

A NOVEL STAIR-CLIMBING MOBILE PLATFORM AND ITS MOTION CONTROL SYSTEM

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Declaration

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Abstract

Independent life is one of the most significant concerns for a disabled person specially when considering their mobility requirements. Due to the availability of facilities, both indoor and outdoor, wheelchair users face many difficulties when entering a building via staircases. Particularly, in the developing world, the concern about difficulties faced by the disabled and elderly community in accessing buildings is inadequate. As a result, most of the wheelchair users are forced to stay home and it makes their lives dependent. Since many years, scientists and researchers have been working for providing effective solutions for the mobility issues of disabled community. Stair-climbing wheelchair is one of the most powerful and popular solutions which is currently in use for mobility requirements of the disabled community. But most of the existing stair-climbing wheelchair designs have a drawback of the lack of adaptability especially at the top and the bottom of the staircase

As a solution, a novel stair-climbing mobile platform with improved stability and safety is presented in this thesis. In this research, the novel mobility platform has been designed referring to the standards of staircases which have been accepted worldwide. Based on those stipulated parameters, the maximum operating angle of this design is selected as forty degrees, which is the highest angle as per the standards. Based on the literature review, track based arrangement is used as the basic mechanism for the mobile platform design because of speed, grip and user comfort. By considering the main problem of the track mechanism, variable configuration of track mechanism is used for the design in order to achieve adaptable arrangement to the staircase. Also detail analysis of design safety based on different postures on staircases are discussed and basic conditions for stair-climbing operation are derived. By considering the prototype construction, a detailed description of development stages of prototype is explained based on practical approaches in order to minimize the defects in the final product.

In order to validate the stable and safe operation, simulation and experimental studies have been carried out. According to proposed novel motion plans for stair-climbing operation, the simulation study illustrates that there does not exist any sudden disturbances on the user's operating path over staircase. By following the same procedure as used in simulation study, experimental studies have been carried out by implementing motion plans for each stage of operation. Based on the results, it confirms that the operating path of the design follows a similar behaviour as discussed in the simulation study. For further justification of the safety of the design, the actual operating path is well observed by using a video tracker software. Based on the actual operating path of the design, it confirms that throughout the staircase, the design maintains a stable operating path without creating any sudden disturbances on the mobile platform. Thus, it confirms that this design can provide a comfortable operation for the user whilst maintaining stable and safe posture throughout the operation.

Index terms— stair-climbing, mobile platform, wheelchair, track mechanism

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List of Abbreviations

Abbreviation	Description
a	Going
b	Rise
c	Hypotenuse
θ	Angle of staircase
l_f	Length of front arm
l_m	Length of middle arm
l_r	Length of rear arm
l_c	Half length of contacting points of chassis
h_c	Minimum stair edge clearance height of chassis
h'_c	Marginal value for minimum stair edge clearance height
θ'	Angle of margin
r	Radius of arm
M_{fg}	Weight of front arm
M_{mg}	Weight of middle arm
M_{rg}	Weight of rear arm
M_{bg}	Weight of body
T_f	Tractive force of front arm
T_m	Tractive force of middle arm
T_r	Tractive force of rear arm
T_{ft}	Total tractive force acting on front arm
T_{mt}	Total tractive force acting on middle arm
T_{rt}	Total tractive force acting on rear arm
τ_t	Required minimum torque
τ_m	Torque of driving motor
N_f	Normal reaction force on front arm
N_m	Normal reaction force on middle arm
N_r	Normal reaction force on rear arm

l_b	Distance to CM of body from front joint
θ_b	Angle of CM of body
l_1	Distance to step from rear joint
θ_s	Incline of chassis
l_2	Distance to step from front joint
M_{tg}	Total weight of design including user
λ	Stable marginal angle
d	Distance to stable marginal angle
l_t	Distance to CM of design from stair edge
μ	Friction coefficient
x	Height of user's placement
ω	Orientation of user's position
α	Angle of front arm
β	Angle of middle arm
γ	Angle of rear arm
F_{res}	Total resistance force
P_{flat}	Power consumption in flat surface
P_{stair}	Power consumption in stair-climbing
P_{max}	Required maximum power
V_{flat}	Speed in flat surface
V_{stair}	Speed in staircase
η	Coefficient of power transmission
K_s	Safety factor
τ_{stair}	Required torque in stair-climbing
ω_s	Angular velocity of wheel
x_{f1}, x_{f2}, x_{f3}	Parameters of front arm geometry
x_{m1}, x_{m2}, x_{m3}	Parameters of middle arm geometry
x_{r1}, x_{r2}, x_{r3}	Parameters of rear arm geometry
α_1	Angle between front linear actuator and front arm
α_c	Angle between front arm and chassis
l_{f1}	Distance to contact point from front joint
F_{fl}	Front linear actuator force
α_{con}	Fixed angle of front arm
β_{con}	Fixed angle of middle arm
γ_{con}	Fixed angle of rear arm

Chapter 1

INTRODUCTION AND LITERATURE REVIEW

The basic mean of a staircase is to provide simple and safe access of mobility between levels. In ancient times, most of the houses and buildings were constructed based on one storey. But, with the time, people realized that the surface area on the ground was inadequate and started thinking about how to utilize area above the ground level in order to increase the space. As a result, staircases were constructed to access the upstairs quickly and effectively. On the other hand, staircases can operate in a more safe and reliable manner when compared to ramp. However, stairs have become a barrier for accessing upstairs specially for the disabled people since many years due to the limited facilities at the staircase and wheelchair design constraint.

Scientists and researchers were working to address these issues in order to develop practical solutions for mobility requirement of the disabled since many years. According to the report on disability published by the World Health Organization (WHO) in 2011, around 15% of people in the world suffered with different types of disabilities and 2.4% of above people were affected with functional disabilities [1]. Stair-climbing wheelchair is a novel concept which can provide accessibility via staircases. But, with the conventional wheel based wheelchairs, mobility over staircases is very dangerous. Wheelchair users face many difficulties regarding mobility requirements in places where ramps or elevators are not available. Especially in developing countries, disabled people face many issues when entering to a building due to being less concerned on providing facilities for wheelchair access when constructing buildings. There are few solutions to address this major issue. But apart from accessing a staircase, the design should have a stable and safe operation. Most of the research papers based on stair-climbing considered about developing mechanisms for accessing stairs, but did not pay much concern on providing stable and safe operation specially at top of the staircase.

Operation over stairs by using a stair-climbing wheelchair is considered to be risky. According to the Food and Drug Administration (FDA) of USA, stair-climbing wheelchairs are considered as Class II devices as "devices for which general controls are insufficient to provide reasonable assurance of the safety and effectiveness of the device" [2]. In the stair-climbing wheelchair design, the main approach should be the stable and safe operation over stairs. In order to achieve these objectives, wheelchair mechanism should have a better arrangement to maintain the static and dynamic stability. Also the mechanism should have a proper grip with the staircase in order to prevent slippage. In this study, the main problems of existing stair-climbing wheelchair designs are discussed in detail. Based on the existing problems in the available platforms and mobility requirements of the disabled, a novel stair-climbing mobile platform is explained in this study.

1.1 Literature Review

It is uncertain about the available evidence for the first wheelchair development as it had several attempts since thousands of years. The first wheelchair was developed in 1595 for King Phillip II of Spain and it was called as an "Invalid's Chair" [3]. The wheelchair was developed by attaching small wheels to the end of a chair's legs. Also the design composed with a footrest and adjustable backrest and the wheelchair was operated by a servant. In 1665 three-wheel chassis based wheelchair with self-propelled was invented by Stephen Farfler who was a paraplegic watchmaker. It was built for his own mobility aid when he was only 22 years after he met with an accident. John Dawson of Bath in England invented the Bath Chair in 1783 and named it as the town of Bath. This design composed of two large wheels and one small wheel. The basic wheelchair design used in today was initially invented in 1800. In 1869, a new wheelchair design with rear push wheels and small front casters were invented and it was patented. Based on its design, it could be self-propelled. During 1867 to 1875, some modifications were added to the wheels of the wheelchair by developing hollow rubber wheels, which were similar to bicycle wheels. The push rims were added to the wheelchair in 1881. In 1894, a USA patented wheelchair was used in Civil War and the First World War. In 1900, the first spoke wheels were used for wheelchairs and in 1912, "Invalids Tricycle" was made by using a motor. Subsequently, in 1916, the first motorized wheelchair was manufactured in London. The first folding, tubular steel wheelchair was built in 1932 by Harry Jennings and this was the earliest

wheelchair which is similar to the modern wheelchair design. In 1956, Everest and Jennings began the manufacture of the electric wheelchair in a mass scale.

Since the initial development, technology has been used to develop wheelchairs based on size, weight, cost and customized designs. Also based on the customer requirements, the control methods have been improved by introducing the hand operated joystick and wheelchairs controlled by mind. Even the wheelchair development provides a solution for the mobility issue of disabled community, in areas where elevators and ramps are not available, mobility over stairs is particularly critical. Since many years, inventors tried to develop a wheelchair which could provide mobility over stairs. In 1962, Ernesto Blanco invented a stair-climbing wheelchair and presented the invention to a design challenge competition organized by the USA National Inventors Council. The design composed with retractable, spring-loaded, rubber-tipped spokes that came out of the rim. Although, he didn't win prize and in fact, the council never picked a winner. In 1995, Nagasaki Stair-climber was introduced in Japan which was an electro-mechanical chair based on the track mechanism. After few years, Dean Kamen (later famous for building the Segway scooter) developed an iBot which was based on the wheel-cluster mechanism.

Based on the available stair-climbing wheelchair designs in the market, it can be categorized mainly to three groups as follows.

- Wheel based stair-climber
- Crawler based stair-climber
- Leg based stair-climber

Based on these stair-climbing mechanisms, advantages and disadvantages of each mechanism are mainly discussed by considering stable and safe operation.

1.1.1 Wheel Based Stair-climber

This is the most common type of wheelchair mechanism used for wheelchair development. Also there exists a higher demand for this type of wheelchairs among the disabled due to many reasons. Most of the wheel based mechanisms has a barrier to operate over the stairs. But with some modifications to these types of mechanisms, these designs could be operated over a single step and stairs.

1.1.1.1 Single Step Climbing Mechanism for Wheelchairs

These types of wheelchairs are designed for facilitating single step climbing as illustrated in Figure 1.1. Also these modifications could be attached to manually propelled and powered wheelchairs which are commonly available in the market [4]. In these types of wheelchair designs, front wheel casters were modified by attaching another wheel or curb catcher by placing it a little bit forward and higher than the casters placements. When the curb assistive wheel or curb catcher hit the curb, it helped to lift the caster wheels easily and place the front casters on the step. After the front caster wheels placement on to the step, the rear wheels could be operated to access the step easily.



Figure 1.1: Curb assistive mechanisms of step climbing

- Advantages:
 - Can be easily attached to manually and powered wheelchairs
 - Low cost
 - Simple design
 - Light weight
- Disadvantages:
 - Can only negotiate with single step climbing
 - Limitation of step height
 - Cannot be operated backwards
 - Incompatible with all types of wheelchairs

Five-wheeled wheelchair with a single wheel drive unit was developed for one step climbing [5]. The wheelchair design composed of a new configuration of five wheels. In this design, there were four passive wheels which were placed as in a manual wheelchair. Also there was a drive wheel which was located behind the rear wheels. In the flat surface, the wheelchair was driven by using this drive wheel. When the wheelchair came closer to a step, the drive wheel moved backwards while lifting the front casters more than the step height. In this stage of the operation, the wheelchair was on three-wheel arrangement and the user placement was also inclined. The sequence of single step climbing is demonstrated in Figure 1.2.

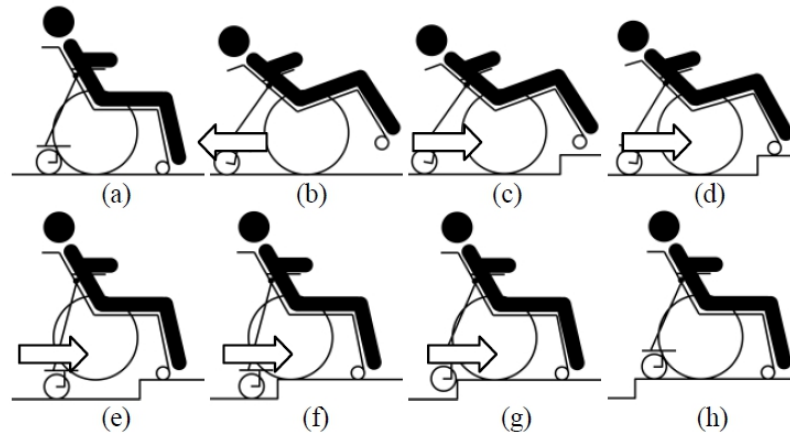


Figure 1.2: Sequence of climbing over a step by the five-wheeled wheelchair

Due to the design constraints, the step should have enough space to place the front caster and large wheels at the same time. As a result, this design is only suitable for single step climbing and cannot be used for stair-climbing. Also, due to the drive wheel placement at the backside for wheelchair operation, this design needs more space to complete the single step climbing. Based on the step height, the front wheel should lift more than the step height. As a result, there is a limitation to access steps in real environment. Also due to front caster lifting technique, the user placement is also inclined based on the step height and there is no any suggestion to address this issue as well. As a result, the user feels uncomfortable operation.

Only by attaching a modified front caster wheel and lock-function, the existing four-wheel manual wheelchair could be converted into a step climbing wheelchair [6]. In this design approach, the limitation of the front caster wheel was resolved

by considering the step height. Not only the step height, but also this design had properly addressed to increase the efficiency of driving force needed for step climbing. In existing manual four-wheel wheelchairs, the diameter of caster wheels were around $100\text{-}150\text{mm}$ and they were only suitable to climb steps of $1/3$ height of its diameter. As a solution, this design proposed an assistive plate which could be attached to the caster. By using this technique, the radius of the caster wheel was enlarged imaginary. When the wheelchair came closer to a step for climbing, the front caster wheels could be rotated around the yaw axis. As a result, the assistive plate could not be used properly when accessing a step. As a solution, this design proposed a lock function to the root of the caster unit to prevent the assistive plate movement. As a result, user could easily operate the wheelchair for one step climbing.



Figure 1.3: Overview of the wheelchair equipped with the caster unit

Based on the design, the wheelchair can only access a limited height of steps. Also there should be adequate space on the step to complete the operation. Due to lack of traction force in between large wheels and stair edges when climbing a step, there is a high risk of slippage [7] [8]. As a result, it could affect the stability of the design.

1.1.1.2 Mobility Scooters and Powered Wheelchairs

Mobility scooters are mostly popular among the aged and the disabled because of many reasons [9]. These types of wheelchairs are mainly used for outdoor usages. Due to its design technique this can be used in most of the outdoor environment specially in rough terrain. Also these types of scooters have acceptable speed range than power wheelchairs. As a result, it has a huge demand among the users. Also these designs have more battery capacity for long distance travel.



Figure 1.4: Mobility scooters

- Advantages:
 - Specially designed for outdoor use
 - Acceptable speed range
 - Capable of step and stair-climbing
 - Suitable for rough terrain
- Disadvantages:
 - Not recommended for stair-climbing
 - Need more space to operate
 - Large turning circle
 - Size
 - Cost
 - Difficulties to operate

For indoor wheelchair users, the mobility scooter is not suitable because of two reasons. First reason is that the mobility scooter needs more space to operate because of its size. As a result, it is hard to operate the scooter in a limited space area. The other reason is that due to the driving mechanism and size, the scooter needs a large turning cycle. Thus, it will become hard to turn the scooter especially when it is used in indoor. Also when compared to mobility scooters, power wheelchairs have a joystick controller which provide facilities to control the wheelchair for almost all the disabled persons [10]. As a result, power wheelchair is more popular for indoor use.



Figure 1.5: Power wheelchairs

- Advantages:
 - Can be operated easily
 - Need small space to operate compared to scooter
 - Capable of step climbing
 - Light weight
- Disadvantages:
 - Not recommended for stair-climbing
 - Not suitable for rough terrain
 - Limitation of step height

As explained in above paragraphs, most of the mobility scooters have the ability of step and stair-climbing. But based on the existing wheel designs for scooters, step or stair-climbing may become more risky. Also, due to rear drive configuration, maximum step climbing height is reduced because of lack of force available in front wheels. As a solution, 4WD transmission provided extra force for front wheel of a scooter to access steps, which was three times higher than the step height of RD transmission capable scooters [11]. Also this was achieved without changing the motor specification and wheel diameter. In order to overcome drawbacks of the conventional 4wD wheelchairs, an omnidirectional wheelchair was introduced [12]. The omnidirectional motion of the design could provide movement in sideways with maintaining its orientation constant. Also this helped to increase the accessible step height as well [13]. Also, the introduction of the chair

tilting mechanism for 4WD omnidirectional wheelchair helped to maintain stability and increase the safety in step climbing [14]. Also this provided a comfortable operation for the user.

1.1.1.3 Planetary Wheel Based Stair-climbers

Even the step and stair-climbing operation is possible, powered wheelchair and mobility scooter are highly recommended for operation in flat and slope surfaces. Because based on the wheel arrangement there exists less stability when climbing stairs. As a solution, planetary wheel based mechanism was introduced for wheelchairs. This mechanism could be divided into two parts which were wheel cluster and dual wheel cluster. The most important aspect to be considered in planetary wheel based mechanism was tip-over stability in stair-climbing. Due to the mechanical constraint in the wheel cluster mechanism, stair-climber needed an assistance to access stairs. Faults of both wheelchair mechanism and assistance could cause to tip-over problem. In some cases, it may caused injuries for both the user and the assistant. Both parties must pay special attention when the wheelchair was on the stair-climbing operation. Figure 1.6 shows wheel cluster type of stair-climbing wheelchair [15].



Figure 1.6: TGR Scoiattolo 2000 wheelchair

- Advantages:
 - Stair-climbing ability
 - Suitable to almost all stairs
 - Light weight

- Easy to operate
- More stable than mobility scooter
- Disadvantages:
 - Need an assistance to operate in stair-climbing
 - Stair-climbing operation become uncomfortable for passengers because of oscillation
 - Operate backwards

As mentioned earlier, the main problem which exist with the wheel cluster mechanism was tip-over issue when climbing stairs. As a solution, anti-tip-over bracket was introduced to improve the stability during stair-climbing [16]. In this mechanism, two hybrid planetary wheel clusters were fixed to the wheelchair frame symmetrically. These wheel clusters consisted of a hub motor and two free wheels, which had the same configuration with the hub motor. Also the anti-tip-over bracket was installed at the bottom of the supporting frame which could be controlled by a linear actuator. When the wheelchair was on the stair-climbing operation with the support of assistance, the linear actuator controlled the anti-tip-over bracket until the idle wheels at the front of the bracket touched the ground. The anti-tip-over bracket maintained contact with steps until stair-climbing operation was completed.

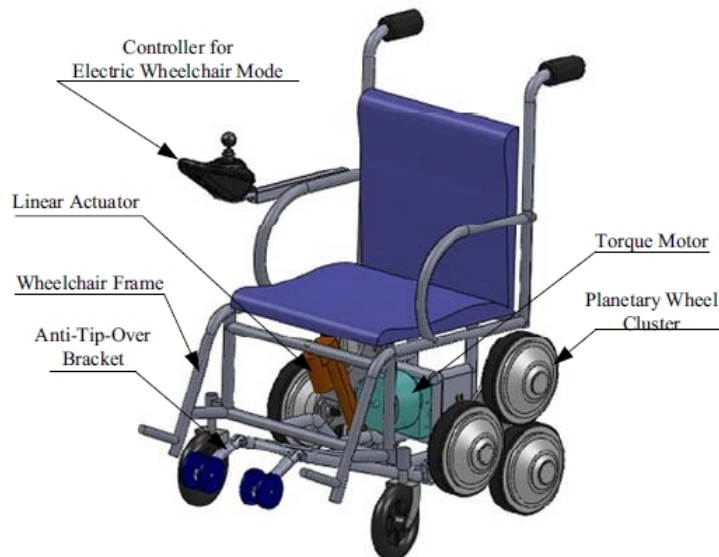


Figure 1.7: Wheel cluster wheelchair with anti-tip-over bracket

In order to address the main two problems of wheel cluster mechanism, which were tip-over issue and assistance support, a dual wheel cluster mechanism was introduced [17]. This design had stair-climbing ability, suitable for most stairs and it could be operated by the user without others assistance. In Figure 1.8 shows a dual wheel cluster wheelchair called "Freedom". In order to drive the wheelchair, RD transmission was used. When the wheelchair started to operate over stairs, front caster wheels were arranged as shown in Figure 1.8.



Figure 1.8: "Freedom"- Dual cluster wheelchair

- Advantages:
 - Suitable for almost all stairs
 - No need of assistance to operate
 - Tip-over problem is minimized
 - More stable and safe mechanism
- Disadvantages:
 - Stair-climbing operation become uncomfortable for passengers
 - Operate backwards
 - Need more space to operate
 - Size
 - Weight

NOROROT and iBOT are another type of wheel cluster based stair-climbing wheelchairs, which maintained the COG on two wheels. NOBOROT was a wheeled robotic vehicle which could climb stairs, developed by the University of Tokyo's Kamata lab [18]. By using proximity sensors, NOBOROT could detect steps and maintained stability when ascending and descending stairs and

also this ensured smooth ride. The system maintained its stability by implementing inverted pendulum control model. Also by using new technologies in sensors and control designs, the NOBOROT had improved its stability especially in stair-climbing operation.



Figure 1.9: NOBOROT- University of Tokyo

The iBOT 3000 Mobility System (iBOT) was a battery-operated, programmable wheelchair manufactured by Independence Technology, a Johnson & Johnson company in Warren, NJ, US [19]. This design had many advantages than power wheelchairs. On flat surface based on the user's requirement, this wheelchair could be arranged into 2WD or 4WD. With the 2WD arrangement, the user could stand in adult eye-level and cross uneven terrain. Also by using 4WD mechanism, the wheelchair could operate on sand, gravel or uneven terrains. The iBOT may be difficult to manoeuvre indoors due to the seat height, but it operated well outdoors. Another major benefit of this wheelchair was that when the wheelchair moved over a curve or incline, the seat placement was automatically levelled and as a result, it created more stable arrangement for the user.

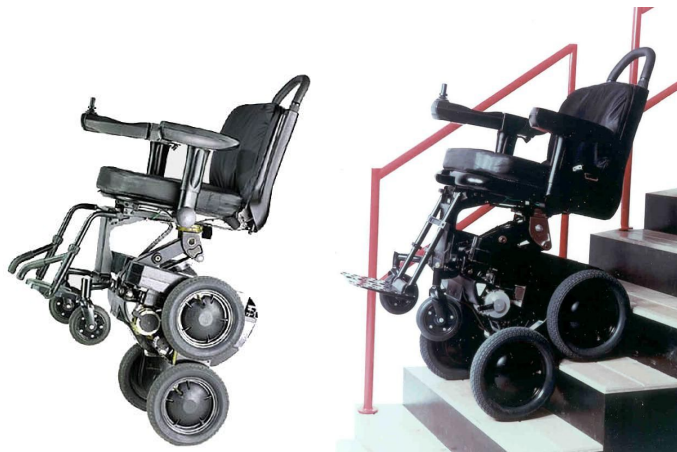


Figure 1.10: iBOT- DEKA and Johnson & Johnson's

- Advantages:
 - Suitable for almost all stairs
 - Provide acceptable height for user (eye level communication with standing persons)
 - Operates in almost all environments including rough terrain, inclined surfaces and staircases
 - More stable and safe mechanism
- Disadvantages:
 - Need assistance to operate in stair-climbing
 - Operate backwards
 - Expensive
 - Stair-climbing operation become uncomfortable for passengers due to oscillation

1.1.1.4 Wheel Based Stair-climbing Attachments

As explained earlier there are many wheelchair developments which provide stair-climbing facility by itself based on wheel based mechanism. But due to the price and availability, it is not affordable for everyone to purchase a wheelchair which has stair-climbing capability. As a solution, in 1986, a battery powered stair-climbing attachment called "Scalamobil" was developed and in 1988, "Scalamobil S10" was introduced to the market [20]. This attachment could be easily attached to most of manual wheelchairs. Basically this design had two pair of wheels which were on separate axes. When climbing the stairs with the support of assistance, one pair of wheels was used to lift the wheelchair. Also by using the other pair of wheels, it maintained the contact with top of stairs. As a result, it created orbiting motion for the passenger.



