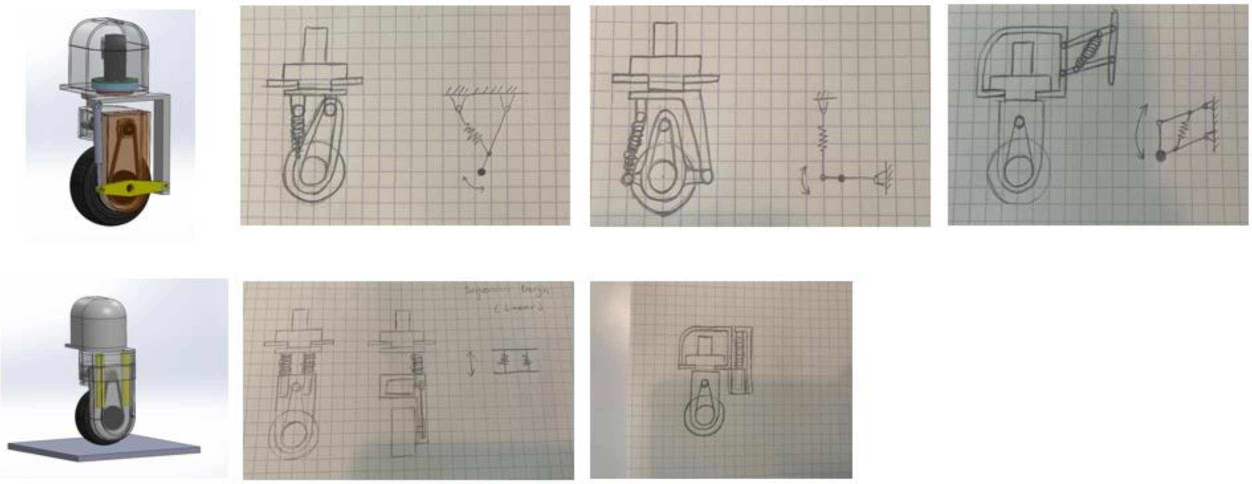


Figure 17 - Sketch and 3D model of linear suspension design vs rotary suspension design

        - Designed and created 3D models for the modular drive/steering wheels for the base module.

    - Designed and modeled base module frame and cover
        - Completed the overall design of the body and inside frame for the base module based on the technical requirements.
        - Compared and requested quotations for different prototyping and manufacturing methods from several vendors. Improved design manufacturability based on the feedback received.

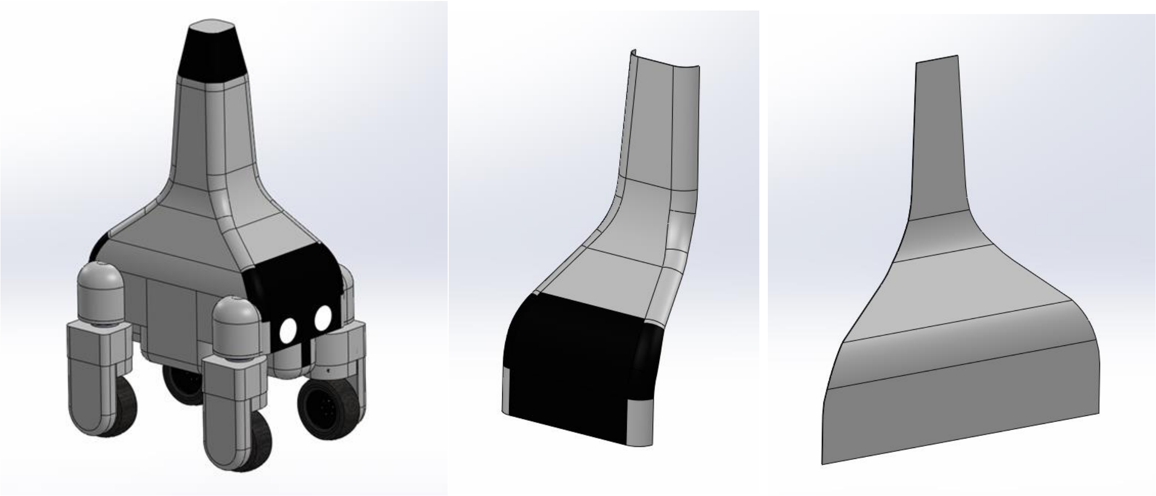


Figure 18 - Break down of Base Module cover design for manufacturability

    - Battery System
        - Studied and compared several types of batteries, including lead-acid, lithium, nickel-metal hydride, and nickel-cadmium. Then further conducted an in-depth comparison between Lithium-ion batteries, Lithium iron phosphate batteries, and lithium polymer batteries.
        - Defined the battery system requirements. Calculated, sized, and selected the battery. The final decision is to use a 100Ah LiFe battery system.
- Studied and added hearing and vision disabilities and impairment-related features
    - Studied and gathered requirements for hearing and speech impairment-related features and functions. Devised detailed scenarios and designed components accordingly.
    - Studied and gathered requirements for vision impairment-related features and functions. Devised detailed scenarios and components accordingly.
    - Reached out to the National Federation of the Blind and Hearing Loss Association of America for meetings geared towards further brainstorming and discussions.

Sensing Network and Artificial Intelligence

Under this group of activities, the team completed the research, design, and development for the cameras and sensor network; began the work on machine vision and AI with the following achievements:

- Designed the robotic control architecture and selected the controller
    - Researched and studied the robotic control architecture and logic for the mobile robot regarding the main control unit (MCU), microcontroller, motor controller, safety

    controller, framework, programming language, robotic operating system (ROS), and other operating systems.
  - Studied and compared different existing robotic platforms' control systems as reference.
  - Searched, compared, and selected control components.
  - Studied related safety regulation and industrial standards such as ISO 3691-4, ISO 13482, ISO 10218, IEC 61508, ANSI/RIA R15.08, and UL 3100 .
  - Studied communication protocols and wireless communication methods between different modules.
- Conducted sensing requirement analysis, comparison, and selection
  - Conducted deeper study and comparison for several types of sensors and their performance under different weather and radio traffic conditions.
  - Revised and improved the detailed sensing requirements.
  - Listed all sensing scenarios with detailed description.
  - Searched, studied, compared, and selected perception sensors such as depth camera, 3D LiDAR and 360-degree cameras.
  - Searched, studied, compared, and selected safety sensors such as 2D laser scanner, ultrasonic sensor, inclinometer, limit switch and other proximity and physical sensors.
- Finalized sensor mounting location and quantity for 2D Laser Scanners, ultrasonic sensors, depth cameras and 3D LiDARs.
- Machine vision and AI
  - Started to research the built-in object detection, human detection, face detection, pedestrian detection, object detection and text detection functions from depth cameras.
  - Started to research the built-in object detection and navigation functions using the 3D LiDAR sensor.

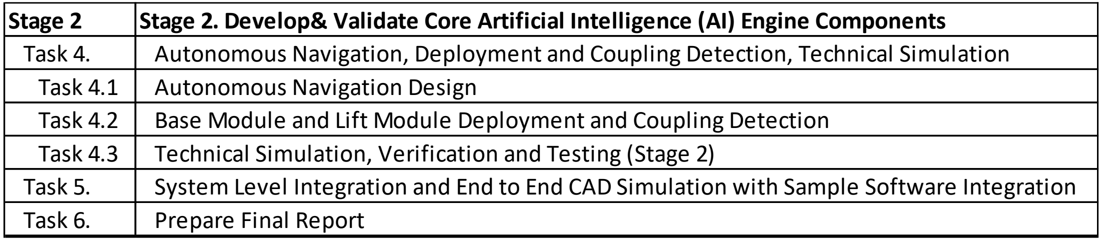
Integration Design and Technical Simulations

During this part of the work, the project team conducted the integration design of the different modules to ensure different components can work together in concert as one integrated system.