Figure 1.11: Scalamobil-stair-climbing attachment

A similar concept was implemented in "C-Max" stair-climber as used in "Scalamobil" [21]. The only difference on this mechanism was that one pair of wheels were replaced by leg mechanism. Also "C-Max" could not be attached to an existing wheelchair as "Scalamobil". Passenger should be transferred to this wheelchair before climbing a staircase. Due to its design approach, this could be used in narrow and spiral stairs and it had automatic safety brakes to stop at steps.



Figure 1.12: C-Max-stair-climber

- Advantages:
 - Suitable to almost all stairs
 - Can be used in narrow and spiral stairs
- Disadvantages:
 - Need an assistance to operate in stair-climbing

- Operate backwards
- Stair-climbing operation become uncomfortable for passenger

1.1.2 Crawler Based Stair-climber

Mainly, based on the comfortable drive, rubber tires are designed to be used for vehicles on roads. But in off-road drive, tires are not suitable for many reasons. As a result, crawler based vehicles are developed for different types of applications. Due to the design approach, most of the crawler type vehicles have the ability to operate in any environmental condition. Mainly, there are two types of materials used for crawler mechanism, which are rubber and metal. Based on the application, the designer can select the appropriate material for crawler selection.

1.1.2.1 Track Based Stair-climber

Almost all the types of crawler based stair-climbers use rubber tracks for many reasons. One of the main reasons is that rubber based track mechanism can provide comfortable operation over stairs without damaging the stair edges. Also the other advantage of this mechanism is the independence or robustness regarding the type of stair or surface it is negotiated. It has more adaptability than other mechanisms. But, track based stair-climbers are only suitable for stairs that have strong stair edges. The reason for this issue is that the total weight of the wheelchair is applied on the stair edge that has a small area. As a result, there exists a higher pressure on a single location rather than pressure distribution [22]. But nowadays, constructors use stair edge protectors in order to minimize damage to stair edges and also provide more strength to stair edges. The other major benefit of the track mechanism is that it provides more grip with steps than other mechanisms. But even there exists enough grip for the track mechanism, there exists lack of adaptability to the staircase when it is on the top and the bottom of staircase [23] [24].

The Scalevo is a rubber track based stair-climbing wheelchair developed by students from the Swiss Federal Institute of Technology and Zurich University of the Arts [25]. Basically, this design had two wheels to operate on flat surface. Due to this design approach, a specially designed robust controller was implemented to maintain the balance on two wheels. In the stair-climbing operation, two rubber tracks were used. But even though the design had the ability of stair-climbing, there exists issues regarding the stability and safety when climbing stairs. Hence,

the design used single section track mechanism for stair-climbing. As a result, there existed less adaptability to a staircase when a wheelchair transfers in between stair edges and flat surface. Therefore, it could create unstable and risky operation [26].



Figure 1.13: Scalevo and TopChair-S

In order to overcome from the lack of adaptability to the staircase, a new design was introduced by Mr. Alan Lee who is an inventor of the B-Free Chair and founder of B-Free Technology Limited [27]. In this design, multiple rubber tracks were used to increase the adaptability when accessing stairs. But, when compared to other designs, the seat placement was very high and it may cause uncomfotability for the passenger especially when the wheelchair was on staircase. Also due to the stair-climbing mechanism, the wheelchair followed an orbital motion. As a result, user may felt uncomfortable. In order to increase the adaptability another version of this design was introduced. But in the stair descending operation, the rubber track could not be able to maintain proper contact with staircase. As a result, there could exist a slippage.



Figure 1.14: B-Free wheelchair

- Advantages:
 - Suitable to almost all types of stairs
 - Variation of step dimension does not affect the operation
 - Speed operation over stairs
 - Maintain proper grip with stairs
 - Comfortable operation for the passenger because of the operating path over stairs (Scalevo and Topchair S)
- Disadvantages:
 - Lack of adaptability (Scalevo and Topchair S)
 - Lack of stability and safety
 - Operate backwards
 - Total weight apply on stair edges

1.1.2.2 Track Based Stair-climber Attachments

Most of the wheelchair users use wheel based manual wheelchairs for their mobility because of the price. As a result, they face many difficulties to access stairs. As a solution, the track based stair-climbing attachment was introduced by Lehnar Lifttechnik called "Stairmax" [28]. This attachment could be easily attached to most of the manual wheelchairs without any support from an assistant. When accessing stairs by the user himself, the user needed to have a good arm

and finger functionality. Also, the staircase required to have at least one good handrail for safety. This solution provided access to staircases for both indoor and outdoor. The most important benefit of this design was that it could provide stair-climbing capability to a manual wheelchair for a lower price. But the drawback of this application was that the user needed to have proper functionality of hands if the user operated this attachment. On the other hand, this solution was proposed as an attachment for the wheelchair. For each staircase, there should be several stair-climber attachments to serve for many wheelchair users. As a result, there existed some practical issues with regard to the maintenance of this service. Also there should be an assistance for some disabled person when attaching the attachment to their wheelchairs.



Figure 1.15: Stairmax

- Advantages:
 - Suitable for almost all types of stairs
 - Variation of step dimension does not affect the operation
 - Comfortable operation for the passenger
 - Can provide stair-climbing capability to manual wheelchairs for cheap price
- Disadvantages:
 - Operate backwards
 - The user should have a good arm and finger functionality
 - Lack of adaptability
 - Should be available for all the staircases

1.1.3 Leg Based Stair-climber

Except the other two mechanisms, leg based arrangements are not commonly used in the stair-climbing wheelchair design mainly because of uncomfortable operation for the user. In 1986, one legged hopper was developed by Marc Raibert at MIT [29]. However, two-legged (Biped Model) [30], four-legged [31] and six-legged [32] arrangement were also used for many applications. Normally, these types of mechanisms were used to operate in irregular surfaces and slippery surfaces. In robotic applications, this mechanism provided facilities to navigate rough terrain and cross large, dispersed obstacles [30]. Also due to less surface area of the leg it provided less contact surface with the ground.

Even in stair-climbing wheelchair designs, also different types of leg arrangement are used. Zero Carrier wheelchair designed by Jianjun was an eight unified prismatic joint legs, four of which attached active wheels and other four attached passive casters. Legs were mainly consisting of square aluminium alloy outer pipe and inner rod, which provide the rod to slide up and down driven by a motor. All eight legs were separately driven by eight motors and based on the operation, system can handle each leg separately. By adjusting the length of each leg, Zero Carrier could move forward even on the rough ground, while keeping its body horizontally.



Figure 1.16: Zero Carrier wheelchair

- Advantages:
 - Suitable for most of the staircases
 - Variation of step dimension does not affect the mechanism

- Operate forwards
- Can operate in rough terrain
- Disadvantages:
 - Stair-climbing operation become uncomfortable for passenger
 - Need more time to access one step
 - Complex design
 - Lack of contact with step

Summary of Literature Review

In the literature review, the basis mechanisms used for stair-climbing wheelchair development were explained by using available designs in the market. Most of the available designs could be categorized as wheel based, crawler based and leg based mechanisms. Also in some designs, two or more mechanisms were used together based on operation. Wheel-leg mechanism was an example for such development. Also, the other common popular mechanism was the wheel-track mechanism (Scalevo, topchairS). The main reason for such development was to provide comfortable operation in both stair-climbing and flat surface operation. In the following table, the features of the main three mechanisms are summarized based on five parameters. These are very important and critical factors to select the best arrangement for a stair-climbing mobile platform development. Importance of these parameters will be further analyzed in next chapter.

Table 1.1: Comparison of different stair-climbing mechanism

Mechanism	Grip	Speed	Comfortability	Adaptability	Complexity
Wheel based	Low	Low	Low	Low	Low
Crawler based	High	High	High	Low	High
Leg based	Low	Low	Low	Low	High

1.2 Research Objectives

- To design and develop a novel stair-climbing mobile platform which can provide stable and safe operation in entire stair-climbing process.
- To design and develop an appropriate stair-climbing mobile platform controller considering the different stages of stair-climbing.

- To develop a force and angle based controller system to achieve smooth and safe operation for stair-climbing mobile platform.

1.3 Outline of the Thesis

The structure of chapters of the thesis are as follows:

- Chapter 1: Introduction and Literature Review
In this chapter, detailed discussion of research and development of existing stair-climbing wheelchair designs are presented. Also based on different functionalities, comparisons have been presented for existing stair-climbing wheelchair mechanisms.
- Chapter 2: Proposed Stair-climbing Mobile Platform
A novel stair-climbing mobile platform development approach is discussed in this chapter. Also a conceptual novel design is further discussed based on stable and safe operation.
- Chapter 3: Development of Prototype
By considering all the important aspects of prototype development, development stages are explained in detail. In order to validate the design safety, simulation studies have been presented in detail.
- Chapter 4: Design of Controller
Hardware composition of the controller design and usages of motion plans for mobile platform control are discussed in detail. Implementation of PID controllers in order to execute motions plans are explained as well.
- Chapter 5: Simulation and Experimental Results
Detailed analysis of the simulation study of the novel stair-climbing mobile platform has been presented for both stair ascending and descending operations. By considering the simulation study, an experimental study has been carried out in order to validate stable and safe operation of the design.
- Chapter 6: Conclusion and Future Works
Finally a summarized conclusion of the novel design is presented based on simulation and experiential results with compared to existing development. Also based on product development, recommended further developments are explained in summarized format.

Chapter 2

PROPOSED STAIR-CLIMBING MOBILE PLATFORM

Operation over stairs by using a stair-climbing wheelchair is considered as a risky operation as discussed earlier. In stair-climbing wheelchair design, the main approach should be the stable and safe operation over stairs. In order to achieve these objectives, wheelchair mechanism should have better arrangements to maintain the static and dynamic stability. Also, mechanism should have proper grip with the staircase in order to prevent slippage. In this chapter, this will be further studied and finally a novel design will be proposed.

When designing a novel stair-climbing mobile platform based on stable and safe operation as highlighted above paragraph, it is better to analyze the available mechanisms. Because it can provide a clear demonstration about advantages and disadvantages of existing designs according to the mechanisms. As the first approach, detailed analyze was explained in the previous chapter. Based on that analysis, crawler based rubber track mechanism is selected for this research. By following that mechanism, main benefits are further discussed to justify the selected mechanism. Also, the main drawbacks of crawler based mechanism are discussed further in order to propose a solution. By considering all these facts, finally a novel design is proposed in this research.

2.1 Justification for Track Mechanism

As explained in earlier chapter, there are mainly three types of mechanisms used for stair-climbing operation. These three mechanisms are used for many applications based on different reasons such as design complexity, size, volume, weight, power consumption and stability. For this research and development, justification of crawler based mechanism selection for stair-climbing mechanism is explained based on several facts. Also, in this justification, proven examples of track based solutions available in the international market will be used as references.

2.1.1 Grip of Track Mechanism

When selecting a best mechanism for a stair-climbing wheelchair design the very important factor that should be considered is the safety. In order to have safe operation over stairs, stair-climbing mechanism should have proper grip with the staircase. As discussed in Table 1.1, the crawler type mechanism has higher grip when compared to other mechanisms. Because of the rubber track has grousers placed in a pattern throughout the track. When the grouser has contact with the stair edges, it has proper grip with stair edges because of friction force and shear force. When comparing these two forces, shear force can hold higher amount of force than friction force. As a result, rubber track mechanism can prevent slippage. But, in wheel based mechanism, the slippage is totally controlled by friction force (assumes wheels are rigidity). If the friction coefficient is changed due to surface behaviour, it can cause for slippage. The stability and safety of wheel based stair-climbing mechanism totally depend on the friction coefficient. Also, in leg based stair-climbers, the same problem exists. But, when compared to wheel based mechanism, leg based mechanisms have more protection to prevent slippage. The best method to give explanation to prove above fact is to provide information of rubber track based stair-climbers which are more popular among the disabled people. As shown in Figure 1.13, Scalevo and TopChair-S used fixed track mechanism for stair-climbing operation. Also, rubber track based stair-climbing attachment is shown in Figure 1.15 as well.

2.1.2 Speed of Track Mechanism

The other important factor for selecting appropriate mechanism is the speed. Because even a particular stair-climbing wheelchair has more stable and safe design, it does not provide practical solution if it takes more time to access a single step. But, this does not mean that a wheelchair should have high speed operation over stairs because high speed operation over a staircase may cause some issues to maintain safe operation for the wheelchair. But, a design should have appropriate speed in order to consider as a practical design. This should be further analyzed based on mechanisms.

In this study, operating paths over stairs based on the mechanisms are discussed to identify the variation of speed. In wheel based arrangement when the wheelchair is accessing steps the wheels should be placed onto the step as shown in Figure 2.1 [33]. In each and every step this operation should be continued. Based

on the operating path on the staircase, it will take more time to complete the stair-climbing operation. Because the mechanism should follow the step profile. Also, on the other hand for each and every staircase based on the step dimension, the system controller should adjust the wheel based mechanism to maintain the system stability because in every step-climbing, front and rear wheels clusters should be adjusted properly to synchronize wheel cluster operation. As a result, it takes more time to access the staircase.

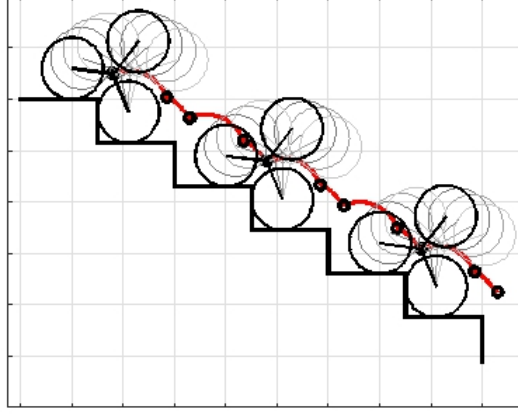


Figure 2.1: Operating path of wheel cluster mechanism over stairs

Also, similar problem exist with leg based stair-climbers. When compared to wheel based mechanism this will take more time to access a single step. Because based on the step dimension the system controller should adjust the leg placement for each and every step as shown in Figure 2.2 [34]. On the other hand when controlling the legs, system controller should also need to maintain the system stability. As a result, leg placement operation will take more time to access a single step. Also, when synchronizing the leg placement according to the step dimension, it will also cause to delay the operation.



Figure 2.2: Leg based stair-climbing operation

In rubber track based mechanisms, the highlighted problems in other two mechanisms do not affect for the operation because of the operating path of track mechanism is totally different when compared to other mechanisms. In this case, the rubber track mechanism is operated over stair edges. As a result, different step dimension does not affect the operating path. This is clearly demonstrated in Figure 2.3 by using dotted line. As it is demonstrated, even the dimension of a step take different values, the operating path over the staircase follows a straight line along the stair edges. On the other hand step synchronization process is not needed for this mechanism because of the operating path. As a result, track based mechanism has the highest speed when compared to other mechanisms.

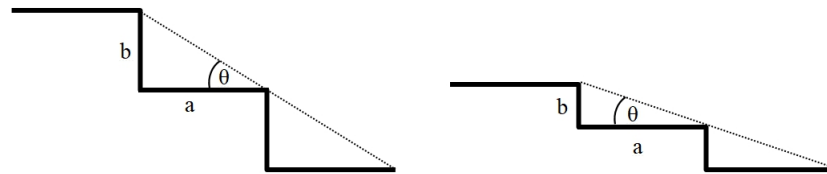


Figure 2.3: Operating path of track based stair-climbing mechanism for different staircases

2.1.3 Lack of Disturbances of Track Mechanism

User's comfort is also a major concern when design a wheelchair specially in stair-climbing because stair-climbing is totally different when compared to flat surface

operation. When accessing a staircase there could be sudden disturbances on the platform because of design constrains. But, for these types of applications such kind of sudden movements are not acceptable because the user is a disabled or elderly person who does not have enough physical strength to bear up uncomfortable operation. When designing a wheelchair, user's comfort should be considered as a main requirement. Otherwise it will not be a practical solution for disabled community.

In wheel based arrangement there is a problem when discussing about the user's comfort because of its operating path. As shown in Figure 2.1 when the wheelchair accessing the staircase the CM (Center of Mass) of the design starts to oscillate by following step profile [35]. As a result, the user placement with respect to the staircase is also oscillated. Thus, it could create uncomfortable operation for the user. This is clearly demonstrated in Figure 2.4. In general, wheel based stair-climbers are considered as uncomfortable design when using for stair-climbing.



Figure 2.4: User placement oscillation in wheel based mechanism

The same problem explained in above paragraph is applicable for Leg based mechanism as well because of the operating path along the staircase. For each and every step climbing the leg mechanism should be adjusted according to the dimension of a step. As a result, it causes for sudden movements for the user

placement as well. This is demonstrated as shown in Figure 2.5. Change of user placement for each step can create uncomfortable operation for the user.



Figure 2.5: User placement oscillation in leg based mechanism

But, in most track based mechanisms, this problem is properly addressed. Due to the operating path over the staircase as shown in Figure 2.6, it is very similar to operation in flat surface except the surface inclined. The CM of the design does not oscillate along the staircase. As a result, user does not feel uncomfortable operation. When comparing to the other two mechanisms, the track based stair-climber has the most comfortable operation.



Figure 2.6: Track based stair-climbing wheelchair operation on a staircase

2.2 Drawbacks of Track Mechanism

As explained in above sections, most of the rubber track based stair-climbing mechanisms have more advantages comparing with other mechanisms. As a result, rubber track based stair-climbing mechanisms are used to develop most of the stair-climbing wheelchairs which are more popular in international market. But, there are mainly two issues come with the track mechanism, which are lack of adaptability to the staircase and pressure exerted on stair edges. These two factors can cause some issues when operating over stairs. But, maintaining the stable and safe arrangements are the highlighted problems when accessing the stairs. This is further discussed in next section in order to identify the problem and also this will help to find a better solution to address the problem accurately.

2.2.1 Lack of Adaptability to a Staircase

In robotic applications, track based mechanisms are more popular because of many reasons. One of the most highlighted reason is the capability of navigation over rough terrain. On the other hand, track mechanism can provide some of the advantages which are available in wheel based and leg based mechanisms. This is very important when selecting a mechanism not only for considering stair-climbing, but also based on flat surface operation as well. In this study, the track based mechanism is further simplified as fixed and variable configuration tracked mechanism in order to address the problem of lack of adaptability.

2.2.1.1 Fixed Configuration of Track Mechanism

Normally fixed configuration of track mechanisms compose a simple mechanism when compared to the other type. Also, it is less expensive and it is used in most robotic application specially in rough terrain operation. Also due to the simplicity of the mechanism the complexity of the controller design is also simplified. But, the main problem exist in fixed track configuration is the lack of adaptability to a surface specially operation over a staircase [36]. In order to maintain the stable and safe operation throughout the staircase, the track mechanism should follow the staircase profile in order to control the operating path of CM properly. But, due to the design constraint this is not possible.

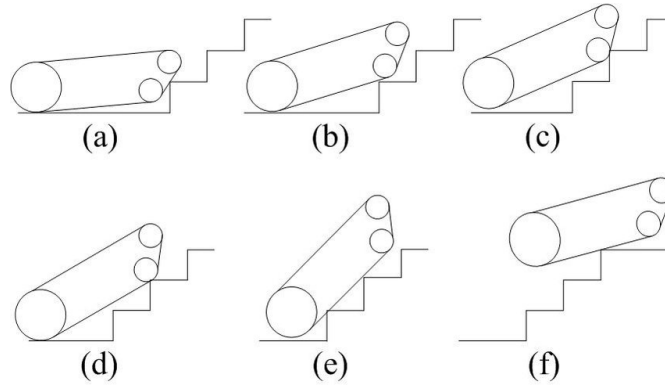


Figure 2.7: Fixed track operation over stairs

The stair ascending sequence of a fixed track mechanism is demonstrated in Figure 2.7. At the bottom of the staircase, track mechanism contacts the first stair edge by using the front track. Then the track mechanism access the first step as shown in Figure 2.7(b). This process is continued until the track mechanism leaves the ground. Throughout this sequence, the track mechanism should follow an orbital path to complete the stair ascending. When these types of mechanisms are used for a stair-climbing wheelchairs then the user will feel uncomfortable operation until the track mechanism leaves the ground. If this design has more adaptable arrangement for the staircase, then the above problem can be avoided.

But, the most highlighted problem exists with fixed track mechanism is the lack of adaptability at the top of the staircase, because operation at the top of the staircase can cause to unstable the design and also it can cause to create tip-over problem as well. As it is clearly demonstrated in Figure 2.7(f), the fixed track mechanism starts to rotate around the top of the staircase edge. As a result, it can cause difficulties to control the rotation of CM by the system controller as it becomes out of control. As a result, this mechanism is not able to maintain the stable and safe operation specially at the top of the staircase. These types of mechanisms are not suitable specially for stair-climbing wheelchairs as it can cause uncomfortable operation for the user. Also, on the other hand at this stage of the operation, the total weight of the design is applied onto one contact point of stair edge. As a result, it can cause damage to the staircase and also can cause to unstable the operation. If this design has more adaptable arrangement at the top of the staircase, it could help to minimize pressure applied to the top of the stair edge. As a conclusion it emphasizes that track based mechanism should have more adaptable arrangement to maintain a stable posture.

2.2.1.2 Variable Configuration of Track Mechanism

In robotic applications specially in rough terrain operation, variable configuration of tracked mechanism is much popular than fixed configuration because of its capability of navigation through most of the obstacles. Basically these types of designs contain two or more track mechanisms with separate actuators to control the tracks independently [37]. These types of track designs have much more complex mechanisms and also these are more expensive than fixed track mechanism. As a result, variable track mechanism controlling will become a more complex task compared to fixed track mechanism. When comparing the adaptability to the surface, variable track mechanism has more capabilities than the other mechanisms.

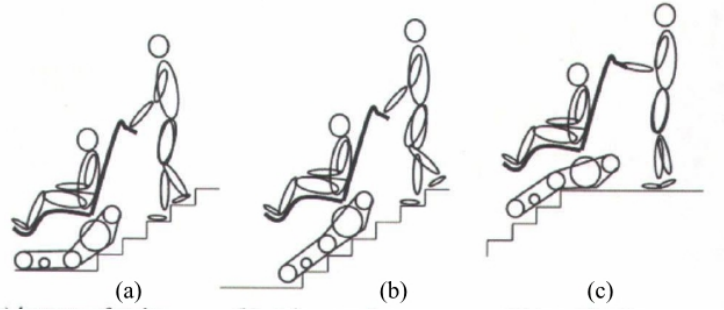


Figure 2.8: Variable track mechanism operation over stairs

The stair-climbing sequence of a variable track mechanism is demonstrated in Figure 2.8. In this variable track mechanism there are dual section track arrangements and these two mechanisms can be controlled separately. At the start of the stair-climbing operation, first the rear side of track mechanism access the first step while keeping the front track mechanism parallel to flat surface. Based on this arrangement it provides more adaptability to the staircase. It will provide more comfortable arrangement for the user. In the next step, both the front and the rear tracks are operated as much as possible to follow the staircase profile until the wheelchair leaves the ground. At the top of the the staircase which is the most critical operation, the variable track mechanism already follows the the staircase profile in order to achieve stable operation as shown in Figure 2.8(c). This arrangement provides more adaptability to the staircase in order to achieve stable and safe operation than the fixed track mechanism.

As demonstrated in Figure 2.8, the intermediate operation in between stage (a) to (b) should be further discussed regarding to the adaptability. But, this sequence is not clearly mentioned in the figure. The reason for highlighting this matter is that there exists lack of adaptability to the staircase because of dual track mechanism. Until the dual track mechanism complete the arrangement as shown in stage (b), the front track mechanism has only one contact point with the flat surface. This happens because of dual track mechanism. If there are triple track mechanisms then it has more adaptable arrangement than dual track mechanism. But, increasing number of track mechanisms for a stair-climbing wheelchair is not a practical solution. The same issue exists at the top of the staircase as well. Before arriving to the arrangement of stage (c), the front and the rear tracks need to arrange into "V" shape to make contact with the stair edge and top of the flat surface respectively. In this arrangement, the dual track mechanism does not have much adaptability to the staircase. The only difference between single track and dual track in the same scenario is that single track has only one contacting point whilst the other type has two contacting points. But, this is not good enough to maintain the stability at the top of the staircase. Also, same thing is happened just after the arrangement of (c) in stair ascending. To address this problem, the solution should be able to provide adaptable arrangement at the bottom and top of the staircase. There may exists some problems when achieving the adaptability without increasing the number of track mechanisms.



Figure 2.9: B-Free wheelchair operation over a staircase

As shown in Figure 2.9, the B-Free wheelchair has five track mechanisms to provide more adaptable arrangement. It is clear that when increasing the number

of tracks, it can provide a more stable arrangement. But, it is not able to provide comfortable operation for the user because even this design has more adaptable arrangement based on stability, it does not provide comfortable operation because of its operating path over the staircase. Also, based on the controller design, the user feels sudden movement and vibration when climbing each and every step.