- Designed and integrated all the modular components inclusive of base module, lift module and coupler module in SolidWorks. Optimized and made modifications to the final design.
- Ran technical simulations conducting detailed comparison, calculation and operability tests of the entire system using SolidWorks (CAD software).
- Tested and successfully verified that the design of the TrainMate Robotic System is feasible, and the software prototypes and blueprints can be used to build the real-life prototype model.
- Made the following modifications as a result of the integration design and technical simulations:
  - Revised and summarized TrainMate Robotic System component weight calculations.
  - Revised the TrainMate Robotic System component power consumption.
  - Revised TrainMate Robotic factor of safety.

STAGE 2. DEVELOP AND VALIDATE CORE ARTIFICIAL INTELLIGENCE (AI) ENGINE COMPONENTS

This stage of the research focused on development and validation of several key algorithms (e.g., autonomous navigation, machine vision and robotic control system) which are mostly Artificial Intelligence driven. Through our past robotic projects which all involved autonomous navigation of robotic rovers or autonomous vehicles on roadways and public domains, we have already developed an extensive library of software procedures and hardware sensor fusion algorithms that were assessed and investigated for their capabilities and applicability to this research.



Stage 2	**Stage 2. Develop& Validate Core Artificial Intelligence (AI) Engine Components**
Task 4.	Autonomous Navigation, Deployment and Coupling Detection, Technical Simulation
Task 4.1	Autonomous Navigation Design
Task 4.2	Base Module and Lift Module Deployment and Coupling Detection
Task 4.3	Technical Simulation, Verification and Testing (Stage 2)
Task 5.	System Level Integration and End to End CAD Simulation with Sample Software Integration
Task 6.	Prepare Final Report

Figure 19 - Stage 2 Project Plan

Autonomous Navigation, Deployment and Coupling Detection

Autonomous Navigation Design

Autonomous navigation of a robotic rover in a train station setting is a complex task that requires sophisticated technologies and advanced algorithms. For the purpose of this research and assess the feasibility of the available technologies we assessed two broadly used technologies:

1. One such technology that can be leveraged for this task is machine learning. Machine learning is a branch of artificial intelligence that enables machines to learn from data and improve their performance over time.
2. Another one of such technologies that can be leveraged for this task is path planning. Path planning is the process of finding a path from a starting point to a destination while avoiding obstacles in the environment.

Machine Learning Technics for Autonomous Navigation of TrainMate

In this section, we will discuss how machine learning can be used for autonomous navigation of the TrainMate system in a train station setting.

The first step in using machine learning for autonomous navigation is to collect data. The data can be collected using sensors such as cameras, LiDAR, and GPS where clear view of the sky is available. The sensors collect information about the environment, such as the location of the rover (in this case the TrainMate base module), the position of obstacles, and the features of the environment. The data is then used to train the machine learning model.

The machine learning model is designed to recognize patterns in the data and use them to make decisions about how to navigate the environment. For example, the model might learn to recognize the location of obstacles and use that information to avoid them. The model might also learn to recognize the features of the environment, such as the location of doors, benches, tracks and ticket machines, and use that information to navigate to a particular destination which could be in a safe zone in the vicinity of tracks or back to the TrainMate’s storage and charging area.

Once the model has been trained, it can be integrated into the TrainMate base module. The robot can use the model to make decisions about how to navigate the environment. For example, it might use the model to decide which direction to turn when it encounters a walking passenger, or to determine the most efficient path to a particular destination.

One important aspect of using machine learning for autonomous navigation is ensuring that the model is accurate and reliable. The model should be tested extensively in a variety of environments to ensure that it can perform reliably in all conditions. The model should also be updated regularly to account for changes in the environment, such as the movement of obstacles or the addition of new features.

Another important consideration is safety, especially in our setting which deals with general public and passengers with disabilities. The robot should be equipped with safety features such as emergency stop buttons and collision avoidance systems. The machine learning model should also be designed to prioritize safety, ensuring that the robot always makes decisions that are safe for the passenger with disability and other users of the train station.

To minimize any safety risk to the passenger with disability during the navigation phase, the TrainMate system will not carry the passengers while in movement and only facilitates a pass-through movement for the passengers while securely stationed adjacent to the railcar to facilitate the life procedure.

In conclusion, machine learning can be a powerful tool for autonomous navigation of the TrainMate system in a train station setting. By collecting data, training a machine learning model, and integrating it into the rover, it is possible to create a system that can navigate the environment autonomously. However, it is important to ensure that the model is accurate and reliable, and that safety is prioritized at all times. With these considerations in mind, machine learning can be a valuable tool for improving the accessibility and efficiency of the robot in train station environments.

Path Planning Technics for Autonomous Navigation of TrainMate

In the following section, we will discuss how path planning algorithms can be used for autonomous navigation of the TrainMate robotic system (rover) in a train station setting.

The first step in using path planning algorithms is to collect data about the environment. Similar to machine learning algorithms, this can be done using sensors such as cameras, LiDAR, ultrasonic proximity sensors and GPS. The sensors collect information about the location of the robot, the position of obstacles, and the features of the environment. This data is then used to create a map of the environment.

Once the map has been created, a path planning algorithm can be used to find a path from the starting point to the destination. The algorithm takes into account the location of obstacles and the features of the environment to find the most efficient and safe path. There are several path planning algorithms that can be used for this task, including A* search, Dijkstra's algorithm, and RRT (Rapidly-Exploring Random Trees).

Once a path has been found, the robotic rover can use it to navigate the environment. The robot can use sensors to detect obstacles and adjust its path as necessary to avoid them. It can also use the map of the environment to navigate to specific locations, such as ticket machines, boarding platforms, tracks or TrainMate storage area.

Similar to machine learning algorithms, one of the most important considerations when using path planning algorithms is safety. The rover should be equipped with safety features such as emergency stop buttons and collision avoidance systems.

Another important consideration is efficiency. The path planning algorithm should be designed to find the most efficient path, minimizing the time and energy required for the robot to navigate the environment. This can help reduce travel time in the train station and improve the overall efficiency of the system.

In conclusion, path planning algorithms can be a powerful tool for autonomous navigation of the TrainMate system in a train station setting. By collecting data about the environment, using a path planning algorithm to find a path, and integrating it into the robotic platform, it is possible to create a system that can navigate the environment autonomously. However, it is important to ensure that safety is prioritized at all times, and that the algorithm is designed to be efficient and effective. With these considerations in mind, path planning algorithms can be a valuable tool for improving the accessibility and the system's efficiency to operate in train station environments.

For the purpose of this research, we studied the most popular path planning algorithms and assessed their strengths and shortcomings to be applied to our use case, these algorithms are:

1. A* search,
2. Dijkstra's algorithm
3. RRT (Rapidly-Exploring Random Trees)

These algorithms are three of the most popular path planning algorithms that are often used for autonomous navigation of robotic rovers in various environments. Each algorithm has its own strengths and shortcomings, and the choice of algorithm depends on the specific application and the requirements of the environment.

A* Search

A* search is a heuristic search algorithm that is commonly used for finding the shortest path between two points in a graph. A* search combines the advantages of Dijkstra's algorithm and a heuristic function that estimates the distance between a given node and the goal node. The algorithm uses a priority queue to explore the graph, starting from the initial node and expanding the nodes with the lowest $f(n)$ value, where $f(n) = g(n) + h(n)$ is the sum of the cost of reaching a node and the heuristic estimate of the remaining cost to reach the goal. A* search is guaranteed to find the shortest path if the heuristic function is admissible and consistent.

The strengths of A* search include its ability to find the optimal path, its efficiency in finding a path in large graphs, and its ability to handle multiple goals. However, A* search can be sensitive to the quality of the heuristic function, and if the heuristic function is not admissible or consistent, A* search may not find the optimal path. Such shortcomings make this algorithm a less desirable choice for our requirements as finding the optimal path in the train station is critical to ensure system useability, efficiency and also energy use of TrainMate.