As a conclusion, when increasing the number of track mechanisms, it can provide a more adaptable arrangement to the staircase. But, there exists difficulties to facilitate comfortable operation. A practical solution should come with a design which can provide more adaptable arrangement to achieve stable and safe operation whilst providing more comfortable operation.

2.2.2 Pressure Exerted on Stair Edges

In most of the track based mechanism, the other highlighted problem is the high pressure exerted on stair edges, because most of the track based mechanisms are operated over stair edges rather than on steps. As a result, there exists high pressure on stair edges and can cause damages to the stair edges as well. On the other hand, in some cases, the total weight of the wheelchair can exist only on one contacting point as shown in Figure 2.7(f). On such situations, it can cause damages to stair edges, resulting in becoming a reason to make the wheelchair unstable as well. Such kind of arrangement is not suitable for a critical application such as a stair-climbing wheelchair.

As explained earlier, most of the track based mechanisms are operated over stair edges. As a result, the total weight of the wheelchair is distributed among the number of contacting points of the stair edges. If it is possible to use a rubber track with acceptable width, then it will cause to reduce the pressure apply on stair edges. Also, on the other hand, if a design has more contacting points, then the total weight of the wheelchair can be distributed among those contacting points. This will also help to decrease pressure on each contact point as well. On the other hand, when constructing staircases, constructors use different methods and arrangements to provide finishing and more protection to stair edges by using concrete, steel or solid timber. As a result, almost all the staircase edges can bear up high pressure. As a result, operation over stair edges does not create damages anymore.

2.3 Design Study

In this section, a detailed study of the novel design of the stair-climbing mobile platform is discussed. As the design approach, first of all, it is better to study the staircase construction standards used in locally and internationally. In this study, one local and three international staircase construction standards are used to identify the possible and most practical dimensions for a step. Based on these parameters, the selected dimensions for the design are explained based on different aspects. Also, other design aspects are described based on adaptable arrangement for staircases.

2.3.1 Standards for Staircases

In past, when constructing staircases, constructors followed different dimensions for steps based on particular application and available space. As a result, for some users who use crutches or any other supporting devices for their mobility, it became harder to access the staircases. Hence, almost all countries introduced national policies regarding staircase constructions. As explained in Appendix A, there are many types of staircases and step shapes used in different countries. Based on the shape of the step, the measurement of rise and going also take different values. Basically, there are two types of staircases available, which are linear and non-linear (twisted) staircases. In most of the public and private places, linear staircases are commonly used. Also, most of the available stair-climbing wheelchairs in the market are designed for linear staircases only because of the availability of linear staircases in common places. Moreover, if a wheelchair is operated on a twisted staircase, wheelchair mechanism should have separate arrangements to twist the chassis to adapt the staircase. In this research, linear staircases are only taken into consideration. In this study, four stair construction standards used in different countries are considered as explained in Appendix A. In Sri Lanka, according to the extraordinary gazette, it did not clearly mention about the exact dimensions for a staircase, but it clearly mentioned that staircases should follow uniform risers and goings and also it should be of gentle gradient. By considering the construction standards, the maximum hypotenuse and maximum staircase angle are calculated as explained in Appendix A. After referring Table A.1, the maximum angle and maximum hypotenuse dimension for a step are selected as shown in Table 2.1. Based on these values, the design can be converted into a practical solution which will be able to access most of staircases.

Table 2.1: Selected staircase dimension for the study

Max Hypotenuse(mm)	Max Angle(Deg)
400	40

2.3.2 Proposed Design

The chassis design takes the most important point of this research study because stable and safe operations are mainly depended on this novel design. Throughout the last chapter, the advantages and disadvantages of different types of stair-climbing mechanisms were discussed based on different parameters. Also, clear justification for rubber track mechanism selection was provided earlier. As highlighted earlier, in stair-climbing operation, the most critical operation exists at the top of the staircase. Because when transferring the CM of the design from flat surface to stair edges and vice versa, there may exist tip-over issue and slippage because of lack of controllability of CM operation. When designing this novel design, the above problems are mainly focused. By considering all these facts, a novel track based stair-climbing mobile platform with improved adaptability to the staircase is invented as shown in Figure 2.10.

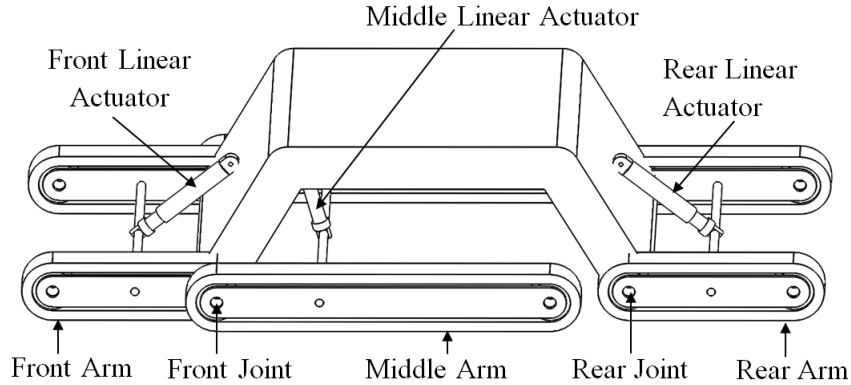


Figure 2.10: Proposed mechanical design

2.3.2.1 Design of the Chassis

As discussed earlier, with the fix track mechanism, there exists lack of adaptability to the staircase. As a solution, variable track based mechanism can provide more adaptable arrangement to the staircase. This was discussed in detail by using the available products in the market. Also, in that discussion, it concluded that increasing the number of track mechanisms could provide more adaptability, but it can create uncomfortable operation for the user as well. In this research study,

a novel variable track mechanism is proposed as shown in Figure 2.10. The most important point of this design is that it can provide the best adaptable arrangement to the staircase when comparing with the available designs. This will be clearly demonstrated in coming sections by using staircase operation for both ascending and descending.

In this design, shape of the chassis takes the main responsibility to facilitate the adaptability. When the design is on the top of the staircase, the chassis should have appropriate design to maintain the adaptable arrangement throughout the operation. There should be a defined minimum stair edge clearance area to prevent conflict in between the chassis with the top of the stair edge. Based on the selected postures for both ascending and descending, the minimum stair edge clearance area can be calculated by using two methods as explained below. Based on applications such as stair-climbing platform, robotic applications, appropriate method can be used to define the minimum stair edge clearance area.

Calculation of Minimum Stair Edge Clearance Area - Method 1

This method provides the basic shape of the chassis design, which can be used for both stair-climbing platform and robotic applications. This can be calculated based on the design placement at the top of the staircase as shown in Figure 2.11

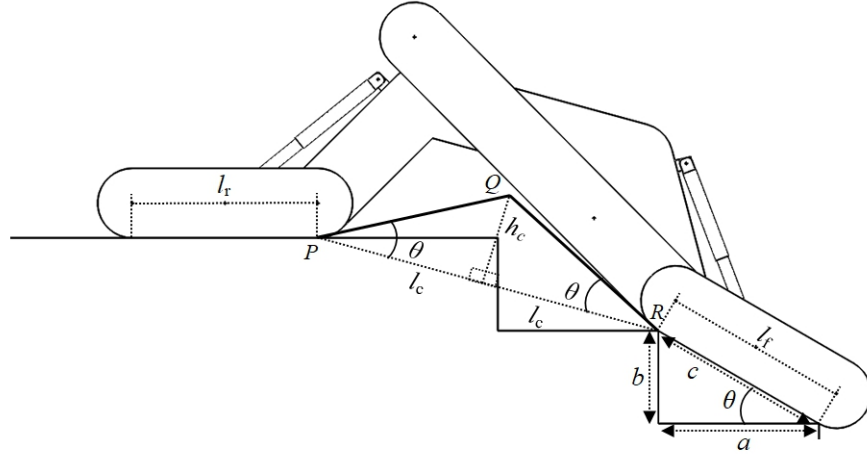


Figure 2.11: Minimum stair edge clearance area calculation by using method 1

Based on the geometrical design as shown in Figure 2.11, the minimum stair edge clearance height can be obtained as follow. In this calculation, the length

in between front arm contact point (R) and rear arm contact point(P) and angle of the staircase (θ) are considered.

$$h_c = l_c \tan(\theta/2) \quad (2.1)$$

By replacing the selected maximum staircase angle for θ , the minimum stair edge clearance height can be calculated by using equation 2.1 for particular application. Based on the minimum stair edge clearance height, it is possible to calculate the minimum stair edge clearance area by using equation 2.2 which is denoted by PQR triangle in Figure 2.11.

$$A_c = l_c h_c \quad (2.2)$$

Within this area, there should not be any object attached to the design. Otherwise, it can collide with stair edges and the design operation cannot be continued furthermore. By following this chassis design condition, any types of shapes can be used for the design based on the application. Due to this defined minimum stair edge clearance area, all the postures defined in Appendix C can be implemented with this chassis shape.

Calculation of Minimum Stair Edge Clearance Area - Method 2

Basically this method is recommended for stair-climbing wheelchair development platform because this method can provide a lowest minimum stair edge clearance area and a lowest minimum stair edge clearance height when compared with method 1. In this method, two assumptions are considered which are front arm contact point (R) is operated over stair edges and rear arm contact point(P) maintain contact with flat surface when the design is at the top of the staircase. In this calculation also the design placement at the top of the staircase is considered as shown in Figure 2.12.

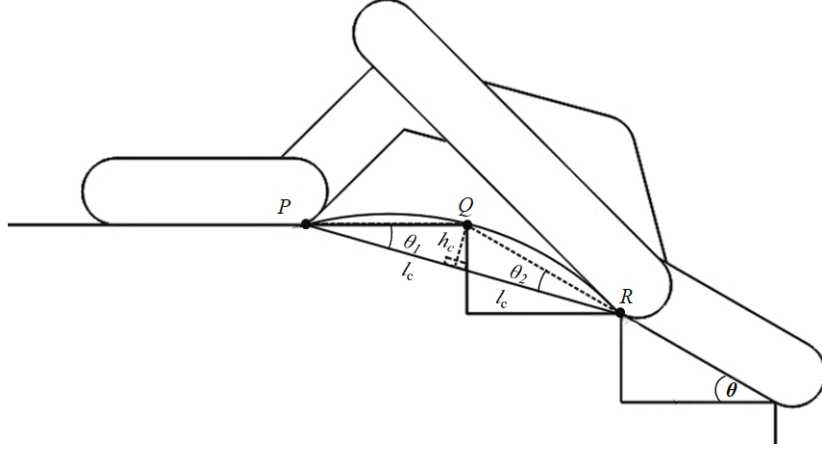


Figure 2.12: Minimum stair edge clearance area calculation by using method 2

According to the geometrical relationship, the minimum stair edge clearance height can be obtained by using the length in between the front arm contact point(R) and rear arm contact point(P) and angle of the staircase (θ) as used before. In this method, minimum stair edge clearance height can be calculated by using following equations. According to the equation 2.3, 2.4 and 2.5, minimum stair edge clearance height takes a maximum value when the θ_1 and θ_2 equal to half of the staircase angle which is θ .

$$h_c = 2l_c(\tan \theta_1 \tan \theta_2)/(\tan \theta_1 + \tan \theta_2) \quad (2.3)$$

$$\theta = \theta_1 + \theta_2 \quad (2.4)$$

$$0 \leq \theta_1 \leq \theta \quad (2.5)$$

As demonstrated in Figure 2.12, the area denoted by $PQRP$ which is called segment of circle is considered as the minimum stair edge clearance area. In order to observe the path of the arc, angle of θ_1 should be substituted as shown in equation 2.5. By substituting values for angle of θ in equation 2.3 and equation 2.4, the path of the arc can be observed. As explained earlier within this area there should not be any object attached to chassis. Otherwise it can collide with stair edges and operation cannot be continued furthermore. When comparing with the previous method, the main disadvantage of this method is that all the postures mentioned in the Appendix C cannot be implemented with this chassis

As illustrated on the above figure, a marginal angle which is θ' , is considered as 20 degrees. But, based on different applications, this marginal value can be selected. By combining the total angle of the chassis and minimum stair edge clearance height, the required shape and dimension for the design can be observed as shown in Figure 2.13. For this research and development, the total angle is considered as 60 degrees and with extra margin, the minimum stair edge clearance height it is considered as 250mm.

2.3.2.2 Arm Design with Rubber Tracks

When designing the supporting arms for the chassis, it should be able to provide facilities to increase the adaptability while maintaining the safety as well. Also, on the other hand arrangement and placement of arms should have proper contact with the staircase. On the other hand, rubber track arms should have acceptable number of contacting points with stair edges to minimize pressure.

As shown in Figure 2.10, this design consists of a pair of three rubber track arms which are called front, middle and rear arms. Front and rear arms are used mainly at the beginning or end of the staircase operation whilst the middle arm is used at the middle of the staircase operation. The usage of each arm will be explained based on operation in coming chapters. When ascending and descending, the design should have a method to observe the angle of the staircase in order to control the operation. In order to achieve this objective, front and rear arms are designed based on the summarized details of stair construction standards as shown in Table 2.1. Based on the table, the selected maximum adjacent length of two stair edges is 400mm. It means that front and rear arms should have a minimum length of 400mm to properly contact at least two stair edges as shown in Figure 2.11. For this research and development, the length of the front and rear arms are considered as 400mm, because more than the minimum length can provide more stable arrangement for the design, but it can cause difficulties to control arms and also will take more space as well. Also, when selecting dimensions for the middle arm, the length of the front and the rear arm contact point is considered which is called $2l_c$. The length of the middle arm should be less than or equal to this length. Otherwise, the middle arm can act as a barrier to maintain the desired postures in some stage of operation. By considering all the facts, 800mm is selected as the length of the middle arm in this research and development.

When the front arm or the rear arm has proper contact with at least two stair edges, then the system controller can be able to calculate the staircase angle for further operation. In order to get a feedback whether the arms are properly contacted with the stair edges, load cells are placed in series with the stroke of the linear actuators. There are three linear actuators to control the three set of arms and three load cells are implemented for each linear actuator. Based on this arrangement, the controller can observe the applied force by the linear actuator on each arm. The load cell placement for each linear actuator will be discussed in coming chapters. In middle arm design, the same parameters used for the front and the rear arms are applied. The middle arm should have a minimum length of $400mm(D)$ and should not exceed the chassis length which is length between P to R as shown in Figure 2.13.

2.3.3 Adaptability of the Design for Staircases

Based on the geometrical design, it should have the adaptability to the standard staircases as discussed earlier. In order to illustrate adaptability, staircase standard in Building Code of Australia (BCA) is considered in this study. Because it has the maximum and minimum staircase angle and maximum hypotenuse for a step. Also, to demonstrate the adaptability to the staircase at top, the middle and the bottom, design postures at those stages are illustrated on the same figure. In this study, the actual dimensions for design and staircase are used to draw the sketch. As illustrated in the Figure 2.14, arms maintain parallel arrangements with particular surfaces to maintain the required postures. Thus, it concludes that this design can maintain adaptable arrangements for standard staircases as discussed earlier. Moreover, this can be further simplified as, this design has the adaptability for linear staircases which are summarized in Table 2.1.

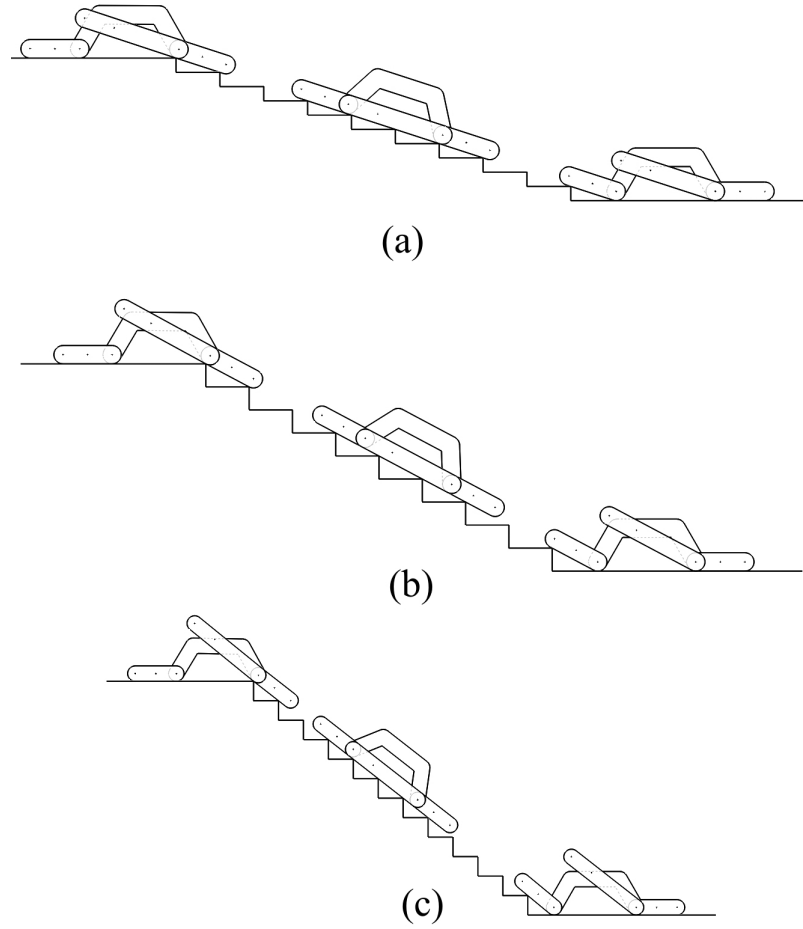


Figure 2.14: Adaptability of the design for staircases of (a) 18deg (b) 28deg (c) 38deg

2.4 Detailed Analysis of the Dynamics for Stair-climbing Operation

In this study, the design postures for stair ascending are further discussed based on different stages of the operation. As the first approach, the basic stages of stair ascending operations are discussed by using sequence diagrams. Also, by using classical mechanism, static analysis will be carried out to study the safety of the design for selected stages. Also, basic conditions for stair-climbing operation are further discussed. In order to simplify the study, the basic shape of the design is considered. Also, user placement is also neglected to simplify the study.

2.4.1 Simplified Basic Stages of Stair Ascending Operation

Based on the geometric configuration of the design, there are several stages to be followed when accessing a staircase. In these basic stages, there are some impor-

tant operations where both front and rear arms should be properly synchronized in order to create more adaptable arrangement to the staircase. In this study, all these stages are selected for the static analysis in order to discuss the safety of the design. Also, in order to discuss about the basic conditions to access a staircase, staircase approaching arrangement is further discussed in this study. Also, the stable marginal angle of the design is discussed based on the selected maximum staircase angle.

In order to follow a static analysis study, these basic stages are selected to represent the design operation in stair ascending. These stages are called approaching, climbing, ascending and leaving as shown in Figure 2.15. In these four basic stages the forces exist in between the design and the staircase get different behaviour based on different aspects. In this static study, several factors have been considered as assumption in order to minimize the complexity of the analysis. Here are the assumptions used for this study.

- The mass distribution of the design is uniform
- Deformation, suspension and slippages of the rubber track are neglected.
- Staircase is a solid object

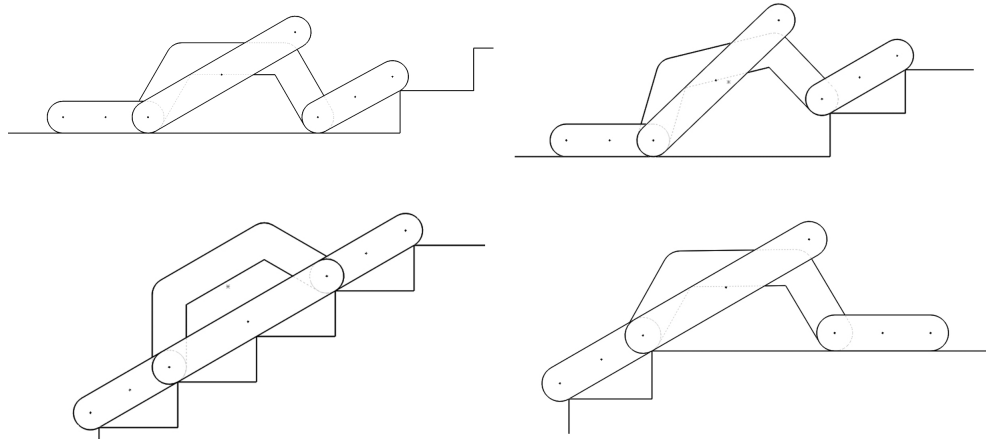


Figure 2.15: Simplified basic stages of stair ascending

2.4.1.1 Approaching

As shown in Figure 2.16, the design starts to contact the first step of the staircase. In this case, the rear arm angle is adjusted according to the staircase angle for

clear demonstration. Here, the angle of attack of rear arm is equal to the staircase angle. Also, the middle arm angle is adjusted to follow the staircase angle as well. In order to maintain proper contact with the floor, the front arm always maintains a parallel arrangement with the floor. By using classical mechanics, the static behaviour of this stage of operation is derived as follow. Based on force equilibrium and torque equilibrium, the following equations can be derived.

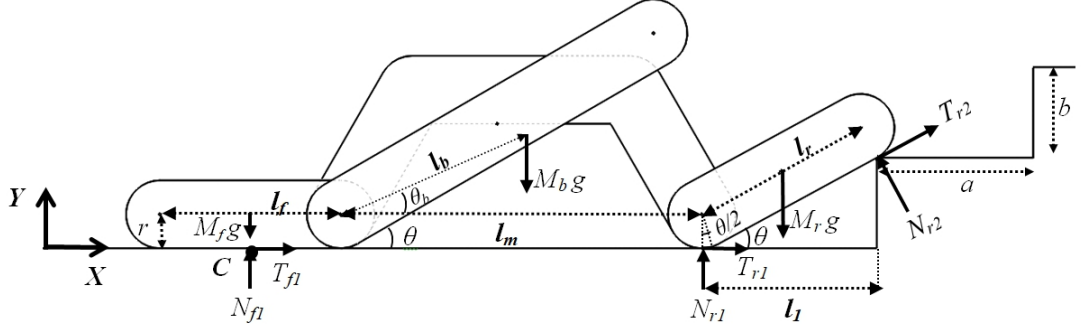


Figure 2.16: Design arrangement when touching first step

$$F_x = T_{f1} + T_{r1} + T_{r2} \cos \theta - N_{r2} \sin \theta \quad (2.6)$$

$$F_y = N_{f1} - M_f g - M_b g + N_{r1} - M_r g + N_{r2} \cos \theta + T_{r2} \sin \theta \quad (2.7)$$

$$M_c = -M_b g(l_f/2 + l_b \cos \theta_b) + N_{r1}(l_m + l_f/2) - M_r g(l_m + l_f/2 + l_r/2 \cos \theta) + N_{r2} \cos \theta(l_m + l_f/2 + l_1) + N_{r2} \sin \theta(b) - T_{r2} \cos \theta(b) + T_{r2} \sin \theta(l_m + l_f/2 + l_1) \quad (2.8)$$

$$l_1 = r \sin(\theta/2) + b / \tan \theta \quad (2.9)$$

The traction forces of the design when approaching the staircase can be derived by using above equations. Also, when the design is on approaching stage the required driving torque can be observed as follow.

$$\tau_t = (T_{ft} + T_{rt})r \quad (2.10)$$

2.4.1.2 Climbing

In this stage the rear arm starts to contact multiple stair edges and keep the rear arm parallel to the staircase. This parallel arrangement provides more adaptable arrangement with the staircase. In this case also, the middle arm angle is fixed to

the staircase angle for providing support to maintain this adaptable arrangement. Throughout this stage, the front arm keeps a parallel arrangement with the floor to ensure proper contact. Based on force equilibrium and torque equilibrium, following equations can be derived.

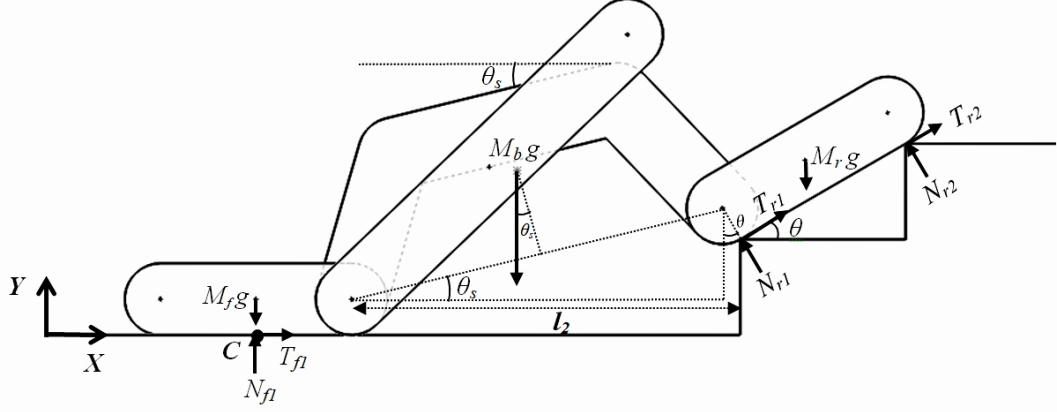


Figure 2.17: Design arrangement when climbing a staircase

$$F_x = T_{f1} - N_{r1} \sin \theta + T_{r1} \cos \theta - N_{r2} \sin \theta + T_{r2} \cos \theta \quad (2.11)$$

$$F_y = N_{f1} - M_f g - M_b g + N_{r1} \cos \theta + T_{r1} \sin \theta + N_{r2} \cos \theta + T_{r2} \sin \theta \quad (2.12)$$

$$\begin{aligned} M_c = & -M_b g(l_f/2 + l_b \cos(\theta + \theta_s)) + N_{r1} \cos \theta(l_f/2 + l_2) + N_{r1} \sin \theta(b) \\ & + T_{r1} \sin \theta(l_f/2 + l_2) - T_{r1} \cos \theta(b) - M_r g(l_f/2 + l_m \cos \theta_s + l_r/2 \cos \theta) \\ & + N_{r2} \cos \theta(l_f/2 + l_2 + a) + N_{r2} \sin \theta(2b) + T_{r2} \sin \theta(l_f/2 + l_2 + a) \\ & - T_{r2} \cos \theta(2b) \end{aligned} \quad (2.13)$$

$$l_2 = l_m \cos \theta_s + r \sin \theta \quad (2.14)$$

Also, by following same method as explained in approaching stage, the traction force and the driving torque can be calculated by using above equations.

2.4.1.3 Ascending

In this posture, all the rubber tracks arms are operated over stair edges. Throughout this stage of operation, all the arms maintain parallel arrangements with the staircase. It means all the arms are parallel to each other. In this case also, the force equilibrium and torque equilibrium can be observed by using the classical mechanism analysis.

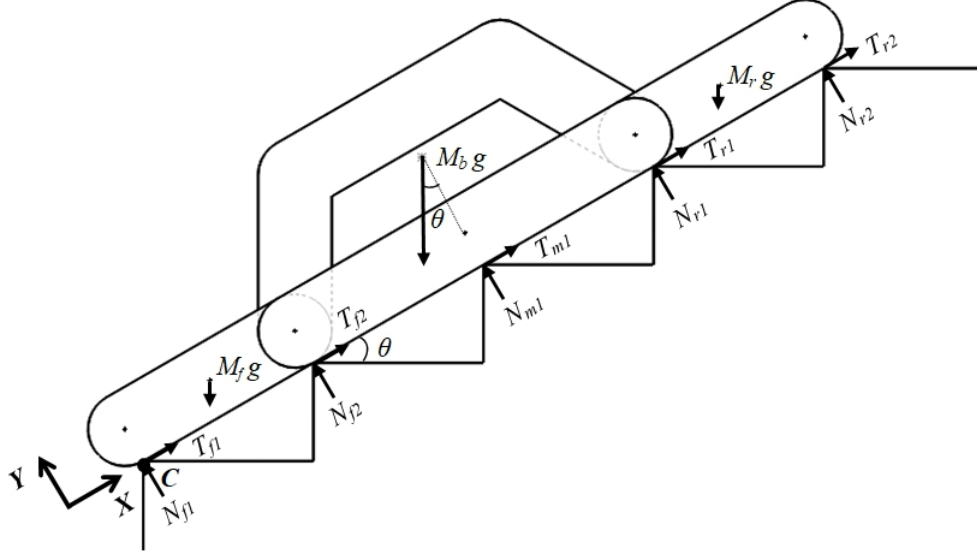


Figure 2.18: Design arrangement when ascending

$$F_x = T_{f1} - M_f g \sin \theta + T_{f2} - M_b g \sin \theta + T_{m1} + T_{r1} - M_r g \sin \theta + T_{r2} \quad (2.15)$$

$$F_y = N_{f1} - M_f g \cos \theta + N_{f2} + N_{m1} - M_b g \cos \theta + N_{r1} - M_r g \cos \theta + N_{r2} \quad (2.16)$$

$$\begin{aligned} M_c = & M_f g \sin \theta(r) - M_f g \cos \theta(l_f/2) + N_{f2}c + N_{m1}2c - M_b g \cos \theta(l_f + l_b \cos \theta_b) \\ & + M_b g \sin \theta(r + l_b \sin \theta_b) + N_{r1}3c - M_r g \cos \theta(l_f + l_m + l_r/2) + M_r g \sin \theta(r) + N_{r2}4c \end{aligned} \quad (2.17)$$

By following the same method as explained in approaching stage, in ascending operation also, the total traction force and driving torque can be calculated by using above equations.

2.4.1.4 Leaving

This is the last step of stair ascending operation which is much similar to approaching posture. When comparing to approaching, in this posture, the front arm maintains a parallel arrangement with the staircase while maintain a parallel arrangement with the floor by the rear arm. In this case also, a similar behaviour is used for middle arm operation in order to support the operation. Also, the force equilibrium and torque equilibrium can be observed by using the classical mechanism analysis.

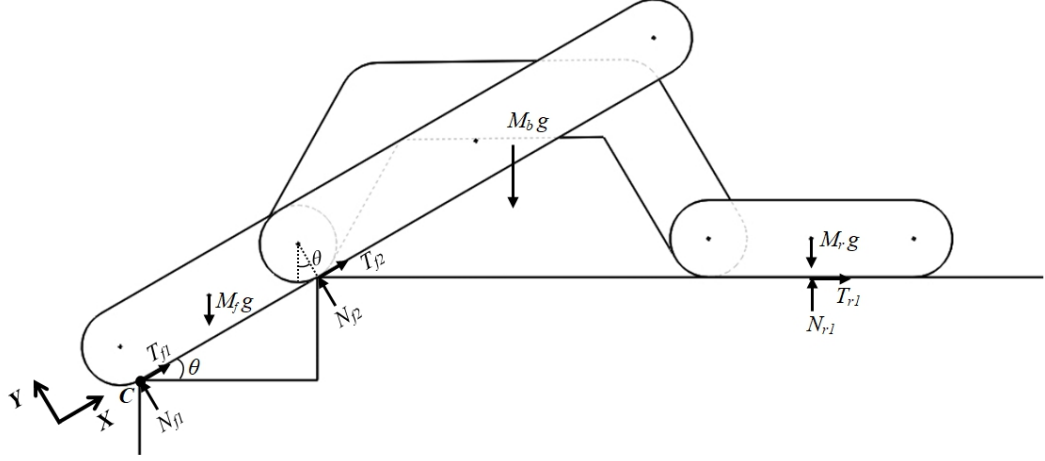


Figure 2.19: Design arrangement when leaving a staircase

$$F_x = T_{f1} - M_f g \sin \theta + T_{f2} - M_b g \sin \theta - M_r g \sin \theta + N_{r1} \sin \theta + T_{r1} \cos \theta \quad (2.18)$$

$$F_y = N_{f1} - M_f g \cos \theta + N_{f2} - M_b g \cos \theta - M_r g \cos \theta + N_{r1} \cos \theta - T_{r1} \sin \theta \quad (2.19)$$

$$\begin{aligned} M_c = & M_f g \sin \theta (r) - M_f g \cos \theta (l_f/2) + N_{f2} c - M_b g (a - r \sin \theta + l_b \cos \theta_b) \\ & - M_r g (a - r \sin \theta + l_m + l_r/2) + N_{r1} (a - r \sin \theta + l_m + l_r/2) - T_{r1} b \end{aligned} \quad (2.20)$$

By following the same method explained in above three stages, the total traction force and driving torque can be calculated by using above equations. By analyzing all the four basic stages by using classical mechanics, it provides clear illustration of the design operation over stairs in stair ascending. Also, a clear explanation has been derived for the traction forces and driving torque for each stage. Thus, it helps to clearly describe the basic conditions to maintain safe operation over a staircase.

2.4.2 Basic Conditions of Stair Ascending

In this section, the basic requirements for accessing the staircase are discussed based on three main conditions. For these conditions, expressions have been derived. Based on the sequence diagram of stair ascending as shown in Figure 2.15, it is able to derive basic conditions for stair ascending operation.

Geometric Constraint: This condition describes the basic geometric condition of design when approaching the first step as shown in Figure 2.16. In this case, the dimension of the rear arm and its angle directly affect for the approaching. The geometric condition can be observed as follow. In this case, the θ is the selected maximum angle for the rear arm operation.

$$b \leq r - r \cos(\theta/2) + l_r \sin \theta \quad (2.21)$$

Friction Constraint: In all the stages of stair ascending operation, there should be a friction force condition to prevent any sliding effect. In order to achieve this, normal reaction force and traction force should be within the friction cone. This condition can be observed as follow.

$$T_{fi} \leq \mu N_{fi}, T_{mi} \leq \mu N_{mi}, T_{ri} \leq \mu N_{ri} \quad (2.22)$$

Torque Constraint: In stair ascending operation driving motors should have enough power to drive the design. This can be express as follow.

$$\tau_t \leq \tau_m \quad (2.23)$$

As a summary the geometric constraint mainly depends on the selected maximum angle for the rear arm. Also, friction condition mainly depends on the material selection and shape of grouser of the track. Finally, the torque constraint can be achieved by selecting proper motor.

2.4.3 Safety Analysis of Stair-climbing

Based on the geometrical design of this mobile platform, different types of postures can be proposed for stair-climbing based on different aspects. One of the main aspect that should be considered when proposing postures is the design safety. But, when using this design for other applications like robotics, different aspects can be considered when defining the postures. In this study, the design postures at top, middle and bottom are further discussed to analyze the safety of the design.

2.4.3.1 Design Posture at the Top and the Bottom of the Staircase

In this stair-climbing mobile platform development there are several stages defined for both stair ascending and descending as illustrated in Appendix C. Based on those stages, the design postures at top and bottom of the staircase take huge

impact to the design safety because at those stages, the front and the rear arms should maintain parallel arrangements to particular surface. As a result, the design operation at those stages could follow a smooth path in order to avoid sudden disturbances onto the platform. Detailed analysis of design operation on those stages will be discussed in coming sections. If the design could able to maintain these postures then the absolute total angular displacement of both front and rear arms should follow staircase angle as shown in Figure 2.20. Based on these postures it could provide more safe operation.

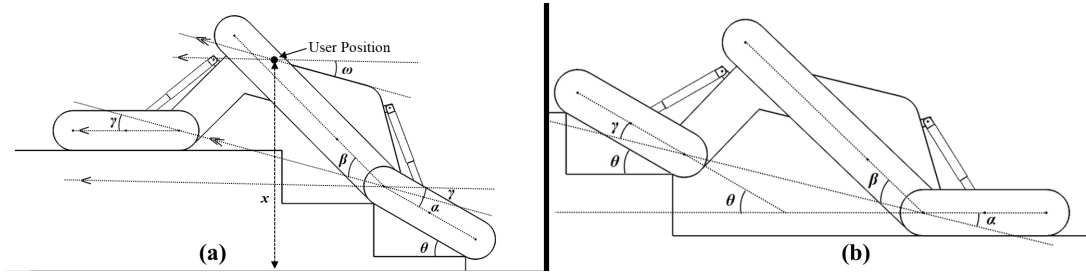


Figure 2.20: Front and rear arms synchronization (a)top of the staircase (b)bottom of the staircase

When maintaining these postures, design speed and linear actuator operation should be synchronized properly. In order to demonstrate the design operation at these stages, basic stages for stair descending operation as demonstrated in Figure 4.5 are considered. In this study, the slope of the staircase was considered as 40 degrees to demonstrate the full range of linear actuator operation. Also, in these stages, the design speed was controlled to a constant value. Furthermore the time interval in between two stages was considered as 40 seconds to illustrate the results more clearly. Based on each stage of the operation, the displacement for each linear actuator can be plotted by substituting the angle values in the equations as discussed in Table 4.3. In this study, the actual placements of linear actuators in the prototype were considered when observing the linear actuator displacement for 40 degrees of staircase. By using these displacements, the velocity profiles for both front linear actuator and rear linear actuator are presented in Figure 2.21 by following the stages.

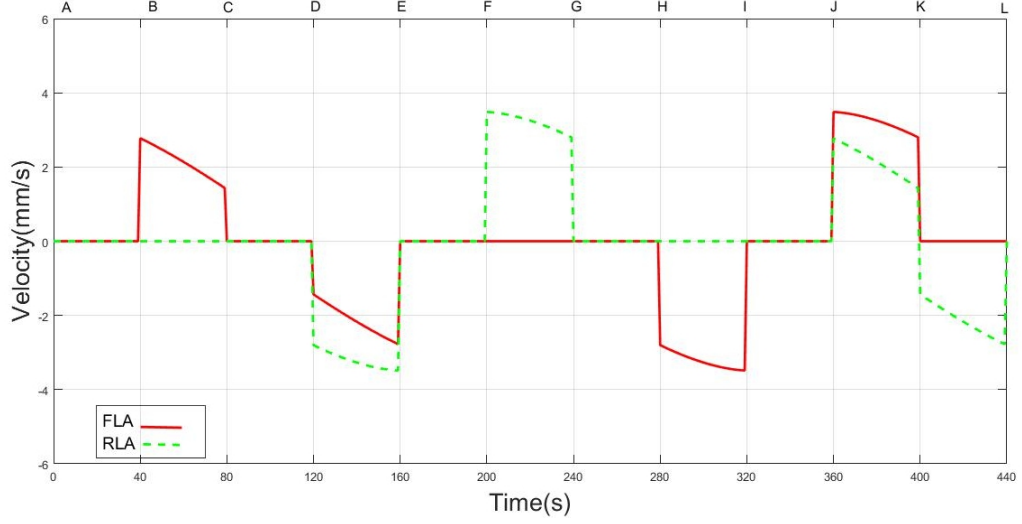


Figure 2.21: Velocity profile for the front and the rear linear actuators in stair descending operation

As it is demonstrated in above figure, stage *D* to *E* and *J* to *K*, both front and rear linear actuators operate simultaneously. In these stages, linear actuators should have the capability to maintain required velocity based on the design speed selection for particular stage. In this case, based on the design speed selection, both linear actuators should have minimum speed of around 4mm/s^{-1} . Furthermore, the required minimum speed can be reduced by decreasing the design speed as well. Also, it is highly recommended to lower the speed in stair-climbing operation to maintain stable and safe operation.

Proper synchronization of front and rear arm operation at the top and the bottom of the the staircase is a major factor to maintain safety of the design. If one or both arms are unable to maintain required operation, then the design will not be able to maintain its safety anymore. As it is a non-redundant design, design operation should be stopped if one of the arm operation is failed. This should be detected by the controller design and should take immediate actions to stop the operation. In this thesis, this issue was not considered in controller design as it will be considered in future works.

2.4.3.2 Avoiding Tip-over on Stair Edges

As discussed earlier, there were three basic conditions to be satisfied in order to maintain the safety while climbing stairs. Except these conditions, there could exists another factor which could affect for the safety which is called the tip-over issue. In stair approaching stage, the design maintains stable arrangement by

keeping the front arm parallel to the flat surface. In climbing stage also, the front arm posture provides more stable arrangement to the design to prevent tip-over problem as well. The same behaviour can be observed for the leaving stage as well. But, in ascending stage, there could exist a tip-over problem due to the slope of the staircase, because in this stage, the design is on the staircase and there is no proper contact with the flat surface by any arm. Based on the tip-over avoiding, this stage of operation should be further discussed. Due to similar posture for stair descending, stair ascending is further considered in this study.

As explained earlier, when the design is on ascending stage, all the contacting points of the design are on stair edges. Based on the dimensions of the design and staircase, numbers of contacting points are varied. Based on these contacting points, the safety of the design gets different behaviour. In order to demonstrate the design arrangement in ascending stage, staircase standards in Building Code of Australia (BCA) is considered in this study, because it has the maximum staircase angle and maximum hypotenuse for a step. Also, in this study, the user placement with seat adjustment is considered. By using SolidWorks software, the actual position of the CM of the design is observed by following the actual dimensions and allocated total weight discussed in Table 3.1. Based on the slope of the staircase and user position, design arrangement for ascending stage is demonstrated in Figure 2.22 and Figure 2.23. As it is demonstrated, the CM of the design will change slightly based on the seat adjustment.

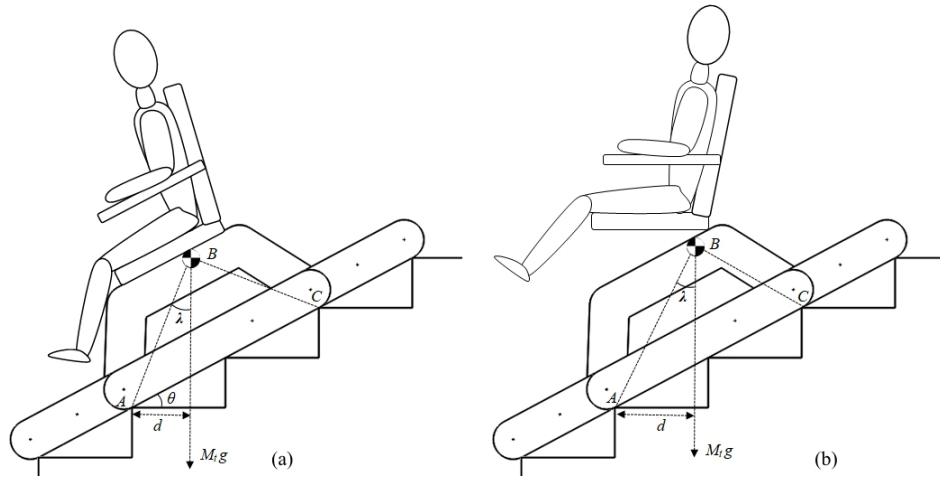


Figure 2.22: Design arrangement in ascending stage for 28deg of staircase (a)without seat adjustment (b)with seat adjustment

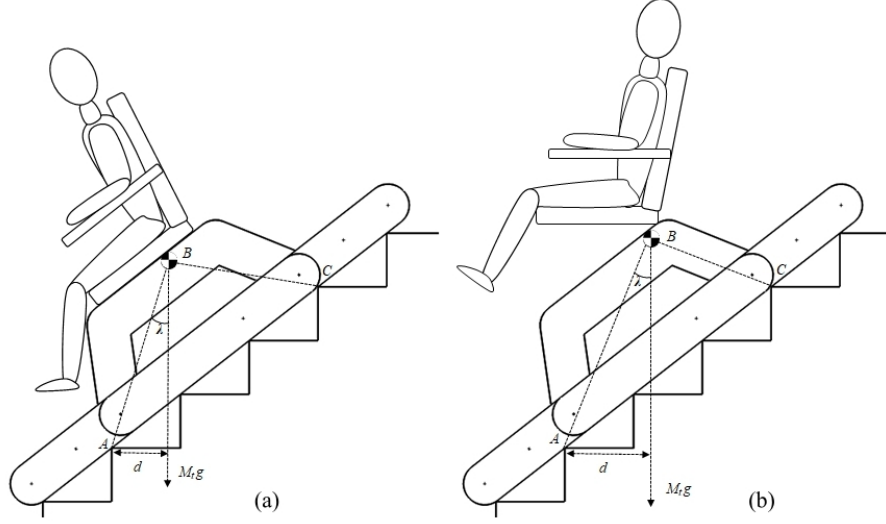


Figure 2.23: Design arrangement in ascending stage for 38deg of staircase (a)without seat adjustment (b)with seat adjustment

Based on stability analysis, different methods can be used for this study such as Center of Gravity Projection Method (CGPM), Longitudinal Stability Margin (LSM), Static Stability Margin, Energy Stability Margin etc. By considering these methods, Center of Gravity Projection Method is used in this study [38]. As shown in the above figures, there are five to six contacting points in between the track and stair edges. But, based on different dimensions, number of contacting points can be varied. In order to get the minimum stable marginal angle, contacting points of chassis with stair edges is considered as the boundary of a polygon. Because minimum stable marginal angle exists when the front arm length is equal to length of adjacent stair edges as shown in Figure 2.22. In other cases where the length of adjacent stair edges are less than the front arm length, the stable marginal angle is extended as shown in Figure 2.22. In these postures the projection of CG is within the boundary of the stability pyramid of ABC . As a result, these postures are stable. Based on this posture, stable marginal angle can be calculated as follows.

$$\lambda = \sin^{-1}(d/l_t) \quad (2.24)$$

When all the arms are in parallel to each other, the boundary of polygon is changed. As a result, the stable marginal angle is extended. Also, in this stage of the operation, all the arms are parallel to the staircase. This can be considered as fixed track mechanism. Due to this reason, the placement of CM of the design

is on a fix position. Staircase angle is the only parameter which affect for the stable margin angle. In order to maintain this stable posture, following conditions should be satisfied. When $d > 0$, the design is on stable posture and when $d = 0$, it is on marginal tip-over state. If the $d < 0$, design will be in unstable state.

$$c \leq l_f \quad (2.25)$$

$$0 \leq d \quad (2.26)$$

Based on the stable marginal angles demonstrated in Figure 2.22 and Figure 2.23, this design can maintain stable posture for standard staircases with a marginal value. Thus, it provides more safety for the stair-climbing operation. Because most of the available linear staircases in public and private places are in the range of 30 to 35 degrees. Also, when operating the design in ascending stage, it is better to use minimum speed to avoid sudden disturbance and to improve the safety. By considering these facts, the speed selection for the design is demonstrated in Table 3.1.

In stair ascending operation, design may not be able to follow a straight path. There may exist side movements in horizontal direction because of many reasons. One of the main reason is the alignment issue when entering to the staircase. The other main reason is the contact issue in between the grouser and step. Except these two reasons, there may be other reasons such as change of friction coefficients of surface, speed fluctuation in left and right tracks. In order to overcome from these issues design should be aligned before entering to the staircase and when it is on the staircase. In order to achieve this task, tilt sensor and alignment sensor can be implemented with this design. If there exists any side movements, the controller can adjust the design to correct the alignment in advance. If the side movement is high, then the controller can take immediate actions to stop the operation based on safety aspects. But, in this thesis, the side movement is not considered in controller design as it is a technical development. This will be considered as a future work in the final product development.

Chapter 3

DEVELOPMENT OF PROTOTYPE

As explained in earlier chapters, this stair-climbing mobile platform should have a unique design to address the main drawbacks of existing wheelchairs. Based on the design approach, in existing products in the market have many drawbacks based on different approaches such as cost, stability, safety, design complexity and size. Also, in certain designs, some of the major requirements of wheelchair users were not addressed properly because of the lack of concern on design study. Design study takes a major role in prototype development in order to achieve the objectives of a research. In this chapter, basically the prototype development is discussed in detail. Also, based on the selected parameters for design, equipment selection is discussed in detail. Finally, a Finite Element Analysis is carried out for the main parts of the design to observe the factor of safety.

3.1 Mechanical Design

One of the main approach of analyzing a mechanical design in prototype development is to carry out 3D model design study. Because by using this study, it provides a clear illustration about placements of all the parts in the prototype development. Thus, it provides to minimize manufacturing failures. In this section, basically, six major parts of the prototype are discussed by considering prototype development and 3D model. This will provide clear explanation for each parts development based on the conceptual design approach and practical implementation. In this study, a 3D model of the design is carried out by using SolidWorks software. In this prototype development and 3D model, total weight of the design including user weight is considered throughout the study.

3.1.1 Chassis Construction

As explained in the previous chapter, this research and development proposed a unique design to support the research objectives. This unique design mainly comes with the chassis development. In the SolidWorks environment, this de-

sign is implemented by following different stages. Because, there should be some simplified steps to follow when constructing each part of the chassis. Also, when designing the chassis in SolidWorks environment, practical problems that can exists when constructing the parts are also considered. Because even there is a novel design sometimes there may exists some practical problems when completing the chassis. As a design approach, practical implementation should be addressed properly and correctly in order to avoid such issues. Otherwise there could exist some design failures.