Dijkstra's Algorithm

Dijkstra's algorithm is a classic algorithm for finding the shortest path between two points in a graph. Dijkstra's algorithm works by maintaining a set of visited nodes and a set of unvisited nodes, starting from the initial node and visiting each unvisited node in the graph until the goal node is reached. The algorithm calculates the distance of each node from the initial node, and the algorithm selects the unvisited node with the shortest distance as the next node to visit.

The strengths of Dijkstra's algorithm include its ability to find the optimal path and its simplicity in implementation. However, Dijkstra's algorithm can be slow in finding a path in large graphs, and it is not efficient in handling multiple goals thus would not qualify to be used for our purpose.

RRT (Rapidly Exploring Random Trees)

RRT (Rapidly Exploring Random Trees) is a probabilistic algorithm that is commonly used for motion planning in robotics. RRT works by building a tree of random points in the environment, connecting them to their nearest neighbor, and expanding the tree in the direction of the goal (e.g. tracks or TrainMate storage area). RRT is designed to quickly explore the environment and find feasible paths, but it does not guarantee optimality.

The strengths of RRT include its ability to handle dynamic and complex environments, its speed in finding feasible paths, and its ability to handle nonholonomic constraints. However, RRT is not guaranteed to find the optimal path, and it may require a large number of iterations to find a feasible path in some environments.

As discussed above, A* search, Dijkstra's algorithm, and RRT are three popular path planning algorithms that each have their own strengths and shortcomings. A* search is good for finding the optimal path, Dijkstra's algorithm is simple and reliable, and RRT is fast and can handle dynamic environments that is why the team chose a simple implementation and simulation of the RRT to assess its feasibility to be used on the TrainMate system which is explained in detail in the next sections. It is worth noting that using machine learning algorithms can also be promising however the task of collecting data and training such algorithms can deem costly and time consuming but definitely an item to be studied and assessed in future research endeavors. The team has also identified valuable research and prior art such as “Socially Aware Motion Planning with Deep Reinforcement Learning” developed by students at Cornell University that can be utilized as reference and a framework to build the machine learning model. A sample of this implementation can be seen at https://www.youtube.com/watch?v=CK1szio7PyA

Image Processing and Recognition

Another one of the uses of Artificial Intelligence and Machine Learning technics in this project is dynamic and real-time image recognition so that the TrainMate robot can fully understand the environment around it, classify and recognize objects and make and execute proper decisions as they pertain to the nature of each object. As evident through literature review, there are well-established image recognition models available that produce reliable results and have been heavily utilized in public environments similar to ours. To ensure the applicability of such algorithms to our use case, the project team used a simple Python code that utilizes a pre-trained MobileNet2 model and defined the classes that the model shall find, in the case of our test, blue ADA handicap signs on the surface of a railcar. The model then reports back the (x,y) coordinate of the sign’s location in the image.

In the test, the team conducted for this work, the model was successful in accurately locating the ADA handicap sign in all of the images that were fed into the algorithm. This was an expected outcome as real-time image recognition algorithms have grown very strong in capability, accuracy, speed and efficiency.

Figure 20 - Sample of images used for image recognition

Base Module and Lift Module Deployment and Coupling Detection

Another one of the topics that the team focused on reliable and simple solutions to determine the deployment and coupling status between the base module and the lift module and zeroed in on using customary limit switches that we have used on other robotic rover projects as well.

A limit switch is a type of sensor that is commonly used in industrial automation and robotics applications. It is a simple switch that is activated when a mechanical object comes into contact with its actuator. The switch can be normally open or normally closed, and its state changes when the actuator is moved, allowing it to sense the position or movement of the object.

In the case of our robotic system, a limit switch can be used to detect the coupling of two parts of the robot. For example, let's consider the lift module that has the coupler for attaching to the base module. The lift’s frame is attached to the base module with a coupling mechanism that allows it to be pulled, pushed and overall moved around in the station environment. To ensure that the two components (the base and lift modules) are coupled together, a limit switch can be placed in a position where it will be triggered when the gripper is fully closed.

The limit switch is connected to the control system of the robot, which can use the signal from the switch to confirm that the modules are properly coupled. When the coupling is complete, the designated part of the lift frame will come into contact with the actuator of the limit switch, causing it to close the circuit and send a signal to the control system. The control system can then use this signal to confirm that the modules are properly coupled and ready to be used.

If the limit switch does not detect the coupling, the control system can take appropriate actions to ensure that the lift module is properly coupled before the robot continues its operation. For example, the robot can be programmed to stop and display an error message, or it can be programmed to attempt to recouple the lift module by repeating the coupling motion until the limit switch is triggered. The team has also investigated the use of multiple limit switches to create a reliable system with sufficient redundancies in place.

SIMULATIONS

In this phase, which is considered the last part of this investigation, the project team conducted a few standalone and end to end software simulations to study the workability of the TrainMate system at its entirety and determine strengths, weak links and opportunities for improvements when it comes to building of a real-life working prototype.

TECHNICAL SIMULATION, VERIFICATION AND TESTING

The technical simulation focused on further simulating real-life scenarios on the designed TrainMate platform using the CAD software, exposing the designed components to live loads and studying of the most important components in the simulated software environment. The following examples are a highlight of such simulations that took place during this phase of the work:

Lift Module Simulation

This following task focused on technical simulating of the lift module and resulted in a more cost effective, lighted and thinner frame that can still meet and exceed the lift modules performance, capacity and safety requirements.

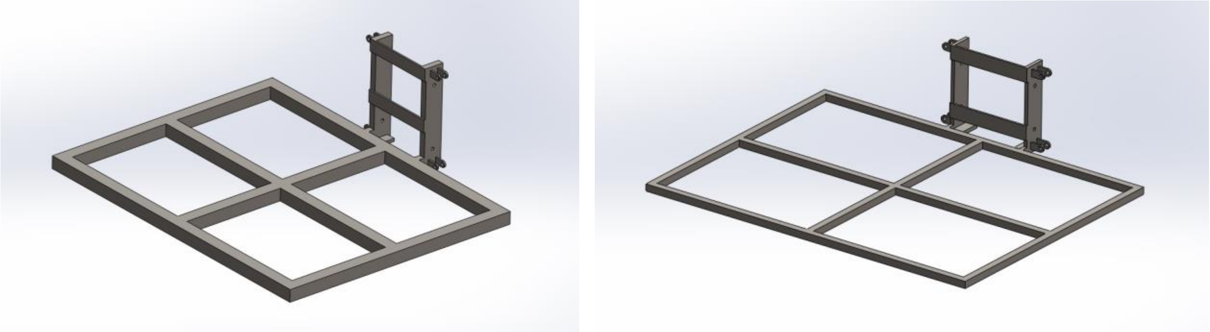
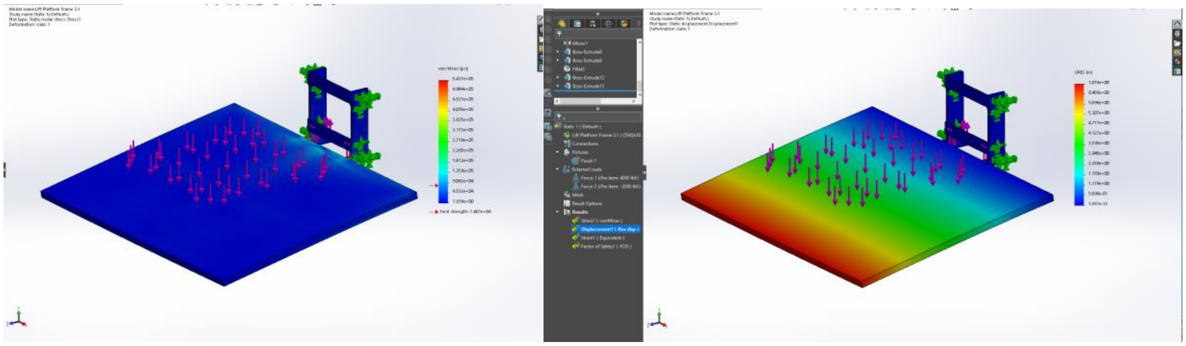


Figure 21 - Frame design

The following results show that the design with thinner frame is not actually performing well thus we increase the thickness of the frame until the simulations show more promising results as seen in the further section of the following results.