Side Frame

Chassis development could be a challenge in prototype constructions due to design complexity. It is better to simplify the construction stages as much as possible. Thus, it could provide more access to minimize the construction failures. In this prototype development, the simplified basic shape used for the chassis construction is shown in Figure 3.1. In this side frame design, the basic requirements of chassis design explained in the previous chapter are considered. The dimension of the side frame is selected according to those parameters as shown in Figure 3.1. When constructing the prototype, a mould was used as illustrated in Figure 3.2. Also, by using this mould, the constructed side frame is shown in Figure 3.3.

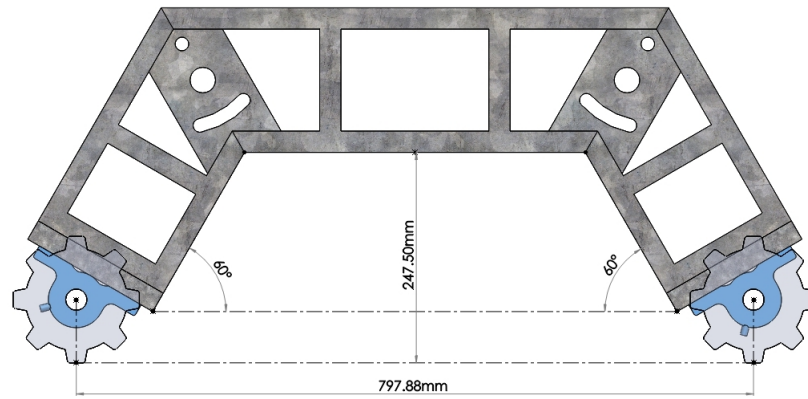


Figure 3.1: Geometrical shape of side frame

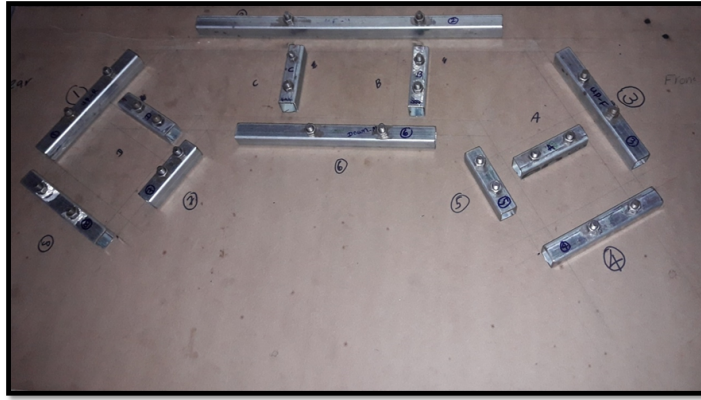


Figure 3.2: Mould for the side frame of chassis on MDF board

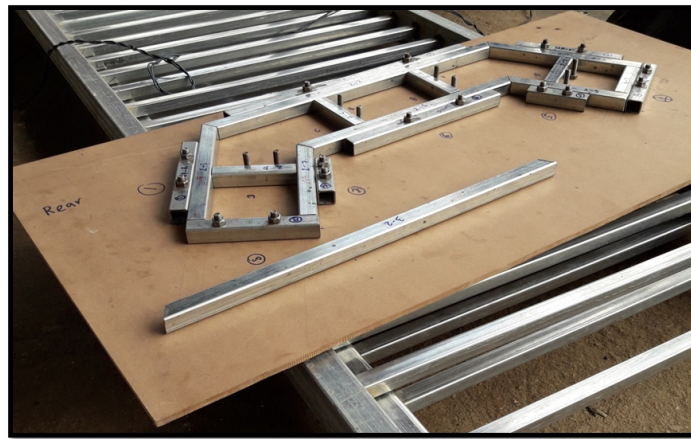


Figure 3.3: Box bar placement on the mould

In this side frame design, a galvanized box bar was used as the material rather than using mild steel pipe because a box bar can provide four plane surfaces when compared to mild steel pipe. This is very useful when conducting the measurements and alignments in the construction. Also, when assembling the frames each other, this box bar shape can facilitate more accurate placement in order to avoid design failures. In prototype development, 25.4mm box bar with 2mm wall thickness was used. The reason for selecting 25.4mm box bar was to get acceptable surface area when assembling and fixing other parts. Also, based on the stress analysis of the design, 1mm wall thickness was good enough for the box bar selection (stress analysis will be explained in coming section). But, due to construction matters such as welding methods, 2mm wall thickness was selected for the prototype development.

As discussed in the previous chapter, the chassis should have a minimum stair edge clearance area to avoid collision with staircase. In this research and development, the maximum staircase angle is selected as 40 degrees. Based on this selected value the angle of the side frame is selected as 60 degree with the margin of 20 degrees. Because it can provide enough space for the linear actuator placement for arm controlling. Also, the length of the bottom part of the chassis is selected as 800mm to compact the size of the design. Based on the selected maximum angle and length of the chassis, minimum stair edge clearance height is selected as 250mm with an extra marginal value as shown in Figure 3.1. On the other hand, there should be enough spaces on top of the chassis to place the seat as well. Thus, it also provides space for the placement for other parts such as battery, linear actuator as well. Also, when transmitting the power from rear side to front side, the frame design should provide facilities for the parts placements as two DC motors are placed on the rear side of the chassis. By considering all these requirements, a trapezoidal shape is used for the chassis design. The selected dimensions for the side frame design is shown in Figure 3.1.

Adjacent Side Frame

In order to construct the adjacent side frame, two side frames were used as shown in Figure 3.4. In this case, these two side frames were fixed parallel to each other with some distance. Thus, it provided space for the placement of some parts for power transmission.



Figure 3.4: Isometric view of adjacent side frame in prototype

Also, by combining two adjacent side frames, the basic chassis design could be developed as shown in Figure 3.5. In this stage also, separate wood frames were used to align two adjacent side frames. Also, by using these wood frames, the length of the adjacent side frames were fixed in order to place the connecting box bars to complete the chassis. When connecting the two adjacent side frames, the same box bars were used. In order to clearly demonstrate the final design of the chassis a 3D model is used as illustrated in Figure 3.6.



Figure 3.5: Constructed chassis design in prototype

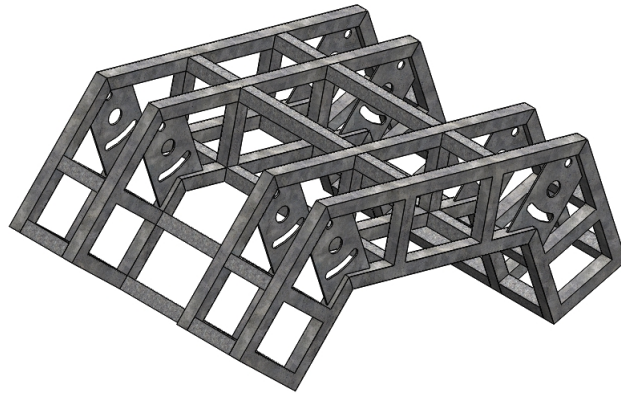


Figure 3.6: Isometric view of basic chassis design

In this case also, the two adjacent frames were fixed parallel to each other with some distance. Here, battery placement, DC motors placement and linear actuator placements were mainly considered when selecting such distances. By using the above steps, complexity of chassis construction could be avoided. On

the other hand, this technique provided facilities to prevent alignment issues in the development of the final chassis.

UCP Bearing Placement Frame for Wheel Alignment

Even the simplified stages are followed in prototype development, there might be some manufacturing defects existing in chassis development. One of the most crucial problem could be the chassis misalignment. As a result, it could create some problems for wheel alignment of final design. There should be a method to avoid such issues in advance. In order to address this matter, a separate frame was used to adjust the misalignment of chassis when placing the wheels. This frame design is shown in Figure 3.7. In this case also, a separate mould was used to construct the UCP bearing placement frame as shown in Figure 3.8.

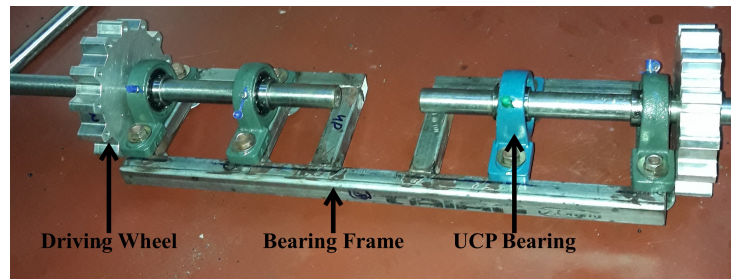


Figure 3.7: Isometric view of the UCP bearing placement frame



Figure 3.8: Mould of side frame for bearing placement

As shown in Figure 3.7, the same box bar was used for this frame construction. The basic idea of implementing a separate frame for the wheel placement with chassis was to take necessary correction for wheel alignment easily because if there existed a misalignment, the wheels of the design could not properly come into contact with the flat surface. By using this frame design, the front and rear

wheel sets could be aligned properly. As shown in Figure 3.7, UCP bearings were used with the frame to fix the wheels. The main reason for selecting the UCP bearing was to get acceptable ground clearance height as shown in Figure 3.9.

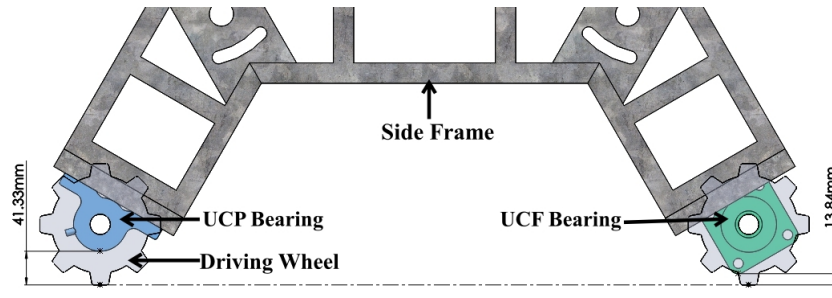


Figure 3.9: Ground clearance height difference of UCP and UCF bearing placements

As shown in Figure 3.9, the UCP bearing can maintain acceptable ground clearance height compared to UCF bearing because of its shape and placement. Also, the other main reason for the selection of UCP bearing is the static and dynamic load capacity, which is good enough for the design.

3.1.2 Arm with Rubber Track

As discussed in the last chapter, there are three set of arms called front arm, middle arm and rear arm for the design. Also, a clear explanation was provided for the selected dimensions as well. For each arm, there are two rubber track arms and total of six rubber track arms are used for the design. In this section, the basic elements of arms construction are discussed in detail. Basically an arm consisting of a rubber track, mild steel plates, driving wheel, idle wheel and track rollers.

Rubber Track

In this prototype development, an industrial rubber track design with customized length was used as shown in Figure 3.10. Basically, a rubber track is made of rubber with Kevlar iron core, which provides high load with less pressure to surface. As a result, it could provide access to almost all the staircase without damaging to stair edges. The selected rubber track design could bear up a load up to $300kg$ which was good enough for the selected weight distribution of the design. Weight distribution will be explained in the coming section. Also, a total of six rubber tracks are used for the design.

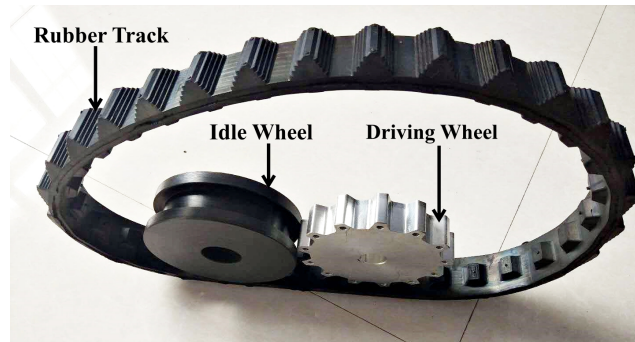


Figure 3.10: Rubber track design

Driving and Idle Wheels

When driving the rubber track, there should be two basic parts on the arm, which are called driving wheel and idle wheel. Driving wheel is responsible for driving the rubber track and idle wheel is used to support rubber track operation at the other end. Based on these reasons, wheel designs get different shapes as shown in Figure 3.11. For driving wheel construction, aluminium alloy was used due to its strength because due to the shape of the driving wheel, there should be strong edges on the wheel to drive the rubber track with the load. Also, High Density Poly Ethylene (HDPE) material was used for idle wheels because of strength, light weight and low cost.



Figure 3.11: Photo of AL sprockets and idle wheels

Track Roller

In order to maintain a parallel arrangement under load, there should be a support in between the rubber track and arm plates. Also, when selecting a solution

for these requirements several factors should be considered. One of the basic conditions is the dynamic and static load capacity. Also, there should not exist a large space in between the track rollers. Otherwise it can cause the creation of non-parallel arrangement for the rubber track under the load. By considering all these factors, 6000 deep groove radial ball bearing was used for the track roller because of its dynamic and static load capacity. Placement of track rollers on all the arms in prototype development is shown in Figure 3.12. Also, due to the dimensions of this ball bearing there exists less space in between the adjacent parts. This helps to maintain parallel arrangement at the bottom of the track. Also, due to low cost and light weight, 14 pieces of ball bearings were used for the construction of each front and rear rubber track arms. Total of 56 pieces were used to complete all the front and rear rubber track arms. Also, for middle rubber track arms construction, total of 72 pieces were used. All these track rollers were fixed to arm plates with acceptable distance in between adjacent parts.

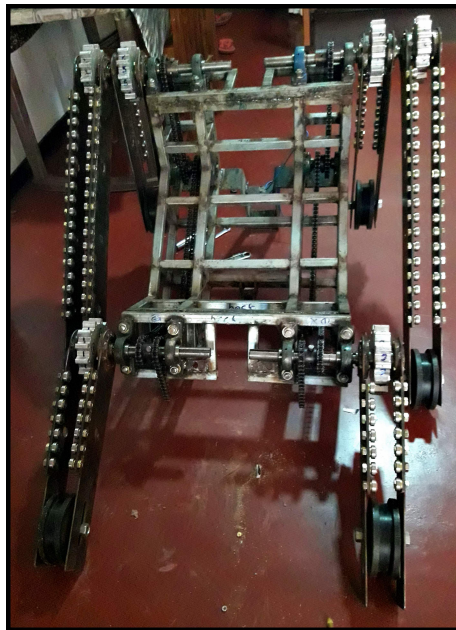


Figure 3.12: Track rollers placements on arms

Arm Plate

In rubber track arm constructions the arm plate is used as the structure of the arm construction. All the parts of the rubber track arms are connected via two arm plates which are placed in parallel arrangement. In this prototype development total of 12 arm plates were used to construct the rubber track arm as shown in Figure 3.13. Mild steel plates were used as the material for construction of arm

plates because of strength, low cost and availability. As shown in Figure 3.14, the driving wheel and idle wheel were connected to the arm plates.



Figure 3.13: Constructed arm plates in prototype

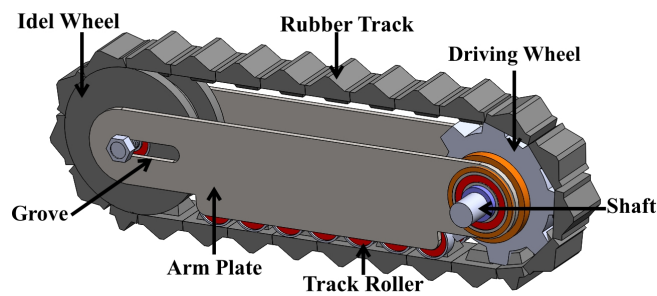


Figure 3.14: Basic elements of arm

In driving wheel placement, the arm plates had additional parts which were used to connect the driving wheel and shaft together. Also, with this mechanism, it provided the facility to rotate the arm plate around the shaft as well. In idle wheel placement, there should be a method to adjust the tension of the rubber track via arm plates. In order to achieve this task, there was a groove in the arm plates. The tension of the rubber track could be adjusted via the idle wheel along the groove of the arm plates. By using a vehicle jack, the tension of the rubber track could be adjusted as illustrated in Figure 3.15.

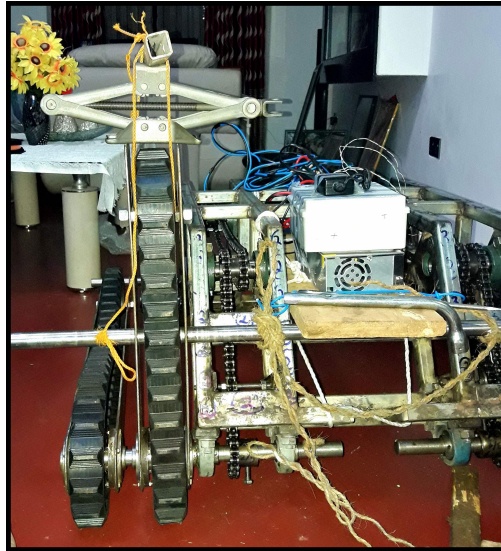


Figure 3.15: Adjustment of tension of rubber track

3.1.3 Linear Actuator Placement and Brackets

As explained earlier, this design consists of three set of arms. In order to control these arms separately, three electro-mechanical linear actuators are used in this design. The main reasons for selecting linear actuators rather than using an angular motors are the cost, size and dynamic load capacity. Because, an angular motor needs more space with some gear trains to support the arm operation. As a result, there could exists placement issues on the design. In this section, linear actuator placement with bracket design is further discussed.

Bracket Design for Linear Actuator Placement

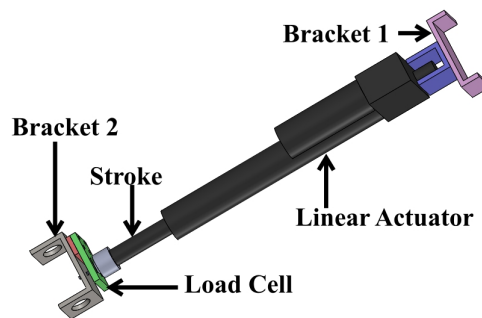


Figure 3.16: Linear actuator with brackets

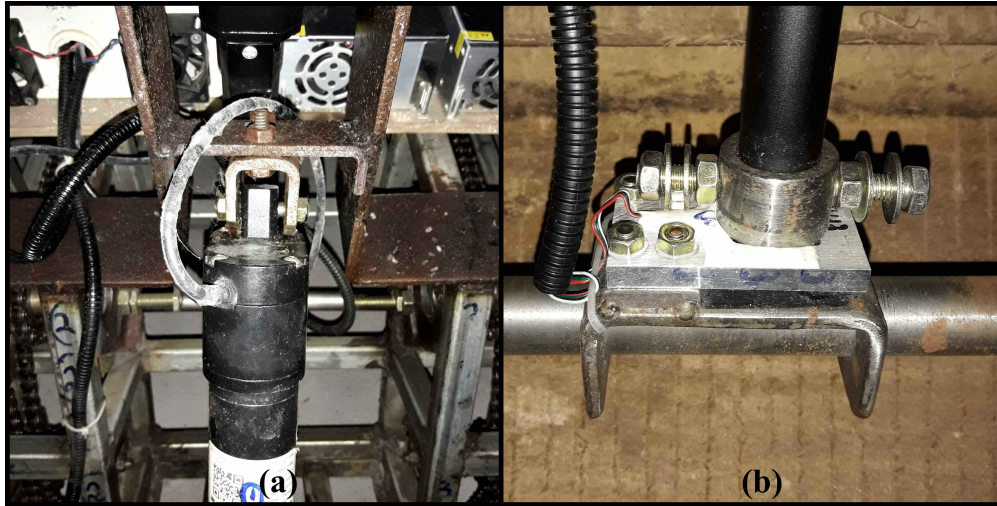


Figure 3.17: Linear actuator placement on chassis (a)bracket 1 (b)bracket 2

In order to place the linear actuator in between the chassis and arm, two brackets were used as shown in Figure 3.16. In this bracket construction, mild steel plates were used because of availability, cost and strength. As shown in Figure 3.16, the bracket 1 was used to fix the linear actuator with the chassis. Also, by using the bracket 2, the other end of the linear actuator was fixed to the arm. The placement of these brackets in prototype development is illustrated in Figure 3.17. In second bracket design, there was a load cell which was attached in series with the stroke of the linear actuator. By using this load cell placement, amount of force applied by the linear actuator on the arm can be observed. This is very useful when implementing the controller design. This will be explained in detail in coming section.

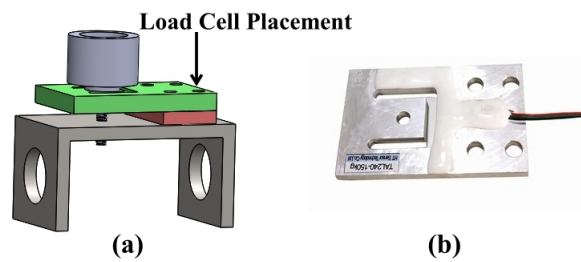


Figure 3.18: Load cell with bracket (a)load cell placement on bracket (b)TAL240 Planar beam type load cell

In order to measure the amount of force applied by the linear actuator, planar beam type load cell was used as shown in the Figure 3.18. The main reason for selecting this type of load cell was size, low cost and availability of different force

range. The selected TAL240 planar beam type load cell could support the load up to 300kg which was good enough for this design.

3.1.4 Motor Placement with Brackets

Based on the design, there are three rubber track arms for each left and right side of the chassis. In order to control these rubber track arms separately, there should be two motors. By controlling these motors, left and right rubber tracks speed and direction can be easily controlled. In order to achieve this task, two DC brush motors are used with this design. More details about the motor selection will be explained in the coming section. Based on the design, motor placement is located in the rear side of the chassis as shown in Figure 3.28. The reasons for motor placement are to transfer the CM of the design to rear side and also to get more space at the front side of the chassis as well.

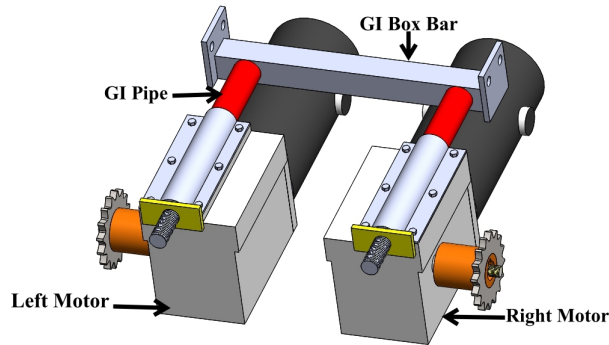


Figure 3.19: Bracket for motor placement

As shown in the Figure 3.19, motor placement bracket was constructed by using GI box bar and pipe. By using this bracket, both motors were fixed to the chassis. Also, there should be a method to adjust the motor placement along the bracket in order to adjust the tension of the power transmission chain. Because in this design, the power transmission in between the motor shaft and other parts were connected through a chain. This could be easily achieved by moving the motors along the GI pipe as shown in the Figure 3.19. The placement of two DC motors in prototype development is illustrated Figure 3.20.

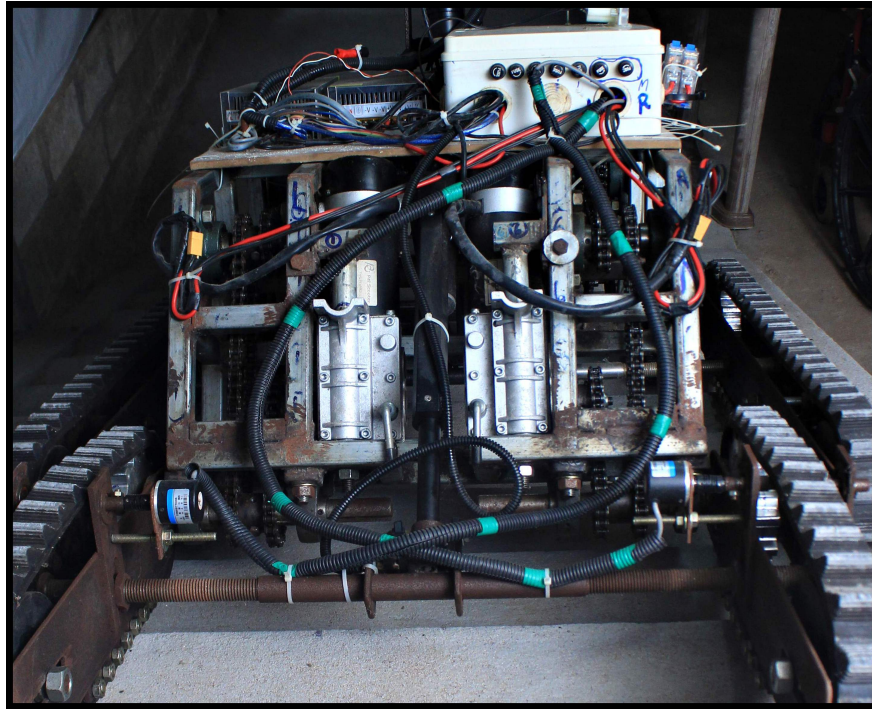


Figure 3.20: Motor placement with brackets in prototype

3.1.5 Power Transmission

In order to transfer the mechanical power from rear side to front side, chain mechanism was used for this design as shown in Figure 3.21. The main reasons for selecting the chain mechanism were high torque, length adjustability and low cost. In this power transmission, UCFL bearings were used in order to adjust the chain tension easily. As shown in Figure 3.21 the chain tension was adjusted via UCFL bearing adjustment path.

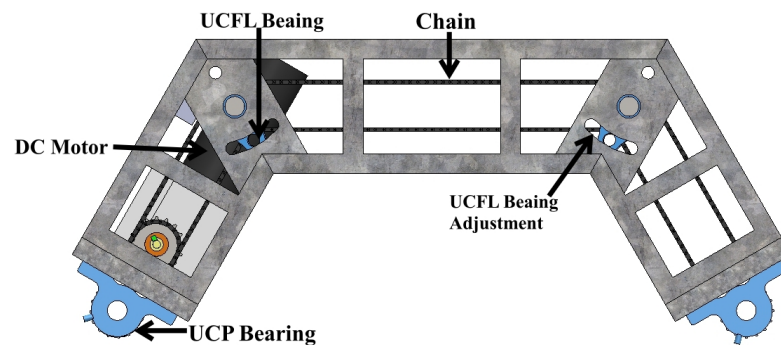


Figure 3.21: Side view of the chassis

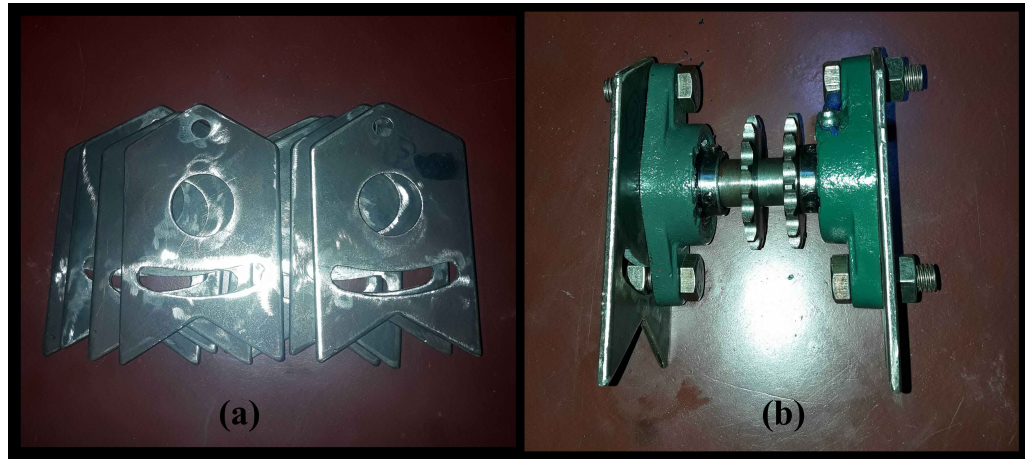


Figure 3.22: UCFL bearing placement construction (a)plates for UCFL bearing placement (b)pair of UCFL bearings

In prototype development, several stages were followed when completing the power transmission. The main reason for following these stages was to avoid any technical issues with regards to misalignment of placement of parts. As explained earlier there were eight UCFL bearing placement plates to adjust the tension of the chain as illustrated in Figure 3.22. In this plate construction, mild steel was used because of low cost, availability and strength. Also, by using another arrangement as illustrated in Figure 3.23, UCFL bearing plates placement were adjusted in a manner that they are parallel with each other.

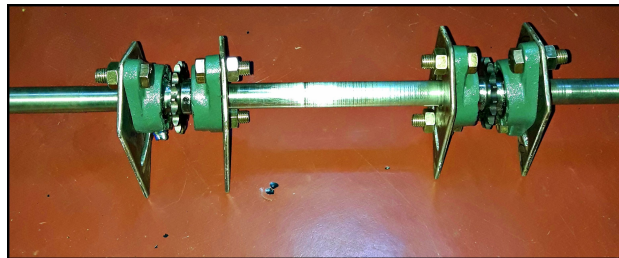


Figure 3.23: Complete one set of UCFL bearing placement with alignment

When constructing the power transmission of the prototype, it is very important to adjust the sprocket placement properly. Otherwise due to misalignment, it could create some power losses when transmitting from rear to front side. In order to solve this matter, sprocket alignment in prototype was carried out as shown in Figure 3.24. In this technique, driving wheels were used to align the sprocket placement. Due to this technique, all the sprockets in each side could be aligned with particular driving wheels in a manner that they are parallel with

each other. As a result, all the sprockets in a particular side could be aligned altogether.

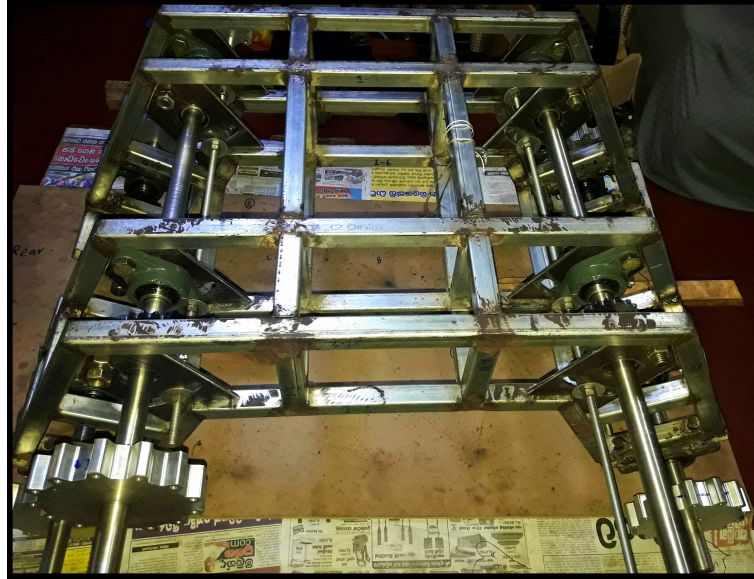


Figure 3.24: UCFL bearing placement on chassis after alignment

3.1.6 Wheel Alignment in Prototype

As discussed earlier in prototype development, there should be a method to adjust the driving wheel placement on the chassis. The main reason for this alignment is to avoid any mechanical issue in the final prototype development. If there exists any misalignment, then all the driving wheels are not properly contacted with the flat surface. In such situations, it could cause the design to become unstable when it operates on a staircase. The process of wheel alignment in prototype development is illustrated in Figure 3.25.

As it is demonstrated, the wheel alignment was carried out on a glass, which was placed on a flat table. Before starting this wheel alignment, the table was levelled. By using vehicle jack arrangement, the chassis was moved downwards until it was properly contacted with UCP bearing placement frame. When it contacted with bearing frame, the chassis placement was also levelled. Also, in this stage, a separate wood frame was used to align the driving wheels of each side as illustrated in Figure 3.25. Due to this technique, it also ensured to avoid misalignment of all the driving wheels together. After completing the above steps, the UCP bearing placement frames were welded to the chassis. The completed chassis design after wheel alignment is illustrated in Figure 3.26.



Figure 3.25: Process of wheel alignment with the chassis



Figure 3.26: Final stage of wheel alignment

The completed prototype design is illustrated in Figure 3.27. In order to further illustrate the components of the design, a 3D model is used as illustrated in Figure 3.28.



Figure 3.27: Side view of the completed prototype

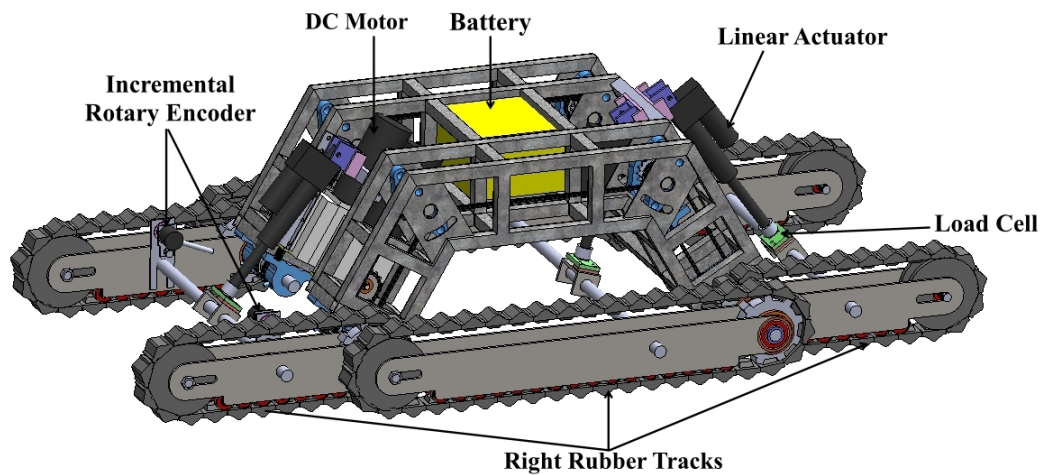


Figure 3.28: 3D model of the stair-climbing mobile platform

3.2 Equipment Selection

In the previous section, a detailed description of the mechanical design was discussed. The next discussion is focusing on selecting equipment used to drive the mobile platform. In this discussion, motor sizing and linear actuator selection are explained in detail.

3.2.1 Motor Sizing

Basically design operation can be categorized as the flat surface operation and stair-climbing operation. In these two operations the required motor power can be varied based on the speed and inclination of the surface. As discussed in the previous chapter, the selected maximum angle of the staircase was 40 degrees. This maximum angle should be considered when calculating the motor power. On the other hand, when calculating the required motor power, design speed in flat and inclined surface should be considered as well. When selecting the appropriate speed for this design, some of the stair-climbing wheelchair designs in the market are referred as discuss in Appendix B. By considering the specifications of the available products in the market following parameters have been selected for the motor sizing as shown in the Table 3.1

Table 3.1: Summarized specifications for the design

Max Angle (Deg)	Max Speed(ms^{-1})		Max Total Weight(kg)		
	Flat	Incline	User	Design	Total
40	1.39	0.19	100	120	220

In this motor power calculations, the following assumptions are considered in order to simplify the calculation.

- After the acceleration, the design keeps a constant velocity
- In the stair-climbing operation, the design is operated over stair edges
- Moment of inertia, track rewinding force and aerodynamic drag resistance are not considered

When the design is driven on a flat surface and inclined surface several forces are acting on the design. When calculating the required motor power, these forces should be considered. Basically, there are four forces which have been considered in this power calculation which are called rolling resistance, gradient resistance, acceleration force and aerodynamic drag resistance [39]. Based on the operation of the surface, acting forces on the design should be considered in the calculation. A detailed description of these forces can be found in Appendix D. In motor power calculation, these forces should be considered according to the operation. The total resistance force acting on the design can be calculated as follows. In this

motor sizing, stair-climbing and flat surface operations are considered separately in order to simplify the calculation.

$$F_{res} = F_r + F_g + F_a + F_d \quad (3.1)$$

3.2.1.1 Power Calculation in Flat Surface Operation

Due to the flat surface operation, gradient resistance is not affecting the motion of the design anymore. Also, due to the selected low speed of the design, the aerodynamic drag resistance can be neglected as well. The required driving power in a flat surface can be calculated by using equation 3.2.

$$P_{flat} = \frac{(F_r + F_a)V_{flat}}{\eta} \quad (3.2)$$

Based on the DC motor power transmission to the system, appropriate power efficiency coefficient can be selected. Normally this range is in between 0.85 - 0.9 based on low gear and direct drive. By considering all these facts the required driving power for flat surface can be calculated by using equation 3.2. Based on the selected parameters for this design as shown in Table 3.1, the driving power can be calculated.

3.2.1.2 Power Calculation in Stair-climbing Operation

By following the same method as explained earlier, the driving power can be calculated as follows. Due to the inclination of the surface, the required maximum driving power can be observed in stair ascending operation. By considering the total resistance force acting on the design in inclined surface, required motor driving power in stair ascending operation can be observed as follow. In this case also, the required power in stair ascending operation can be calculated by referring Table 3.1.

$$P_{stair} = \frac{(F_r + F_g + F_a)V_{stair}}{\eta} \quad (3.3)$$

Based on the operation, the design should have maximum power in flat surface operation because of the selected speed. This can be further justified by substituting numerical values. As a design approach, it is not recommended to follow only theoretical values for power calculation. Because due to several facts, actual required motor power can be varied. As a practise, it is better to consider a safety factor when calculating the motor power. In this case, the safety factor is used

in the equation to calculate the required maximum power for motor selection as follow.

$$P_{max} = K_s P_{flat} \quad (3.4)$$

In this prototype development, the safety factor was considered as 1.5. By following the Table 3.1, the required total maximum power for motor selection can be observed. In this case, total weight of the design including the user was considered as $220kg$ and speeds of the design in a flat surface and stair-climbing were considered as $0.19ms^{-1}$ and $1.39ms^{-1}$ respectively. By substituting these values in above equations, required power based on the operation can be derived. Based on the calculations, two DC motors of $400W$ were selected for this prototype development.

3.2.1.3 Torque Calculation of Driving Wheel

Based on the operation of the design, the maximum resistance force existed in inclined surface operation. As a result, motors have to generate the maximum torque to meet the demand. In this calculation, the stair ascending operation is used to calculate the maximum torque. In order to calculate the torque, the following equation is used.

$$P_{stair} = \tau_{stair} \omega_s \quad (3.5)$$

In order to observe the angular velocity of the driving wheel, following equation is used.

$$V_{stair} = r \omega_s \quad (3.6)$$

By referring the above equations, the torque of the driving wheel can be calculated as follow.

$$\tau_{stair} = \frac{P_{stair} r}{V_{stair}} \quad (3.7)$$

There are two DC motors to operate the design. Based on the calculated maximum torque, motor selection can be done. This calculation will be useful when studying the stress analysis of the design.

3.2.2 Linear Actuator Selection

In previous discussion, motor sizing has been considered based on the operation of the design. Also, in all the operations, three sets of arms should be controlled to support the operation. Based on the stage of operation, required power for each linear actuator can be varied. Also, when selecting an appropriate mechanism to control the arm operation, different factors should be considered as well. In this discussion, linear actuator selection and force calculation will be discussed in detail.

3.2.2.1 Electro-mechanical Linear Actuator

Based on this design, linear actuator is the most appropriate method to control the arms based on different aspects. One of the most highlighted benefits of the linear actuator is the high static and dynamic load capacity it has with compared to cost. Also when compared to the angular motor, linear actuator has a small size based on load capacity. On the other hand, when considering about the placement on the design, linear actuator needs a small area than angular motor placement. Also, based on the placement of the linear actuator in between the arm and chassis, the required linear actuator force for arm operation can be adjusted. This will be discussed in coming sections.

By considering all these facts linear actuator is selected as the controlling mechanism of arm operation. When discussing about linear actuators, basically there are three types commonly use in industrial applications which are called pneumatic, hydraulic and electro-mechanical. In this design, three electro-mechanical linear actuators are used to control the arm operation based on different facts. One of the main reasons for selecting this type of mechanism is the power source which is used to operate the linear actuator because all of the equipment of the design is operated by using a DC power source. By using the same power source, linear actuator can be operated. Also, electro-mechanical linear actuator has identical behaviour in extending and retracting. In some developments, there are position feedback facilities. Thus, it helps to control the linear actuator position accurately and easily. Due to usage for different industrial applications, there are varieties of products in the market based on speed, size, load capacity and cost. Based on the selection criteria of this design, appropriate electro-mechanical linear actuator can be selected due to the availability of products.

3.2.2.2 Linear Actuator Sizing

When discussing the motor sizing, both stair-climbing and flat surfaces operation have been considered separately because based on the design operation, motor power consumption get different behaviour. But, when considering about the linear actuator force calculation, only the stair-climbing operation is considered because in flat surface operation, all the arms are lifted upwards. As a result, only the driving wheels are contacted with the floor. The ground reaction forces are acting along the driving wheels. But, in stair-climbing operation, arms are operated based on the stage of the operation in order to maintain contact with staircase. This arm postures provide facilities to maintain stable arrangement throughout the operation. In order to maintain the defined posture for each arm, linear actuators should have enough static and dynamic load capacity. Based on those stages, the required maximum forces for each arm are observed by using dynamic simulation studies in SolidWorks.

Linear Actuator Force Analysis for Stair-Climbing

In stair-climbing, there are two operations which are stair ascending and descending. Throughout these operations, there are several basic stages for each operation as shown in Figure 4.5 and Figure 4.11. In some of these stages, staircase reaction forces are distributed among all the three arms. As a result, the linear actuators need to have minimum load capacity in order to maintain the posture for each arm. But, in other stages, this reaction forces are acting along the front and rear arms only. These stages exist when the design is at the top and the bottom of the staircase. These stages are called as stage *D* to *E* and *J* to *K* as shown in Figure 4.5. Also, similar stages can be found in stair ascending as well. In these stages, required linear actuator forces get different values based on the slope of the staircase, linear actuator placement of each arm and position of reaction force acting on arm. Based on these parameters, the required maximum force for front and rear arms can be analyzed. In order to analyze this force, a simplified diagram of design posture when it is on top of the staircase is used as shown in Figure 3.29.

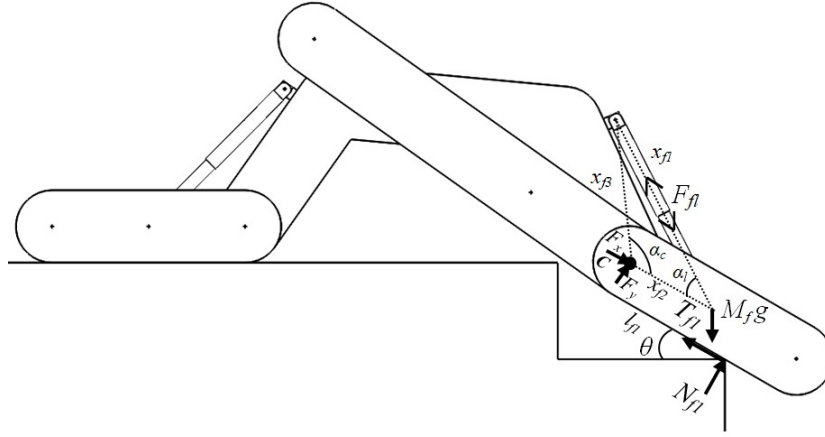


Figure 3.29: FBD of front arm at top of the staircase in stage D to E

An intermediate stage of design arrangement at stage *D* to *E* is demonstrated in Figure 3.29. In this posture, both front and rear arms maintain parallel arrangements to the staircase and the flat surface respectively. Also, in this stage, the driving wheel of the rear arm is properly contacted with the flat surface. As a result, the reaction forces of the flat surface are distributed among the driving wheel and the rear arm. Here, the rear arm liner actuator should have to maintain a minimum force to maintain the posture. But, when considering about the front arm posture, it takes different behaviour based on the contact with stair edges. As shown in Figure 3.29, based on the contact in between the stair edge and front arm, the required load capacity of the linear actuator is varied. This can be expressed as shown in Equation 3.8.

$$F_{fl} = \frac{N_{f1}l_{f1} - T_{f1}r - M_fg \cos \theta x_{f2}}{x_{f2} \sin \alpha_1} \quad (3.8)$$

This expression is derived by referring the FBD of front arm as shown in Figure 3.29. As express in Equation 3.8, the front linear actuator force is mainly depended based on the distance to the contact point and the angle of the linear actuator which creates with front arm. Based on the selected dimension of a staircase, the contacting points of front arm with stair edges can be varied. In order to observe the required maximum force for front linear actuator, it is better to consider the maximum distance to the contact point. Also, based on the slope of the staircase, the angle in between the linear actuator and front arm is also varied. Thus, it also affect for linear actuator force reading as well. By considering all these facts, the required maximum force for front arm in stage *D* to *E*

can be observed. But, in all the other stages of stair descending the front linear actuator needs to have a lesser load capacity compared to this stage because in those stages, the front arm has more contacting points with the stair edges.

Also, when discussing about the stage J to K , a similar posture can be observed for both arms. But, in this case, the front arm maintains a parallel arrangement with a flat surface rather than the rear arm. As a result, the front driving wheel has proper contact with the surface. The reaction forces are distributed among the driving wheel and the front arm. Thus, it causes to reduce the required linear actuator force. But, when considering about the rear arm, the required linear actuator load is varied based on the distance to contact point and angle in between linear actuator and rear arm, which is similar behaviour as discussed for the front arm. When observing the required maximum force for both front and rear arms, these two points should be considered by following standards for staircase construction. In order to observe the dynamic load capacity for each linear actuator, dynamic simulation has been carried out by using motion analysis study in SolidWorks.

Dynamic Simulation Study for Linear Actuator Force Analysis

As discussed earlier basically the dimensions of a staircase can directly affect the linear actuator force study. As shown in Table A.1, three staircase construction standards have been considered for this study. By referring those standards, the Building Code of Australia (BCA) is considered in this study because of two reasons. In this selected standard, it has the maximum and minimum staircase angle and the maximum hypotenuse for a step. This helps to clearly identify the linear actuator force distribution for different dimensions. In order to simplify this study, possibilities of staircase dimensions for given rise and going of a step are explained in Appendix A in Table A.3. By considering all these possibilities, three angular values have been considered in this study which are 18, 28 and 38 degrees because within this selected range, the maximum and minimum angle values and also the maximum hypotenuse are covered.

In order to conduct this simulation study, a 3D model of the design was developed in SolidWorks environment. Also, the total weight of the design with the user was considered as $220kg$. In order to observe the actual behaviour in real world, gravitational force and solid body contact in between design and staircase were defined. Also, a 3D model of a staircase was created by following the dimen-

sions of a step for selected staircase angles. In this study, the design posture at the top and bottom of the staircase were considered for front and rear arm linear actuators force observation respectively as shown in Figure 3.30 and Figure 3.31.

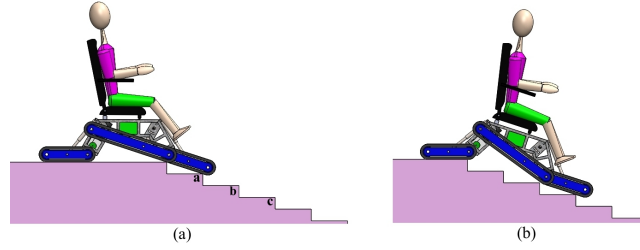


Figure 3.30: Design posture at top of staircase (a)stage D (b)stage E

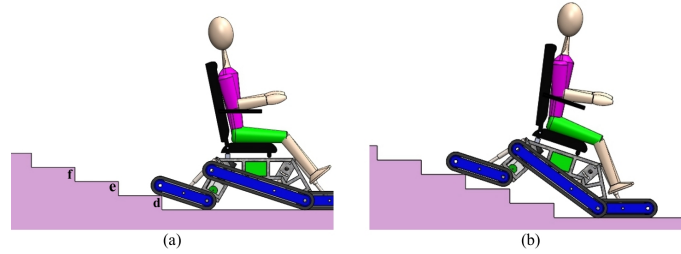


Figure 3.31: Design posture at bottom of staircase (a)stage K (b)stage J

By using three staircases, the front and rear linear actuator force distribution along the staircase were observed as shown in Figure 3.32 and Figure 3.33. In order to provide a clear demonstration of force distribution, simulation study of all the three staircases were included on a same graph. As it is demonstrated in Figure 3.32, there were some maximum values on the graphs. These kinds of behaviours were observed when the front arm had the maximum distance to the contact points of particular stair edges. Based on the selected staircase dimension and arm dimension, the numbers of maximum values on the graph were varied. As it is demonstrated on the graph, the peak values could be observed for 28 degree of staircase because this was the staircase dimension which had the highest hypotenuse value which was $403mm$. As a result, it caused to increase the required linear actuator force for front arm as discussed in the Equation 3.8. Also, when the contacting point came closer to the front driving wheel, the required linear actuator force was minimized. Also, when there exist two contacting points, it also caused to reduce the force reading as well. By considering all these facts, the maximum force reading for front linear actuator could be selected by referring

the force distribution at 28 degree of staircase. Also, as a safety factor, it is better to consider an extra margin for linear actuator selection as well.