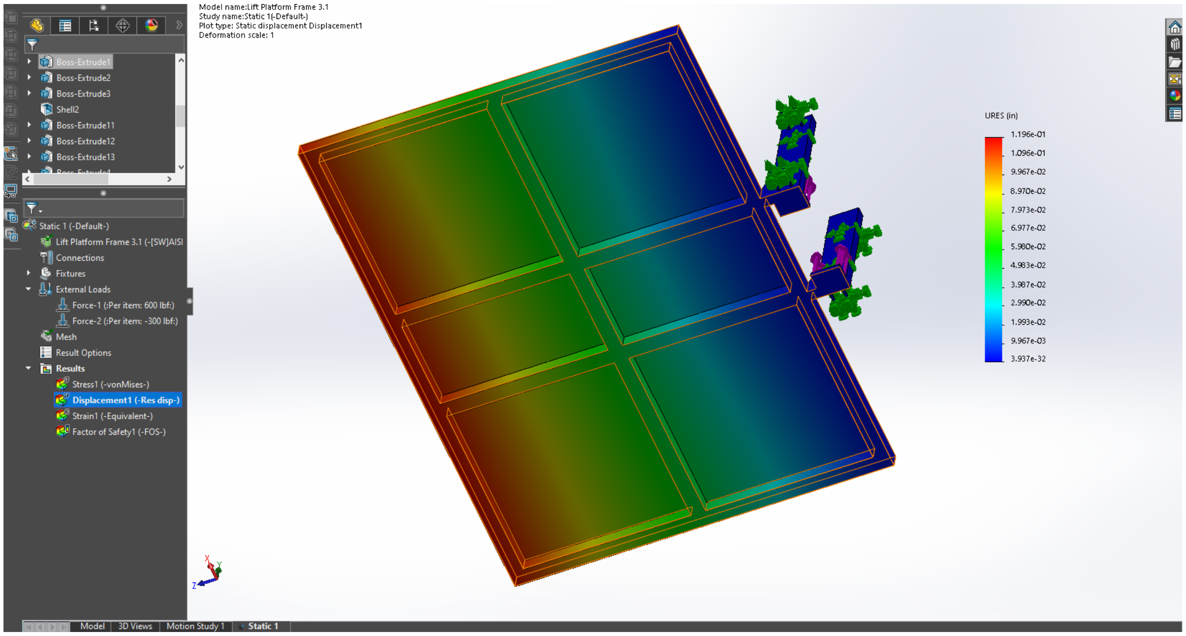

Model name:Lift Platform Frame 3.1
Study name:Static 1(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 1

Figure 22 - Wheelchair lift module simulations

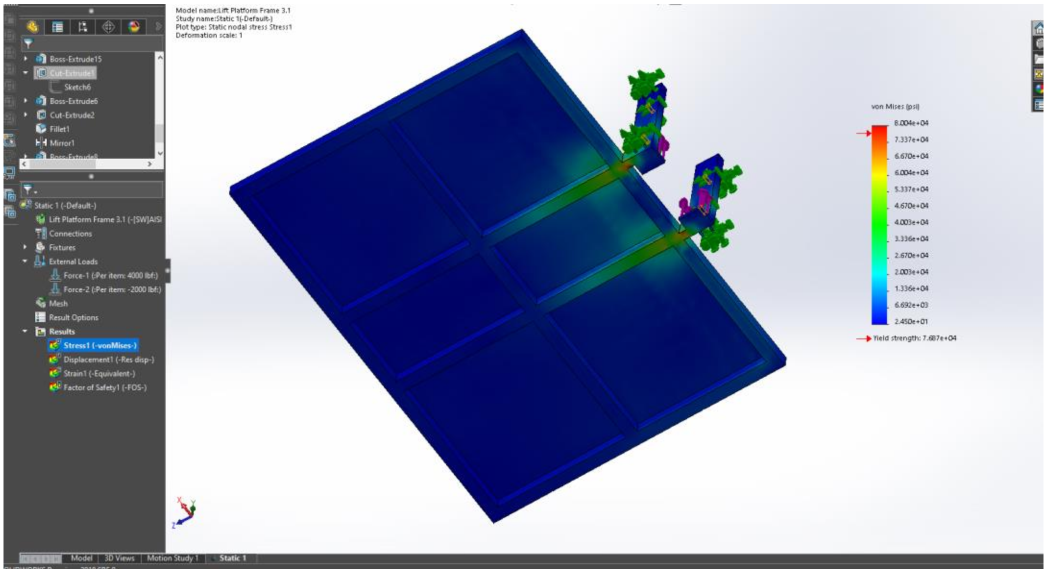

Model name:Lift Platform Frame 3.1
Study name:Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1

Figure 23 - Results under 4000lbf of load

Ramp Module Simulation

Another example that is noteworthy is the simulation of the wheelchair ramp using the Von Mises model. The theory states that a ductile material starts to yield at a location where the von Mises stress becomes equal to the stress limit. In most cases, the yield strength is used as the stress limit. However, the CAD software allows us to use the ultimate tensile or set our own stress limits as seen in the following simulations:

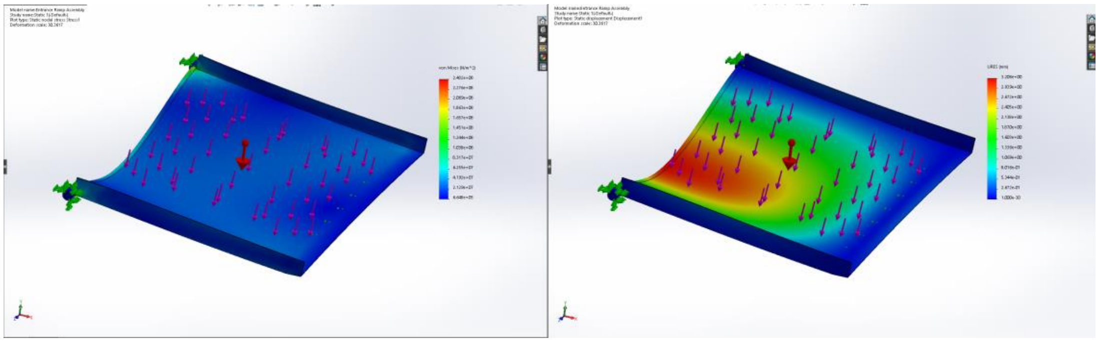


Figure 24 – Results under 600 lbs. of load

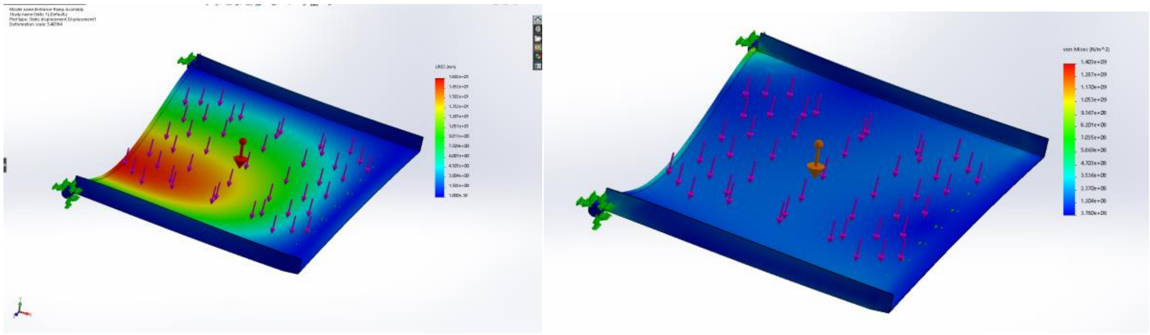


Figure 25 – Results under 3600 lbs. of load

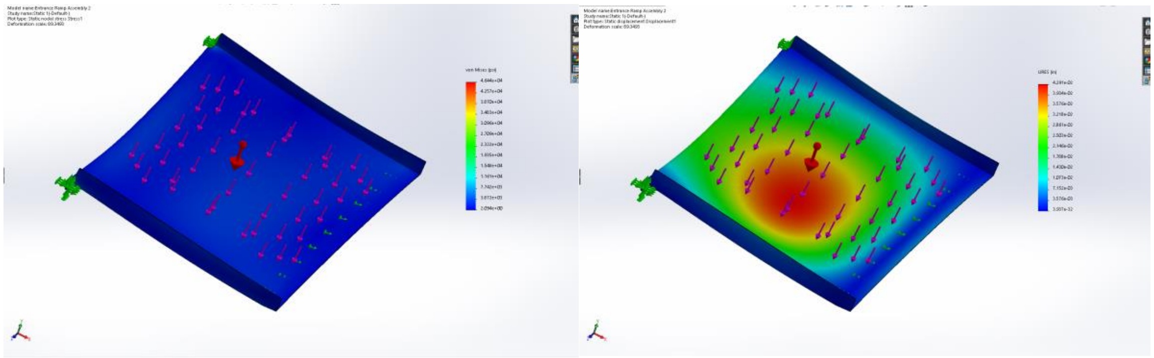


Figure 26 - 2nd design, 0.25” thick plate, results under 600 lbs. of load

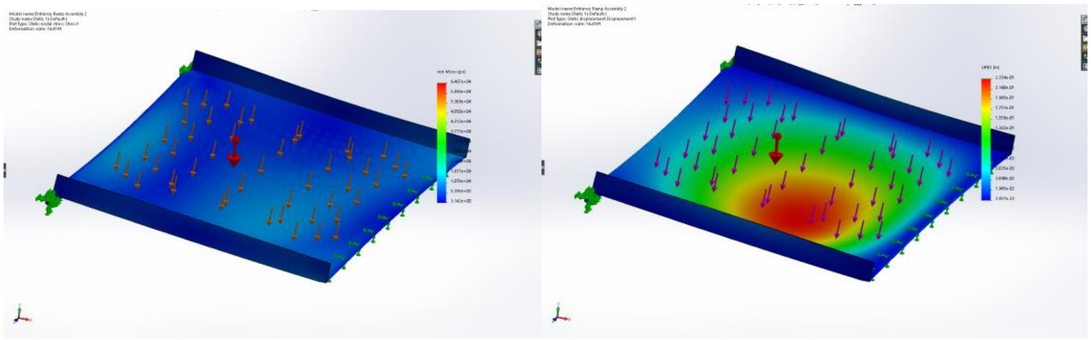


Figure 27 - Changing the plate thickness to 0.125”, results under 1,800 lbs. of load

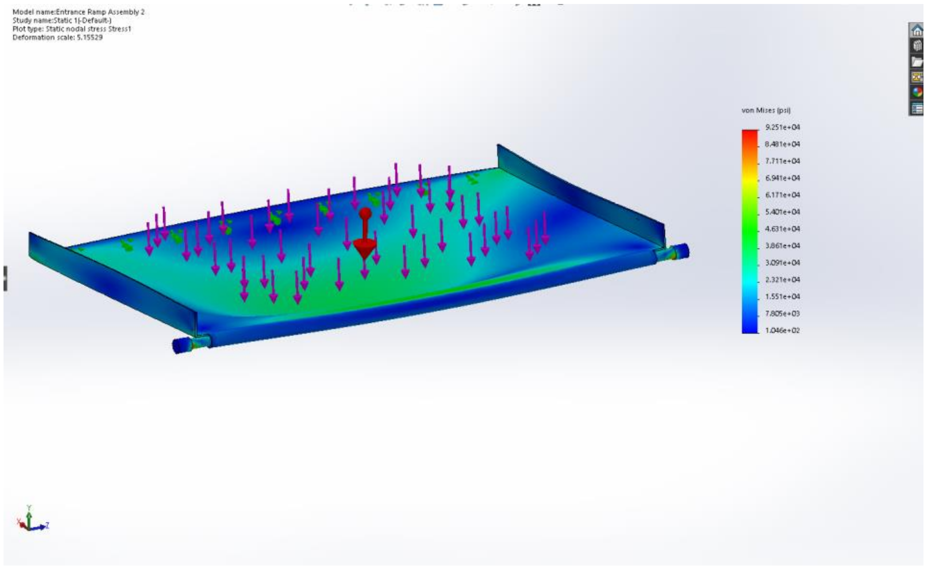


Figure 28 - Increasing shaft thickness to 0.75 under the same load

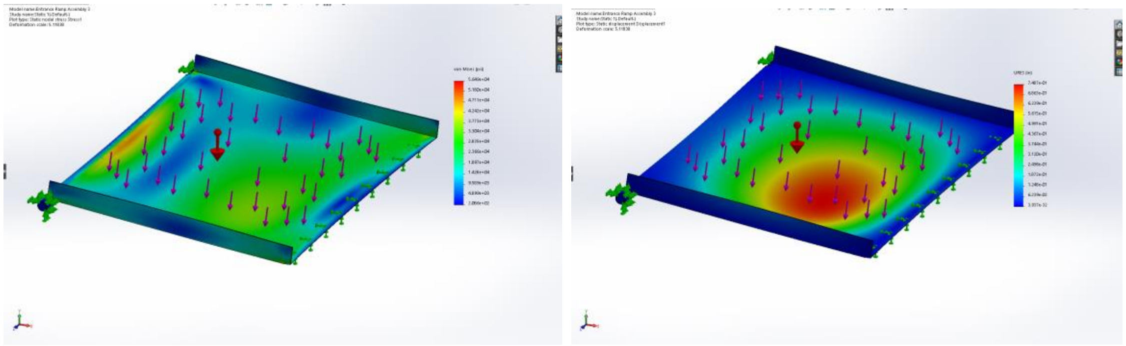


Figure 29 - Now utilizing shaft clamps at the end of the shaft under the same load

As seen in the above examples, the simulations indicate that the last design meets the capacity and factor of safety requirements set forth in the earlier stages of the project. This design has a 0.125” thick 1045 steel plate, with a 0.75” ID, 1” OD 1045 steel tube welded at its ends. The shaft is 0.75” OD with 2 shaft clamps at both ends. As the ramp is considered an item not subject to normal wear and tear, A FOS (Factor of Safety) of 3 is required based on ADA design guidelines. The 1,800 lbf payload is applied in the center of the ramp on a 20”x24” area evenly with the gravity force being active as part of our simulations. The maximal Von Mises stress is 56,490 psi and the maximal displacement is 0.75” in the center. The yield strength of 1045 steel is 76,840 psi which is much larger than the stress. But the 0.75” displacement seems to be a little bit on the higher threshold as a result we increase the thickness of the plate to 3/16”.

It shall be noted that the same design under 600 lbf of force cause by the load performs like the following simulation results. Von Mises stress is only 19,490 psi which gives us an FOS of 3.94. Under this scenario the displacement is 0.25” which is considered high for our use case as in reality, the 600 lbs. payload will not evenly distribute on the lift plate. As an example, the wheels of the mobility device will only make contact with the ramp on 4 small areas. By taking the above factors into account and rerunning the simulations, we clearly witness that the plate thickness has to increase.