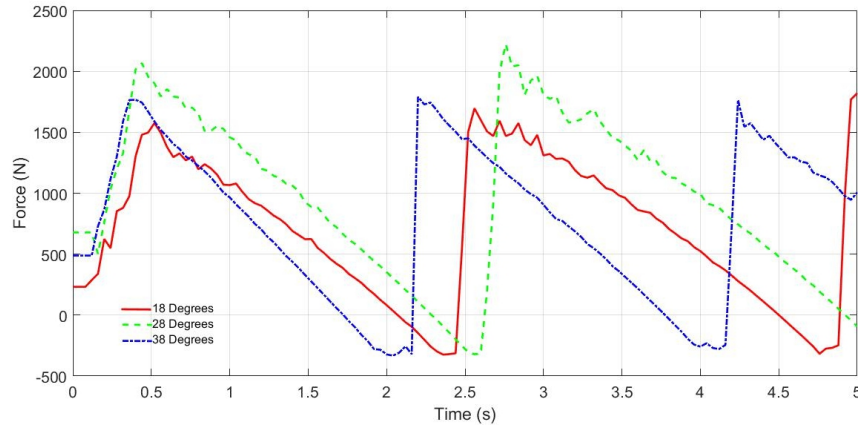


Figure 3.32: Front linear actuator force distribution at the top of the staircase

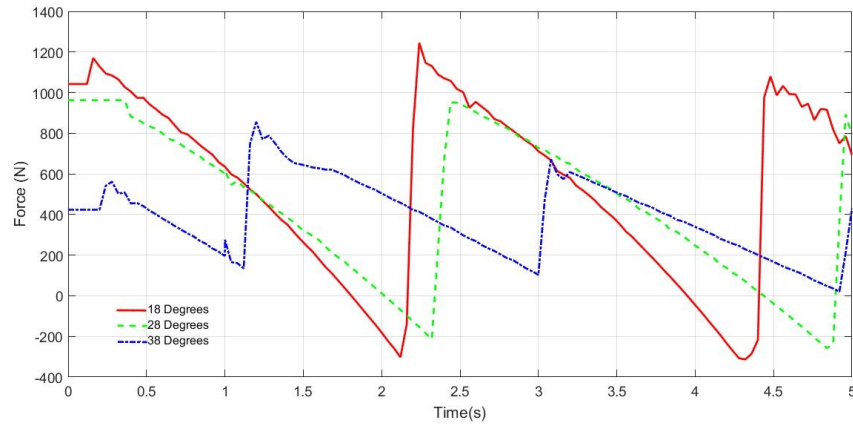


Figure 3.33: Rear linear actuator force distribution at the bottom of the staircase

As shown in Figure 3.33, a similar behaviour could be observed regarding to maximum force observation as discussed in earlier. In this case, the maximum force readings for the rear arm were existed for 18 degrees of staircase because of the rear arm had a lowest angle created in between the linear actuator and rear arm with compared to other staircases. In this graph also, the simulation study of all the three staircases were included on a same graph for clear demonstration. When comparing to the force observation for the front arm, the rear arm had a very low force distribution, because of the angle created in between the rear arm and the linear actuator. This can be expressed as follow by referring Figure 3.29

$$x_{f3}^2 = x_{f1}^2 + x_{f2}^2 - 2x_{f1}x_{f2} \cos \alpha_1 \quad (3.9)$$

As expressed in Equation 3.9, when the linear actuator is extending the stroke, the angle in between the linear actuator and the arm is decreasing. As a result, the required maximum linear actuator force should be increased as explained in Equation 3.8. Based on the front arm posture at the top of staircase, it has lower angle with linear actuator, thus it caused to increase the force reading. But, in the rear arm posture at bottom, the angle in between the arm and the linear actuator was much larger than the front arm. As a result, it helped to reduce the required linear actuator force.

Linear Actuator Force Optimization

As explained earlier, if it is able to decrease the distance to the contact point of particular arm with the stair edge, then the required linear actuator force can be reduced. But, this will be depended based on the staircase dimension. In practically, it is not possible to control the contacting distances. On the other hand, if it is able to increase the number of contacting points, then it helps to decrease the linear actuator force as discussed earlier. This technique can be considered in front arm control in order to minimize the required linear actuator force. In this case, middle arm operation can be used with front arm operation in order to increase the number of contacting points with the staircase. As a result, the required linear actuator force for the front arm can be reduced as shown in Figure 3.34. By using this technique, the required front linear actuator force for 28 degrees of staircase has been reduced by nearly 60%.

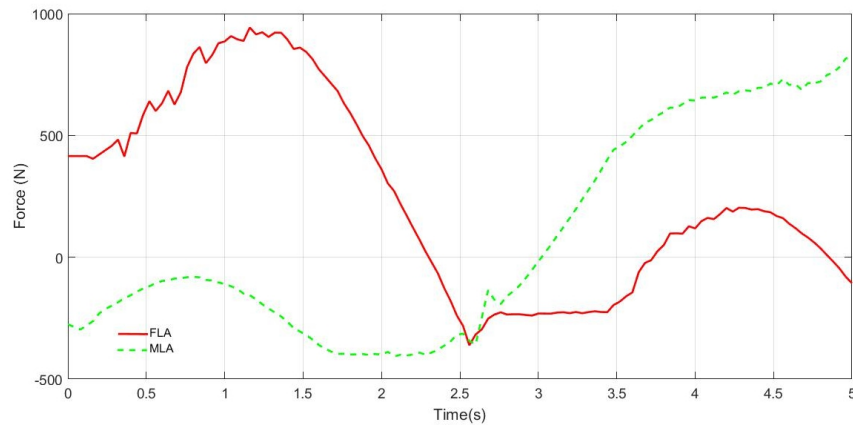


Figure 3.34: Front and middle linear actuator force distribution in force optimize arrangement

In order to maintain proper contact with stair edges, both the front and middle arms should have to maintain parallel arrangement with the staircase. As a result, staircase reaction forces are exerted along both front and middle arms. But, when controlling both front and middle arms simultaneously, there could exists some problems when maintaining parallel arrangement with the staircase because of the conflict of arm operation. As a result, there could exists non-parallel arrangements on both arms with the staircase. Thus, it could causes to make the design unstable. This problem should be properly addressed when designing the system controller. But, in this research and development, middle arm operation is not used in stage *D* to *E* in order to avoid arm conflict.

When discussing about the linear actuator force analysis, basically the user's comfort has been considered throughout the study. Also, when discussing the linear actuator force optimization, the same points has been considered. Because in all the operations the user's position should follow staircase profile in order to avoid sudden movements. Otherwise sudden jerks on the mobile platform can cause some difficulties for the user's comfort. If these kinds of sudden movements are in acceptable range for some applications, the required linear actuator force can be reduced by an acceptable amount.

3.3 Finite Element Analysis (FEA) of the Design

In a stair-climbing mobile platform development, several mechanical parts are connected together to develop the design. Based on the properties of different materials and shape, the behaviour of each part of the design under different loads can be varied. As a result, it could be a tough task to study about the static analysis specially in a complex design. In order to study the static analysis of this design, SolidWorks simulation is carried out by considering different loads existing on the design. This is a very fast and convenient method to conduct a static analysis of this design. In this study, finite element analysis (FEA) is used to analyze the safety measures of the design. By using this analysis, displacement of the parts, strains, stresses and Factor Of Safety (FOS) can be observed. Based on these study results, necessary arrangements can be applied to the design in order to meet to design safety. Also, this study helps to optimize the weight and cost as well.

3.3.1 Finite Element Analysis of the Chassis

In the static analysis of the chassis, mainly three loads were considered which were user weight which was $220kg$, linear actuator reaction forces and chassis weight with other components. Also, the gravitational force was used in this study to consider the weight of objects. In this study, the user's weight was applied on the top surface of the chassis. Also, in order to represent weight of other parts which were battery pack and DC motors, separate forces were applied on particular location of chassis as well. Based on the linear actuator force analysis as discussed earlier, the required maximum linear actuator force can be optimized by using different arrangements. Based on the optimized linear actuator force, $1500N$ forces were applied to the chassis with a marginal value to represent each linear actuator. In this study, front and rear driving wheels were set as fixed parts. In order to conduct the static analysis, three different materials were used for parts of the chassis as explained in Appendix E. These materials were selected based on the prototype development. Also, a detail description of mesh creates for the static analysis of chassis are shown in Appendix E as well.

Study Results

The results for static analysis of the chassis are demonstrated in following figures. In this study, the maximum stress was existed on the connectors of adjacent side frames because of the sharp edges on connectors. With necessary modification for those sharp edges, the stress could be reduced. Also, there existed the maximum displacement on the axle, which was used to fix the middle linear actuator with the chassis. But, this displacement was around $0.2mm$ and it did not create any significant impact to the design. It did not create any permanent deformation for the chassis. Moreover, based on the strain study, the maximum strain was existed on sharp edges of connectors of adjacent side frames and it was very small value that can be neglected. Finally by considering all these studies, FOS study was observed for the chassis as shown in Figure 3.38. Based on the results of this study, it illustrated that the minimum FOS values were existed on sharp edges of connectors of adjacent side frames and axle of middle linear actuator which was used to fix the middle linear actuator with the chassis. Based on the safety aspects, the FOS value should be greater than 1.0 because when it less than 1.0, the design is failed and if it equals to 1.0 then design starts to fail. But, in this study, it illustrated that minimum FOS was around 3.6. Thus, it concluded the safety of the chassis design.

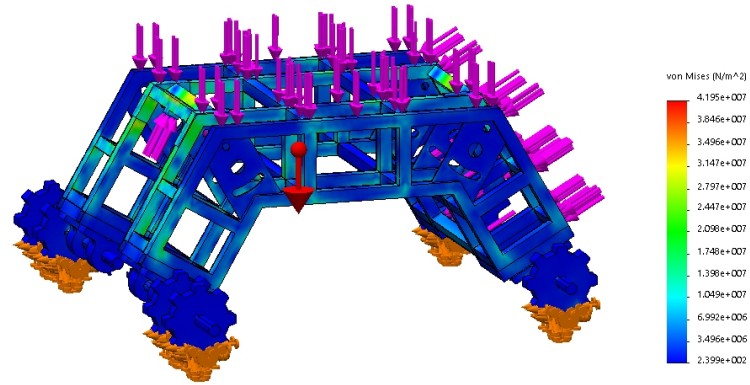


Figure 3.35: Von Mises stress study of chassis

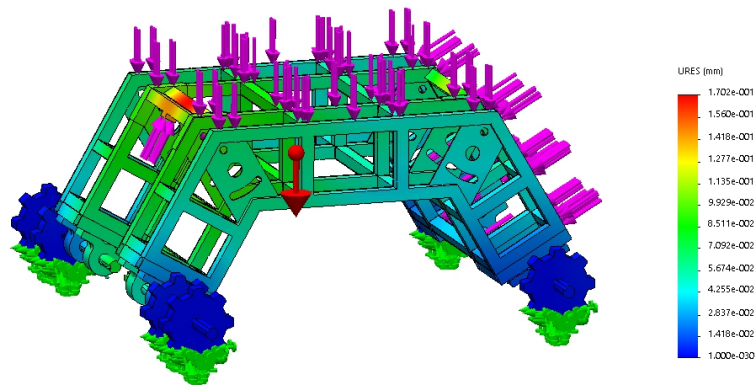


Figure 3.36: Displacement study of chassis

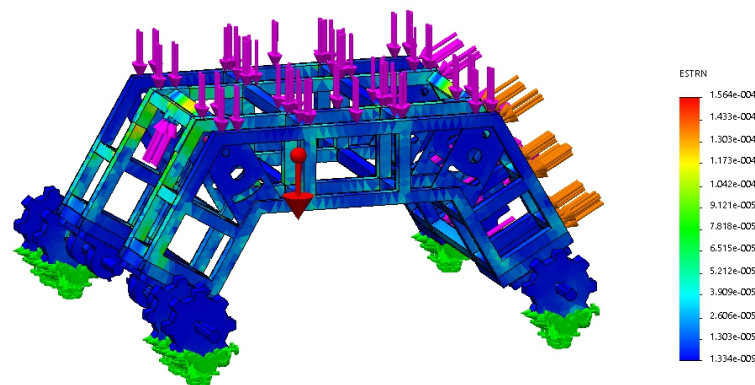


Figure 3.37: Strain study of chassis

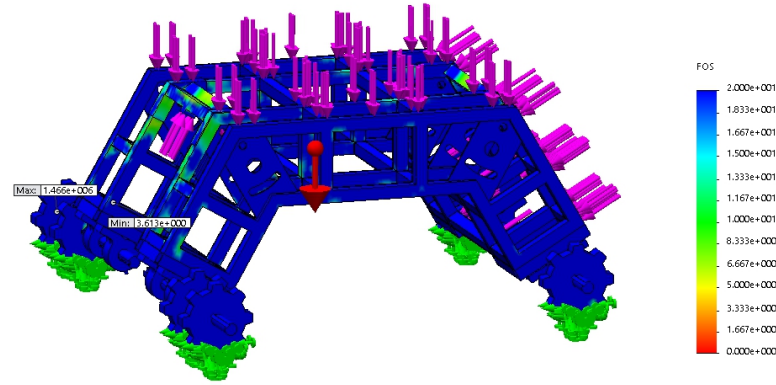


Figure 3.38: FOS study of chassis

3.3.2 Finite Element Analysis of the Arm

In this study, the behaviour of front and rear arms under the linear actuator force were discussed. Based on the design geometry, both front and rear arms were identical to each other. In this study, the behavior of the front arm was further discussed. In this case, front linear actuator force was considered in this study. Based on the linear actuator force optimization as discussed earlier, the magnitude of this force was considered as $1500N$. Also, in this study the gravitational force was used in order to consider the weight of objects as well. In order to conduct this study, idle wheels were set as fixed parts in order to concentrate the reaction force along the idle wheels. Thus, it helped to study the behaviour of arm plates and arm axle under the maximum distance to reaction forces. Also, UCP bearing placement frame was set as fixed part in order to represent the chassis. In order to simplify this study, rubber tracks were removed from arms. Because in this arrangement, the idle wheels were set to fix parts. As a result, there did not exist any reaction forces along the rubber tracks. Based on the prototype development, material selections for parts of the arm are shown in Appendix E. Also, a detail description of mesh created for the static analysis of the chassis can be found in Appendix E as well.

Study Results

The study results of static analysis of arm are demonstrated in following figures. According to this study, the maximum stress and strains were existed on shafts because of the reaction force of arm plates. Also, the maximum displacement could be observed in axle which was around $0.7mm$. This was because of the linear actuator force exerted on axle. By considering all these result, the FOS

study could be observed as shown in Figure 3.42. According, to this result it illustrated that the minimum FOS was existed on axle. This was because of the linear actuator force and axle distance in between the two adjacent contacting points of arm plates. According to the results, the minimum FOS was about 2.7 which was more than 1.0. As a result, the arm arrangement can be considered as safety design.

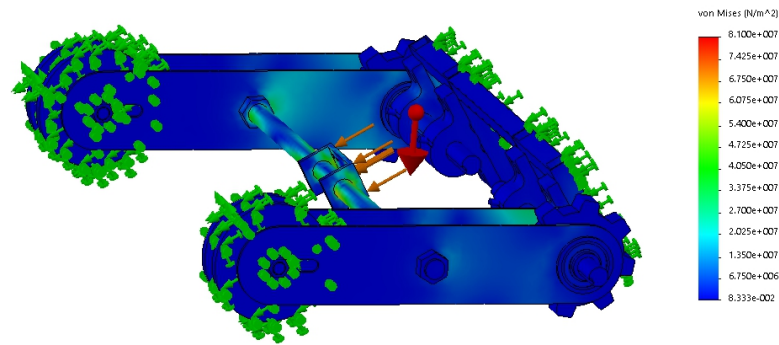


Figure 3.39: Von Mises stress study of arm

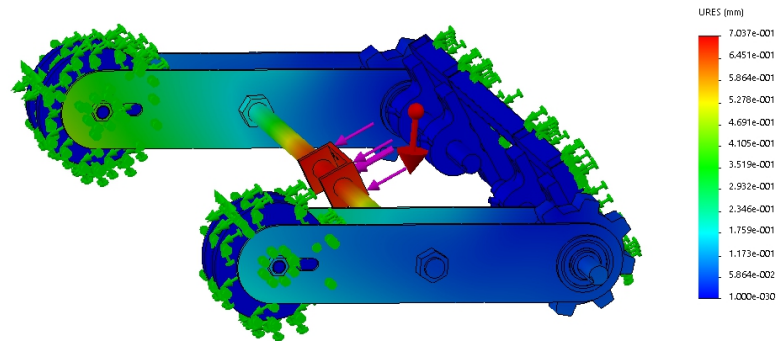


Figure 3.40: Displacement study of arm

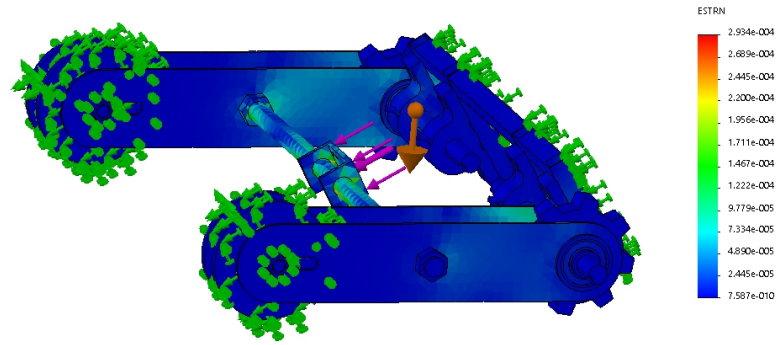


Figure 3.41: Strain study of arm

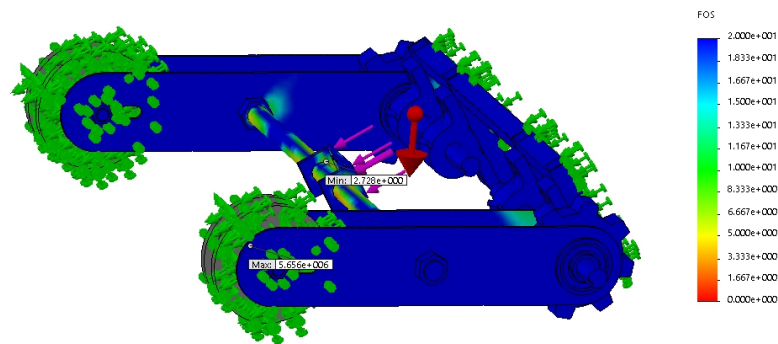


Figure 3.42: FOS study of arm

Chapter 4

DESIGN OF CONTROLLER

In most of the stair-climbing wheelchair designs, the controller implementation approach makes a huge impact on the stable and safe operation of the design. Based on these factors, several controlling algorithms are used in most of the existing designs. In general, most of the stair-climbing wheelchair designs use common controller designs for both stair ascending and descending operations. In some cases, stair ascending and descending operations are considered as same operations because of the design approach. There exists a doubt whether those controllers could be able to maintain stable and safe arrangements throughout the staircase. Also, in some design separate controller algorithms were used to negotiate with adjacent steps of staircases because of the design complexity [37].

In this controller design approach several factors should be considered based on stability, safety, speed and user's comfort. Because due to the design approach, several arrangements can be proposed for both stair ascending and descending operations. But, when considering the most important requirement, which is the user's comfort with stable and safe arrangement, a novel controller design is presented in this thesis. By considering both stair ascending and descending operations as separate operations, two separate controller designs are proposed for the design operation. Due to this design approach, separate motion plans are proposed for the arm operation and the design speed as well. In order to support the design operation, hardware structure of the controller is designed by using two separate micro controllers with several feedback signals to the system.

4.1 Hardware Composition of the Controller

As discussed in the previous chapters, basically this design consists of DC motors and linear actuators to control the design operation. In order to control these two parts, the controller design should have two separate controllers. By considering this requirement a controller design is developed as shown in Figure 4.1.

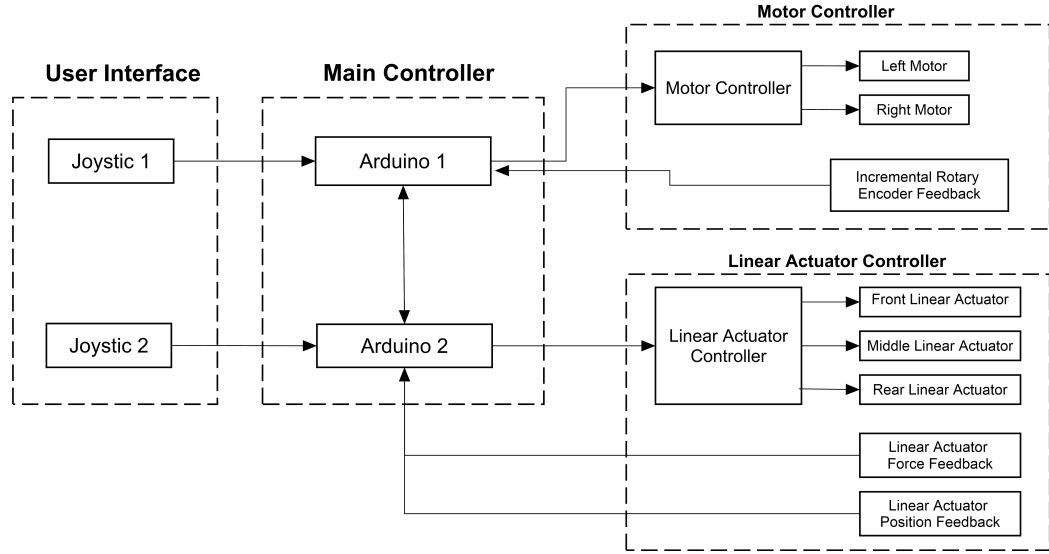


Figure 4.1: Block diagram of system controller

In this design, a semi-autonomous controller design is proposed rather than a fully autonomous controller. As a result, users can give commands to the controller at different stages of operation. This will provide more safe operation for the user. The basic elements of controller design in prototype are illustrated in Figure 4.2.

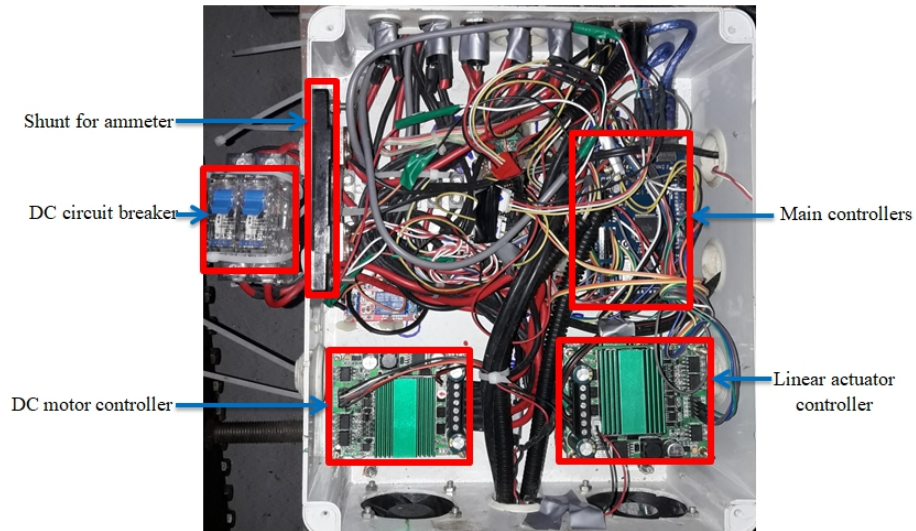


Figure 4.2: Basic parts of controller box in prototype

In each stage of the operation the controller gets a confirmation command from the user to continue the particular stage of the operation. This command is fed to the system via a joystick as shown in Figure 4.1. In the prototype development, two joysticks, a LCD and a keypad are used to design the user interface as shown in Figure 4.3. Through this user interface, the user can select the appropriate stage to operate the design. Based on the selected stage, the user can control the design speed and linear actuator operation through joysticks.



Figure 4.3: Joystick based user interface

Motor Controller

Based on the design approach there are two DC motors to drive left and right rubber tracks separately. Based on the user's command via main controllers, the speed of the design should be controlled. In order to control the design speed, there should be feedback signals to the main controller to measure speed of the tracks. In order to measure the design speed, incremental rotary encoders are connected to the rubber tracks as shown in Figure 4.4. According to the feedback signal, the speed of the design can be controlled.



Figure 4.4: Incremental rotary encoder placement on arm

In order to control the speed of the motor, Pulse Width Modulation (PWM) technique in voltage control mode is used. Based on the selected speed range for stair-climbing and flat surface operation, appropriate control signals are generated for motors via motor controller module. In order to prevent noises when operating the DC motors, a high frequency is used for the PWM signals. Based on the selected motor controller module, it can support the PWM signal up to $60KHz$. By considering the performances of the main controller, $32KHz$ is used to generate the PWM signal to motors. Also, the selected motor controller module is rated as $100A$ per channel with $260A$ of peak current up to 10 seconds. Based on the selected motor rating, this motor controller module is well suited for this application.