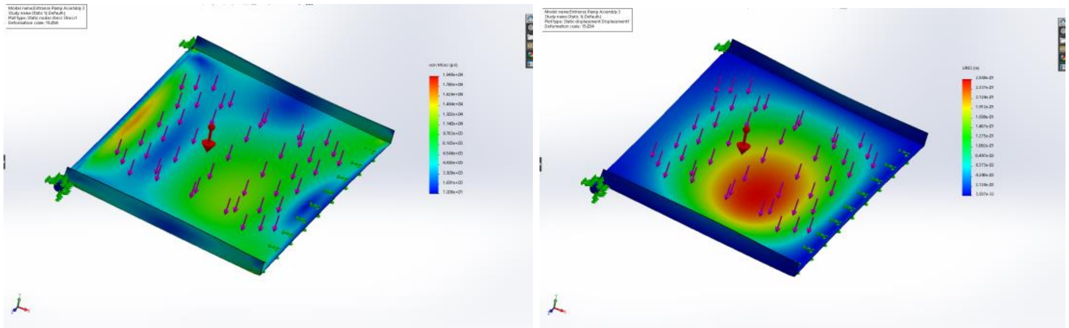


Figure 30 - Same design under 600 lbf

The Von Mises stress is too much under 1800lbf with the shaft diameter of 0.5” causing the shaft to break.

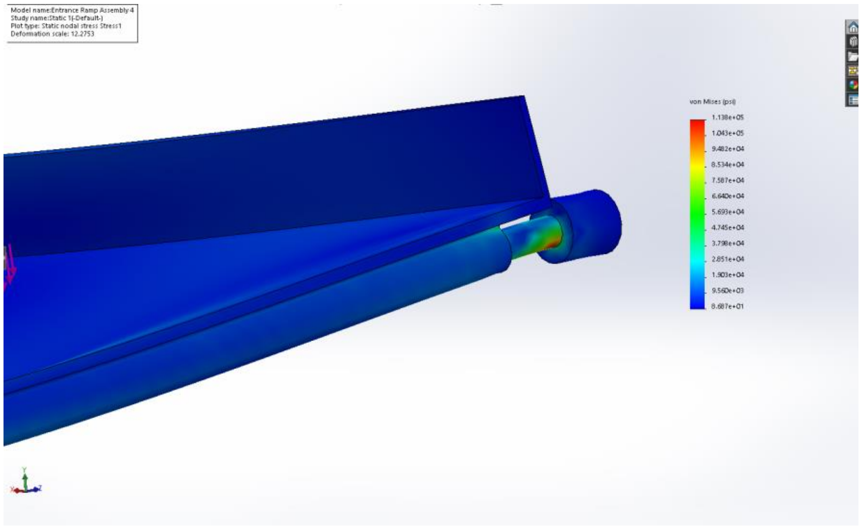


Figure 31 - 1800lbf of load with the shaft diameter of 0.5”

0.625” shaft works regarding stress under 1800lbs. Also, after increasing plate thickness to 3/16”. The displacement under 1,800lbs is also decreased to 0.277”

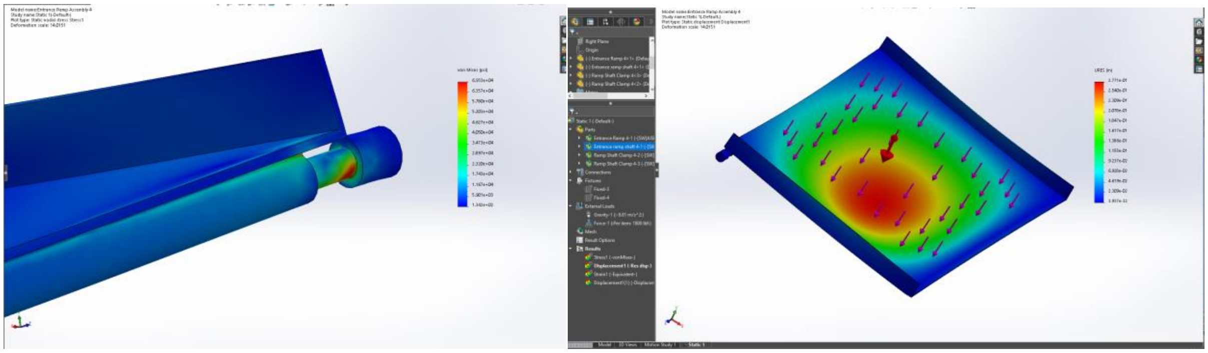


Figure 32 - Increased shaft diameter

Same design under 600lbf of force caused by the payload:

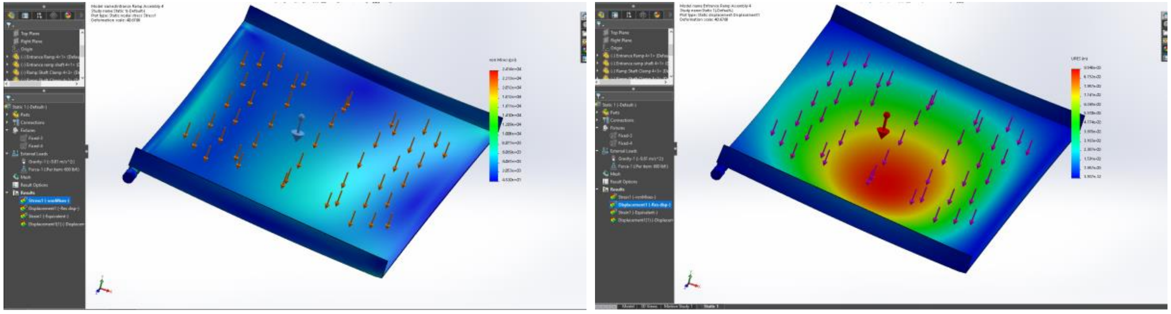


Figure 33- Same design under 600 lbf

The overall conclusion from the above technical simulations indicated that the 3/16" of plate and 0.625" diameter shaft meet the FOS requirements causing relatively small degrees of displacement. However, 3/4" shafts can also be used as 3/4" shafts are a more common size than 5/8" thus could be more abundantly available with perhaps better pricing.

SYSTEM LEVEL INTEGRATION

In robotics, "system level integration" refers to the process of combining and integrating individual subsystems and components into a functioning robot system. It involves designing, developing, and implementing the interfaces and connections between various hardware and software components of a robot, such as sensors, actuators, controllers, and communication systems. The purpose of system level integration is to ensure that all the individual components work together seamlessly to achieve the desired functionality and performance of the robot. This process can involve testing and troubleshooting to identify and resolve any issues that may arise during integration.

Since this project is positioned to assess the feasibility of the TrainMate system and essentially sits one step before prototyping, the project team planned and conducted a desk study and software based "System Level Integration" to ensure the final outcome of the project which is a working prototype of the robotic system is feasible and can be attained once the proper hardware and software components are in place according to the design, blueprints and considerations stated in the previous sections of this report.

Hardware System Integration

For the purpose of the hardware level integration the project team combined and finalized all the hardware designed components of the previous phases and simulated the overall functionalities of the TrainMate system. The main use case that was simulated was the movement of the platform, coupling and lift capabilities of the system. The simulation runs resulted in a total dwell time of 2 minutes and 10 seconds according to the parameters set which is well below what it currently takes the station staff to board a passenger using a mobility device on the train. It shall be noted that the simulation parameters can be changed to observe the results under different scenarios and this duration is a result of erring on the safe side while keeping speeds at minimum thresholds to ensure the passengers feel safe and not rushed during any of the movements.

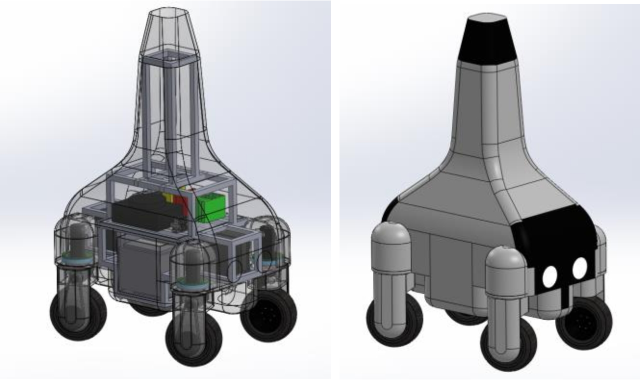


Figure 34 - Integrated base module with and without skin (CAD)

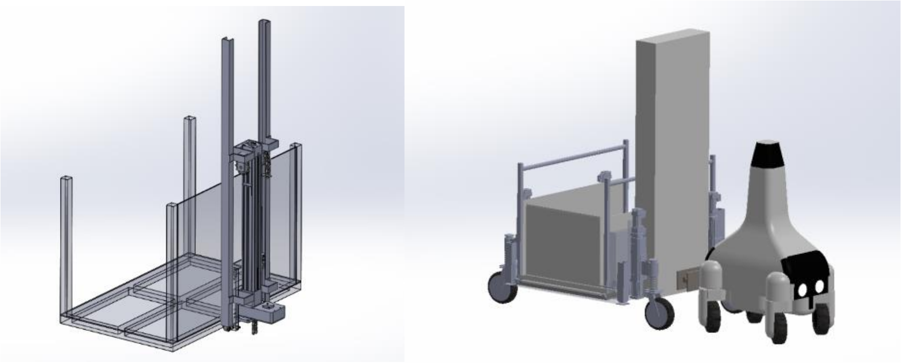


Figure 35 - Base and lift modules (CAD)

As you can see in the figures above, the CAD model includes all the designed components, placed in their respective locations and integrated to work together coherently. This same model was used to run the simulations of the movement and lift functionalities thus making the results as realistic as possible in a software environment.

Software System Integration

Similar to the hardware system integration, the software system was assessed by the project team and the architecture and integration of several software components was studied. The ultimate results that are derived from best practices are depicted in the following figure. This architecture is a matrix design that breaks down the key components into low, middle and high-level controls, spread across devices, controller and functions.

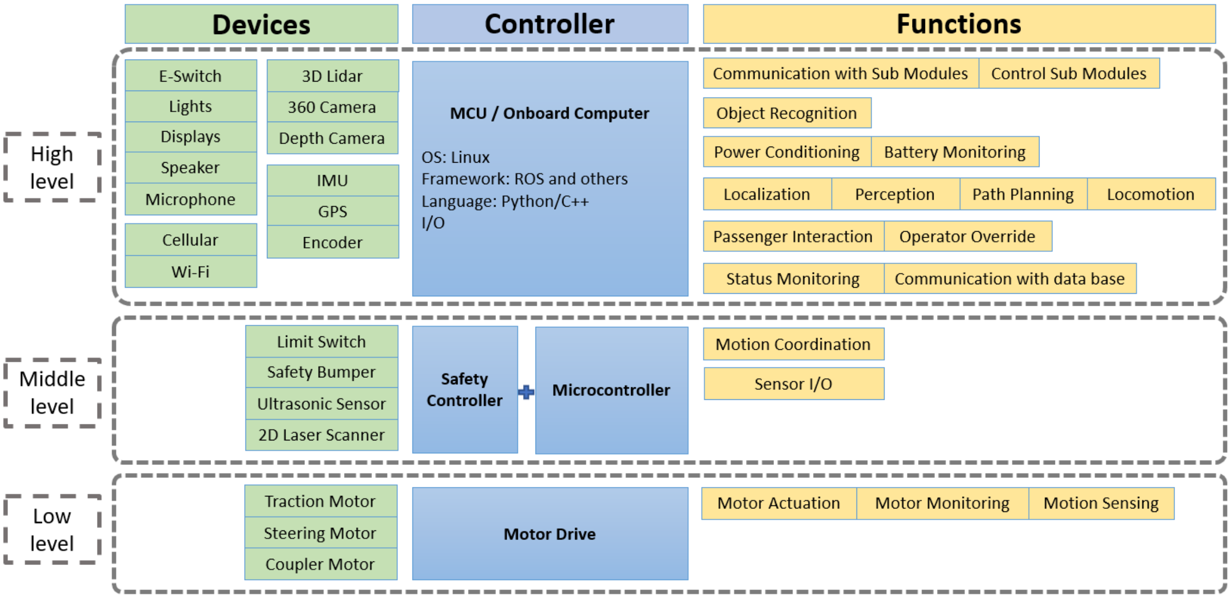
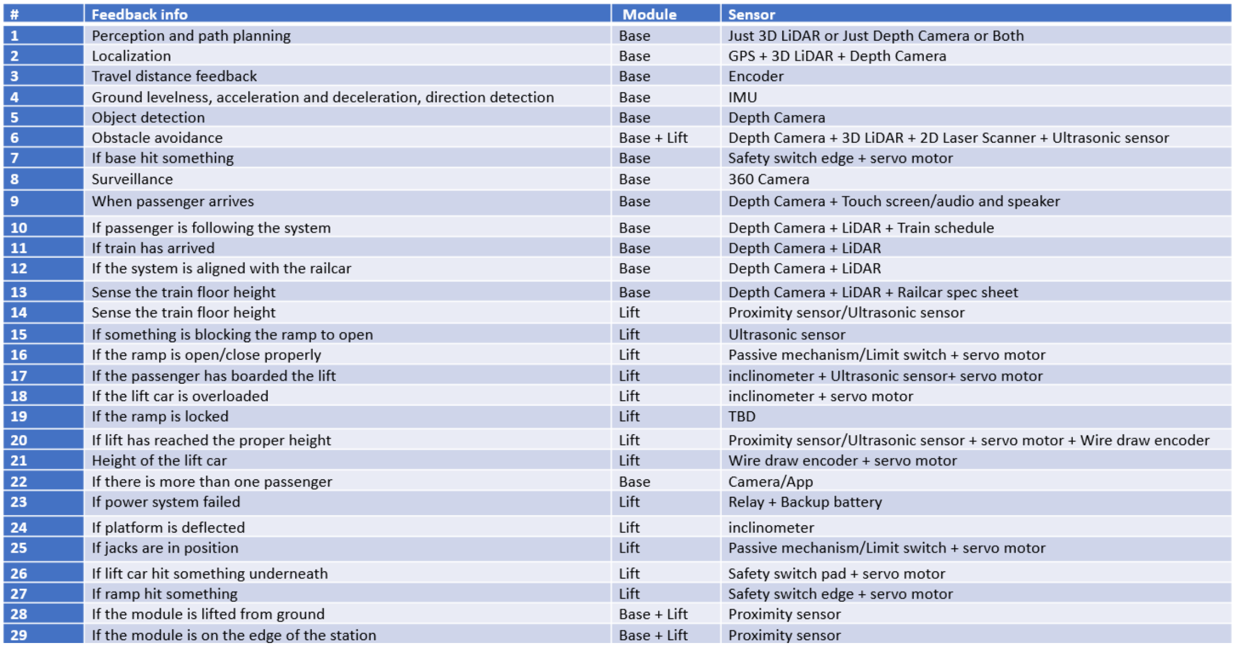


Figure 36 - System's Architecture

Using this model, functionalities such as lift, movement, object detection or communication between components were simulated and the results ensure that such tasks can take place as expected.

As part of this end-to-end simulation the team also assessed the connection between individual sensors that enable the robot's physical functions and how each module and the set of sensors onboard the system would work together to bring the said function to life, results of which are depicted in the figure below.



#	Feedback info	Module	Sensor
1	Perception and path planning	Base	Just 3D LiDAR or Just Depth Camera or Both
2	Localization	Base	GPS + 3D LiDAR + Depth Camera
3	Travel distance feedback	Base	Encoder
4	Ground levelness, acceleration and deceleration, direction detection	Base	IMU
5	Object detection	Base	Depth Camera
6	Obstacle avoidance	Base + Lift	Depth Camera + 3D LiDAR + 2D Laser Scanner + Ultrasonic sensor
7	If base hit something	Base	Safety switch edge + servo motor
8	Surveillance	Base	360 Camera
9	When passenger arrives	Base	Depth Camera + Touch screen/audio and speaker
10	If passenger is following the system	Base	Depth Camera + LiDAR + Train schedule
11	If train has arrived	Base	Depth Camera + LiDAR
12	If the system is aligned with the railcar	Base	Depth Camera + LiDAR
13	Sense the train floor height	Base	Depth Camera + LiDAR + Railcar spec sheet
14	Sense the train floor height	Lift	Proximity sensor/Ultrasonic sensor
15	If something is blocking the ramp to open	Lift	Ultrasonic sensor
16	If the ramp is open/close properly	Lift	Passive mechanism/Limit switch + servo motor
17	If the passenger has boarded the lift	Lift	inclinometer + Ultrasonic sensor+ servo motor
18	If the lift car is overloaded	Lift	inclinometer + servo motor
19	If the ramp is locked	Lift	TBD
20	If lift has reached the proper height	Lift	Proximity sensor/Ultrasonic sensor + servo motor + Wire draw encoder
21	Height of the lift car	Lift	Wire draw encoder + servo motor
22	If there is more than one passenger	Base	Camera/App
23	If power system failed	Lift	Relay + Backup battery
24	If platform is deflected	Lift	inclinometer
25	If jacks are in position	Lift	Passive mechanism/Limit switch + servo motor
26	If lift car hit something underneath	Lift	Safety switch pad + servo motor
27	If ramp hit something	Lift	Safety switch edge + servo motor
28	If the module is lifted from ground	Base + Lift	Proximity sensor
29	If the module is on the edge of the station	Base + Lift	Proximity sensor

Figure 37 - Sensing scenarios and associated technologies

As the last step of this simulation work, the project team studied and assessed the effectiveness of the path planning algorithms identified in the previous sections and used an open-source program to model and observe the movement of the robotic system in an environment with static and dynamic obstacles which resulted in successful navigation of the environment as expected.

PLANS FOR IMPLEMENTATION

With the blueprints of the electromechanical components ready for prototyping and the proof of concept of the software components being successfully tested and finalized, the project team is prepared to build a real-life prototype of the TrainMate robotic system. This entails devising a list of core hardware and software components that can come together to form a Minimally Viable Product (MVP). This MVP shall include the robotic base and the mobility lift module and be capable of conducting basic requirements in a street level train station.

The project team intends to collaborate with its transit agency partners to narrow down a list of functions and features to be included in the MVP and identify a street-level train station as the pilot location. Once the appropriate funding to the build the prototype is secured, the hardware and software integration will begin, which is followed by comprehensive field testing, monitoring and fine-tuning.

CONCLUSION AND FINAL REMARKS

This project proved the feasibility of design and development of a fully autonomous and modular robotic system that is capable of providing service to passengers with disabilities to ensure they benefit from an independent and efficient travel experience. The project successfully produced electromechanical blueprints as well as software components and ran them through end-to-end software simulations to ensure they can work in real-life scenarios.

As a result of this research, the project team is confident that building a fully working prototype is within reach and although a complex job, it is less complicated than was initially anticipated before the beginning of this research. The project team believes that the research is at a stage where the prototyping work can begin immediately using the blueprints and plans developed during the current project.

The benefits of the TrainMate system are significant, particularly for disabled passengers who require accessible transportation. With TrainMate, this population will no longer have to rely on assistance from others or deal with limited mobility when using public transportation. This robot will offer a safe, reliable, and convenient way for people with disabilities to travel with confidence, providing a greater sense of independence and autonomy.

The most important lesson learned during this project is that the use of advanced technologies such as the TrainMate system is only one piece of the puzzle in increasing travel independence of passengers with disabilities. The successful utilization of this platform or other similar technologies in public transportation settings requires a synchronized collaboration between all stakeholders, which is equally important. The frameworks of this collaboration shall be well planned and executed and must be an integral part of any follow-on research or real-life prototyping project.

APPENDIX: RESEARCH RESULTS

Sidebar Info

Program Steering Committee: Transit IDEA Program Committee
Month and Year: April 2023
Title: TrainMate Robotic System, Making Public Transportation, Public!

Project Number: Transit 100
Start Date: January 14, 2022
Completion Date: March 31, 2023

Product Category: IDEA Transit

Principal Investigator:
Amir Rezvani, Project Manager
E-Mail: amir@infrateksolutions.com
Phone: (732) 881-1265

TILTE:
Autonomous Robotic System for Passengers with Disability

SUBHEAD:
Proved feasibility, designed, developed and simulated the blueprints for electromechanical and software components of a fully autonomous modular robotic system to assist passengers with disabilities in public transportation settings.

WHAT WAS THE NEED?

Abundance of non-accessible, street-level train stations that require lifting of passengers on wheelchair to board or deboard railcars is a clear problem and missing link in disabled passengers' travel chain. While it may look simple and straightforward on the surface, upon further investigation and evaluation of the current solutions, it turns out that the problem has many more layers to it.

Consensus among us and our public transit partners is that to properly solve and address the challenge of lifting passengers with mobility impairment, one should not only take into account the mechanical act of lifting but also the nature and characteristics of the payload and how it is handled. In addition, impacts on other passengers as well as the business objective of the agency are other key factors. Matters such as safety, independence, not causing embarrassment, and dignity of the passengers as well as efficiency, practicality and cost-effectiveness should be prioritized as part of the solution and a solution to consider all these factors does not exist today.

The above considerations indicate a need for a custom, innovative solution. A solution that taps into the technological arena, applying the latest and greatest advancements in an innovative, modular, and multifunctional robotic platform that addresses the needs of passengers with disabilities at any location.

WHAT WAS OUR GOAL?

This project aimed to prove the real-life feasibility of the conceptual designs and software prototyping of electromechanical components for the robotic base and wheelchair lift modules, successfully passing all technical verification testing in CAD simulations. Our goal was to have the following items ready at the end of the project so that a follow-on prototyping phase can begin with confidence.

1. Blueprints and CAD designs for different electromechanical components of the base robotic and the lift modules.
2. Machine vision & AI control algorithms demonstrating high accuracy, generalization, and integration and applicability with public transit environments.
3. Field usability CAD simulations showing end to end operation and improved operation and cycle time for sample lift and passenger boarding/deboarding operations.

WHAT DID WE DO?

Our investigation included a comprehensive round of requirements analysis through collaboration with end users as well as subject matter experts. The project team also visited more than 15 street-level, non-accessible train station to understand the limitations travel for passengers with disability and review how the current solutions do not address this populations’ s needs for independence and autonomy. This effort was followed by design and development of a modular robotic system that can help passengers with disabilities navigate the train stations and board and deboard a train at street-level stations using a robotic mobility device lift. The team also developed software components that will be utilized to conduct such functions. Ultimately all the hardware and software designs were simulated and tested in software environments to ensure useability and applicability to the real-life scenarios.

WHAT WAS THE OUTCOME?

This project proved the feasibility of design and development of a fully autonomous and modular robotic system that is capable of providing service to passengers with disabilities to ensure they benefit from an independent and efficient travel experience. The project successfully produced electromechanical blueprints as well as software components and ran them through end-to-end software simulations to ensure they can work in real-life scenarios and will also be used to start the prototyping phase.

WHAT WAS THE BENEFIT?

The benefits of the TrainMate system are significant, particularly for disabled passengers who require accessible transportation. With TrainMate, this population will no longer have to rely on assistance from others or deal with limited mobility when using public transportation. This robot will offer a safe, reliable, and convenient way for people with disabilities to travel with confidence, providing them with a greater sense of independence and autonomy.