Linear Actuator Controller

In this design there are three pairs of arms called front, middle and rear arms. In order to control these arms separately, there are three linear actuators. Basically, a linear actuator consists of a DC motor with other parts to convert the angular motion into linear motion. In order to control the arm position, appropriate control signal should be generated according to the particular stage of the operation. In order to calculate the position of each arm, there is a position feedback signal which is fed to the main controller. Based on this position feedback, the main controller can calculate the arm position. Based on the calculated arm position, appropriate control signal is generated for each linear actuator. Also, in some stages of the operation, the main controller get updates via load cells which are

connected with each linear actuator, in order to observe whether the particular arm is properly contacted with the surface. Based on the defined reference contact force range, appropriate control signals are generated for each linear actuator through linear actuator controller. As same as in the DC motor control explained above, 32KHz of PWM signal in voltage control mode is used to control linear actuator operation. As a result, it helps to prevent noises when operating the linear actuators. In this case also the same motor controller module is used.

Main Controller

This is the main part of the controller design where all the other controllers are connected together to handle the design operation. When selecting a controller for this application, several factors have been considered, such as speed, cost and hardware accessibility. By considering all these factors, Arduino Mega 2560 modules are used for the main controller. Basically, the main controller consists of two Arduino modules to handle motor controller and linear actuator controller separately. Also, these controllers consist of internal communication to synchronize the each stage of the particular operation.

When considering about the speed of the Arduino, it has a 16MHz crystal oscillator to provide fast execution of commands. This speed is good enough for this application. As explained earlier, feedback signal of the design speed is connected to the main controller via digital input. By using an appropriate sample time with average pulse calculation, speed of the design can be controlled. Also, the position feedback and load cell feedback signals are connected to the arduino via analogue input. By using analogue to digital conversion, feedback signal can be processed by using defined conversion factors of this application.

4.2 Stair Descending Controller Design

As explained earlier, in this design two separate controllers are implemented for stair ascending and descending. Based on this approach, a detail analysis can be provided for each stage of particular operation. As a result, it can provide clear demonstration about the design operation throughout the staircase. In this section, stair descending operation is further discussed.

4.2.1 Basic Stages of Stair Descending

In stair descending operation, basically there are twelve stages as shown in Figure 4.5. Based on the stage of the operation design speed and arm position take

different behaviour. As demonstrated in Figure 4.5, there are some stages where the angular position of each arm is controlled one by one. These stages are existed when the design is on the flat surface or stair edges. In these stages of operation, the controller needs to operate the arm position based on angular displacement or contact force range. Except those stages, there are some stages where front and rear arms operation should be handled carefully. These stages are existed when the design moves from flat surface to stair edges or vice versa. In these stages of operation, the main controller should be able to synchronize the front and rear arms operation properly. Otherwise the system does not able to maintain stable and safe arrangements throughout the staircase. As demonstrated in the Figure 4.5, these stages are called stage *D* to *E* and stage *J* to *K*. A detail description of stages of operation are explained in Table 4.1.

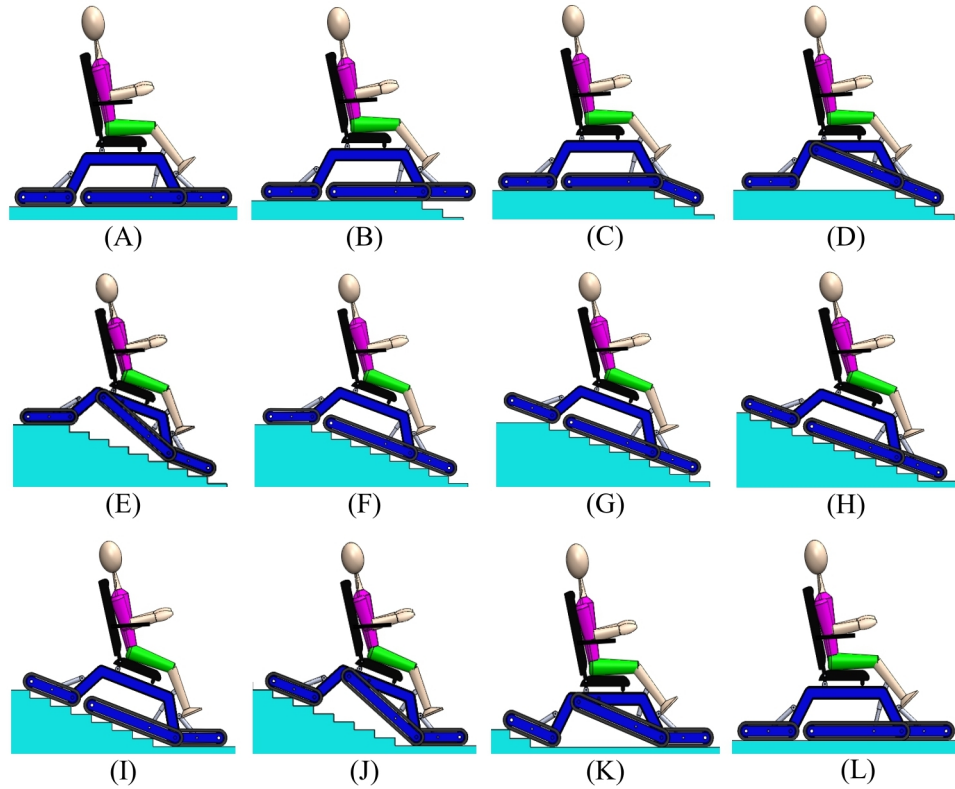


Figure 4.5: Safe motion profile of the mobile platform for stair descending

Table 4.1: Detail description of stair descending stages

Stage	Description
A-B	Design is moved forward at a predefined speed(V_{stair}) until top of staircase edge is detected
B-C	Front arm is operated downwards until it is properly contacted with stair edges. By using front arm angle(α), staircase angle(θ) can be observed. Because front arm is already parallel to staircase
C-D	Middle arm is operated upwards until it is aligned with front arm. In this case middle arm angle(β) is equal to staircase angle
D-E	Design is moved forward at a predefined speed(V_{stair}) while moving front arm in opposite direction and keeping the rear arm parallel to flat surface
E-F	Middle arm is operated until it is parallel to the staircase
F-G	Rear arm is operated until it is parallel to the staircase
G-H	Design is moved forward at a predefined speed(V_{stair}) until front arm is contacted with the ground
H-I	Design is moved forward at a predefined speed(V_{stair}) while moving front arm upwards by keeping it parallel to ground
I-J	Middle arm is operated upwards until it is equal to staircase angle
J-K	Design is moved forward at a predefined speed(V_{stair}) while moving front arm downwards by keeping it parallel to ground and keeping the rear arm parallel to stair edges
K-L	Middle and rear arms are operated downwards until they are parallel to staircase

4.2.2 Motion Planning of Stair Descending

As explained in Table 4.1, design speed and arm position are varied at different stages. In order to analyze the behaviour of design speed and arm operation there should be a motion plan for each stage. By considering these requirements, novel motion plans are developed as shown in Table 4.2. In this motion plans the angular displacements of arms are measured as shown in Figure 4.3. By using these motion plans, it can easily identify the critical operations where both front and rear should be synchronized. Also, based on these motion plans, it provides clear demonstration when designing appropriate controller for each stage of operation. Also, when executing the simulation study, these motion plans provide a clear demonstration of angular displacements of each arm based on the selected time intervals.

Table 4.2: Motion plan for angular displacement of arms in stair descending

Stage	Time Period	Front Arm Angle(α)	Middle Arm Angle(β)	Rear Arm Angle(γ)	Speed
A-B	$0 \leq t \leq t_1$	0	0	0	V_{stair}
B-C	$t_1 \leq t \leq t_2$	$\frac{\alpha(t-t_1)}{(t_2-t_1)}$	0	0	0
C-D	$t_2 \leq t \leq t_3$	α	$\frac{\beta(t-t_2)}{(t_3-t_2)}$	0	0
D-E	$t_3 \leq t \leq t_4$	$\alpha - \left\{ \frac{\alpha(t-t_3)}{(t_4-t_3)} \right\}$	β	$\frac{-\gamma(t-t_3)}{(t_4-t_3)}$	V_{stair}
E-F	$t_4 \leq t \leq t_5$	0	$\beta - \left\{ \frac{\beta(t-t_4)}{(t_5-t_4)} \right\}$	$-\gamma$	0
F-G	$t_5 \leq t \leq t_6$	0	0	$-\gamma + \left\{ \frac{\gamma(t-t_5)}{(t_6-t_5)} \right\}$	0
G-H	$t_6 \leq t \leq t_7$	0	0	0	V_{stair}
H-I	$t_7 \leq t \leq t_8$	$\frac{-\alpha(t-t_7)}{(t_8-t_7)}$	0	0	V_{stair}
I-J	$t_8 \leq t \leq t_9$	$-\alpha$	$\frac{\beta(t-t_8)}{(t_9-t_8)}$	0	0
J-K	$t_9 \leq t \leq t_{10}$	$-\alpha + \left\{ \frac{\alpha(t-t_9)}{(t_{10}-t_9)} \right\}$	β	$\frac{\gamma(t-t_9)}{(t_{10}-t_9)}$	V_{stair}
K-L	$t_{10} \leq t \leq t_{11}$	0	$\beta - \left\{ \frac{\beta(t-t_{10})}{(t_{11}-t_{10})} \right\}$	$\gamma - \left\{ \frac{\gamma(t-t_{10})}{(t_{11}-t_{10})} \right\}$	V_{stair}

4.2.3 Angular Displacement Calculation of Arm

As discussed in the previous sections, the controller needs to have a feedback signal of angular displacement of each arm. In order to achieve this task, separate angular sensors should be attached to each arm. But, in some cases, there could exist some practical problems when placing the angular sensors because of placement issues. Also, in some cases, due to mechanical construction issues, there could exist some problems to measure the angular displacement only by attaching a single sensor. In such kind of situations it is better to attach two sensors for both rubber tracks. Then, by using the appropriate technique, the actual angular displacement can be observed. Rather than placing angular sensors for each arm, there is a method to observe the angular displacement of each arm. This can be achieved by considering the geometrical relationship of each arm as shown in Figure 4.6. Here, the angular displacement of an arm depends on the linear actuator displacement. By considering the linear actuator displacement as the angle changing parameter, the angular displacement of each arm can be calculated as shown in Table 4.3.

Table 4.3: Angular displacement calculation based on linear actuator displacement

Linear Actuator	Angular Displacement
Front	$\alpha = \cos^{-1} \frac{(x_{f2})^2 + (x_{f3})^2 - (x_{f1})^2}{2(x_{f2})(x_{f3})} - \alpha_{con}$
Middle	$\beta = \beta_{con} - \cos^{-1} \frac{(x_{m2})^2 + (x_{m3})^2 - (x_{m1})^2}{2(x_{m2})(x_{m3})}$
Rear	$\gamma = \gamma_{con} - \cos^{-1} \frac{(x_{r2})^2 + (x_{r3})^2 - (x_{r1})^2}{2(x_{r2})(x_{r3})}$

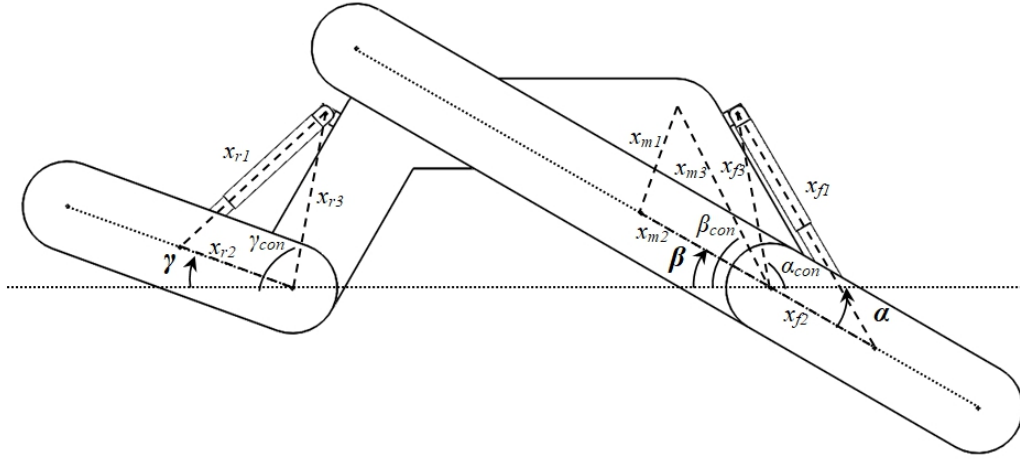


Figure 4.6: Geometrical arrangement of angular displacement

By using the given parameters for each arm, the angular displacement can be calculated. As discussed earlier, all the linear actuators have a position feedback signal to the main controller. By using those linear displacements of each linear actuator, angular displacement can be calculated. By using this technique, the angular displacement can be easily calculated without attaching separate parts to the design. Also, the other benefit of this technique is that it can provide acceptable reading, because the linear actuator is placed at the middle of the connecting axle of two rubber tracks of a particular arm. Thus, it ensures the angular displacement reading gets a proper value.

4.2.4 PID Controller Design for Stair Descending

As discussed earlier, there are several stages defined for stair descending operation. In those stages, all the arms get a different posture to maintain stable and safe arrangements. In order to maintain the defined posture for arms for a particular stage of the operation, there should be an appropriate controller. Also, in some stages, the design should have to maintain a constant speed as well. In order to achieve this task, PID controllers are implemented for this mobile platform. This is one of the most popular controllers used for industrial application because of less of complexity in implementation and tuning method. In this development, basically, four PID controllers are implemented for arm control and design speed control. In this thesis, only the weight of the prototype is considered when selecting appropriate gains for each controller in the experiment study. Because based on the controller design, variation of user weight for the design can be avoided. This will be further explained in following sections.

4.2.4.1 Position Control of Arm (PID_{angle})

In stair descending operation, there are four stages where the middle and the rear arm should be controlled to particular angles. In order to achieve this task, P type controller is used as shown in Figure 4.7. In here θ_1 and θ_2 represents reference angle and current angle respectively. According to the staircase angle, the reference angle is defined. By considering the reference value with the current value, appropriate control signals are generated for linear actuator control. Based on the selected low cost linear actuator, it has a low speed around $5mm.s^{-1}$ under the load. When controlling arm position, the linear actuator should be operated on acceptable speed. Otherwise, it could take more time to complete the task. Also, when operating the linear actuator with higher speed, it can cause to overshoot the reference value as well. By considering all these facts, gain of 125 is selected for P controller. Based on the selected gain, the linear actuator has acceptable speed. Also, due to the response range of the linear actuator for low duty cycle of PWM, the overshooting is prevented.

In this controller design, arm operation is controlled based on the angular position of the arm. In stair-climbing operation, this controller is implemented in different stages. In those stages, any external forces do not affect the arm operation except the weight of arm. Even the user weight is included onto the design, it will not affect for the arm position control based on angle.

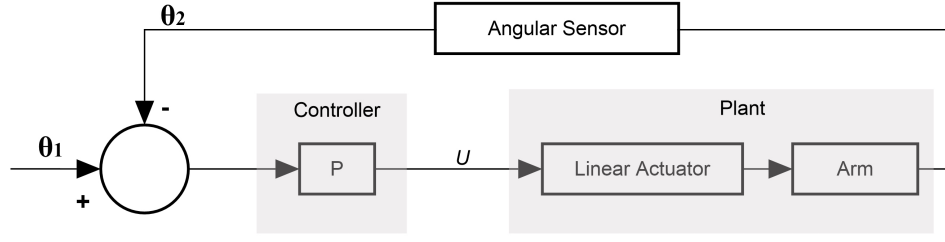


Figure 4.7: Arm position control overview

4.2.4.2 Control of Contact Force of Arm (PID_{force})

Except the angle control of arms, there are some stages where arm displacement should be handled based on the amount of contact force with the surface. For example, in stair descending, there are two stages where the front arm displacement is controlled based on the contact with the surface. By considering the requirement, a P type controller is used for arm operation as shown in Figure 4.8. Here, F_1 and F_2 represents reference contact force range and current load cell reading respectively. The main reason for selecting the reference contact force range is to avoid oscillations when controlling the arm. Based on the linear actuator placement and weight of the design, the reference contact force range can be varied. By considering these parameters, the reference contact force range for the prototype is selected as $300N - 850N$. This contact force range is selected while maintaining a parallel arrangement to a particular surface by an arm. According to the selected reference contact force range and current contact force of the arm, appropriate control signals are generated for linear actuator control. In this controller design, P type controller with a gain of 25 is used due to response range of the linear actuator for low duty cycle of PWM.

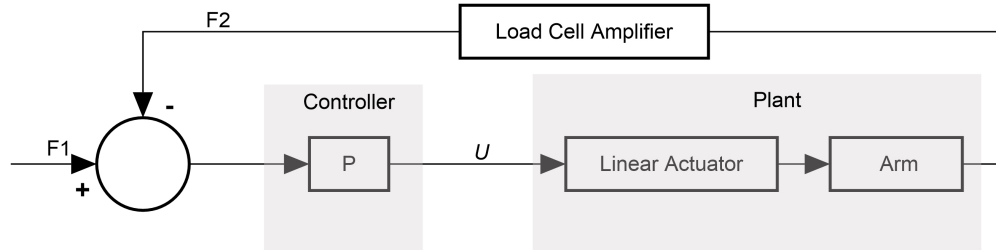


Figure 4.8: Proper contact of arm control overview

When defining the reference contact force range for an arm, mainly two reasons are considered which are linear actuator placement and weight of the design. As the linear actuator placement is fixed to the prototype, only the weight of the design directly affects to define the reference range. In this case, user weight can be considered as the external load to the design. Based on the change of the user weight, reference contact force range should be adjusted. In order to overcome from this issue, a simple technique is used in this controller design. Based on the current weight of the prototype, the reference contact force range is selected as $300N - 850N$. If a particular arm is able to maintain the contact force within this range, it ensures a proper contact with particular surface with parallel arrangement. If a particular arm maintains contact force beyond the reference range, it causes to create non-parallel arrangement. When the user weight is included to the design, the reference contact force range can be extended due to the change of total weight. But, practically, this is not a best approach for a controller design for a stair-climbing mobile platform. To overcome this issue, the reference contact force range is defined only by considering the weight of the design without the user weight. As a result, change of the user weight does not affect the reference contact force range. Due to that reason, it does not also affect for the controller tuning as well.

4.2.4.3 Front and Rear Arm Synchronization (PID_{syn})

Throughout all the stages of stair descending operation, there are two stages where both front and rear arms operation should be synchronized properly to maintain a desired posture. These two stages are existed when the design is at the top and bottom of the staircase. In these stages, controller design should be able to keep both arms parallel to particular surface. In order to control both arms, two PID controllers are used simultaneously as shown in Figure 4.9. According to the controller design as shown in Figure 4.9, front and rear arms are controlled by combining two PID controllers that were discussed earlier. When the design is on top of the staircase, rear and front arms operations are considered as Arm 1 and Arm 2 respectively. First, the Arm 1 is controlled in order to maintain the contact force within the defined reference contact force range. Within this reference range, it ensures that the particular arm is parallel to the surface. Then, by considering the angular displacement of Arm 1 as the reference value, Arm 2 angle is controlled. The same procedure is followed when the design is on the bottom of the staircase. But, in this case, the front and rear arm operation are considered as Arm 1 and Arm 2 as illustrated in Figure 4.9.

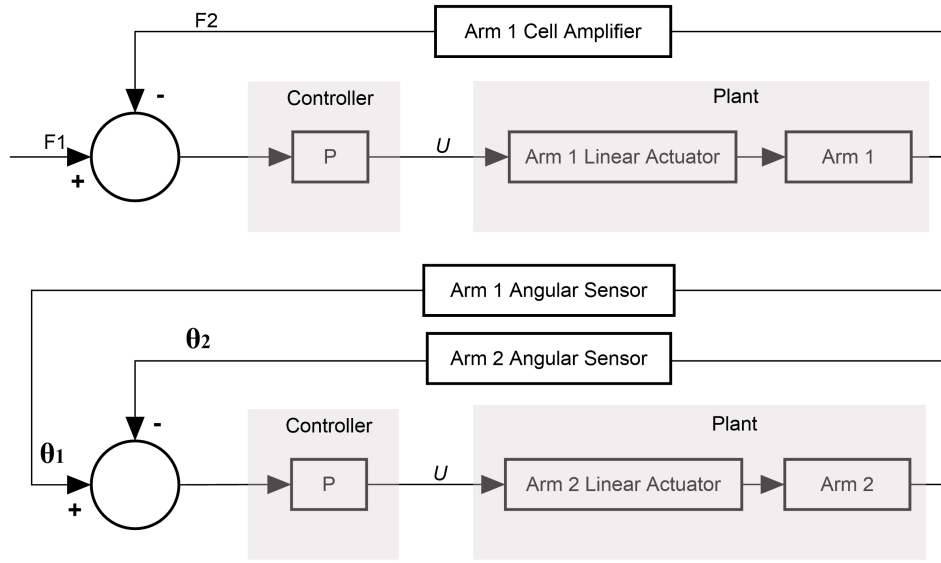


Figure 4.9: Arm synchronization control overview

4.2.4.4 Design Speed Control (PID_{speed})

All the three PID controllers that were discussed earlier are based on linear actuator control of arms. Here, speed controller of the design is discussed. In all the stages of the stair descending operation, design should be able to maintain a constant speed in order to support the arm operation, because constant speed of the design can provide more stable operation to the design. As a result, it can prevent sudden disturbances to the arm operation. In order to achieve this task, PI controller is used as shown in Figure 4.10. Here, V_1 and V_2 represents reference speed and current speed of the design. In order to observe a smooth operation over staircase, PI type controller is implemented for speed control. Also, the gain for P and I controllers are considered as 2 and 20 respectively. When selecting the reference speed for this controller, basically three factors have been considered which are speed of linear actuator, resolution of incremental rotary encoder and sampling time. Based on these factors, acceptable low speed is selected for the design in stair-climbing operation by considering the safety conditions as discussed in Figure 2.21. Even if the speed of the design changes little bit due to mechanical issues or surface behaviour, the linear actuators have acceptable speed range in order to overcome from such sudden variations.

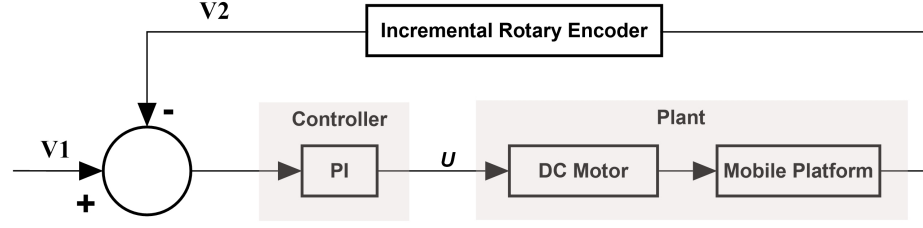


Figure 4.10: Design speed control overview

4.2.5 Usage of PID Controller for Stair Descending

As discussed earlier basically four PID controllers are used to handle design operation. Based on the design operation at different stages, several PID controllers are implemented simultaneously. In order to simplify the usages of PID controllers, summarized details are shown in Table 4.4. This provides clear demonstration of PID usage for arms operation and design speed for all the stages.

Table 4.4: PID controller usage at different stages of stair descending

Stage	Front Arm	Middle Arm	Rear Arm	Speed
A-B				PID_{speed}
B-C	PID_{force}			
C-D		PID_{angle}		
D-E	PID_{syn}		PID_{syn}	PID_{speed}
E-F		PID_{angle}		
F-G			PID_{angle}	
G-H				PID_{speed}
H-I	PID_{force}			PID_{speed}
I-J		PID_{angle}		
J-K	PID_{syn}		PID_{syn}	PID_{speed}
K-L		PID_{angle}	PID_{angle}	PID_{speed}

4.3 Stair Ascending Controller Design

In the previous section, stair descending operation was discussed in detail. In this section, stair ascending operation will be discussed in brief. Because in most of the cases both stair ascending and descending operation take similar behaviour. The main difference between those two operations is the sequence of the defined stages. In stair ascending operation, all the stages which are defined for stair descending is reversed. As a result, motion plans and usage of PID controllers should be updated.

4.3.1 Basic Stages of Stair Ascending

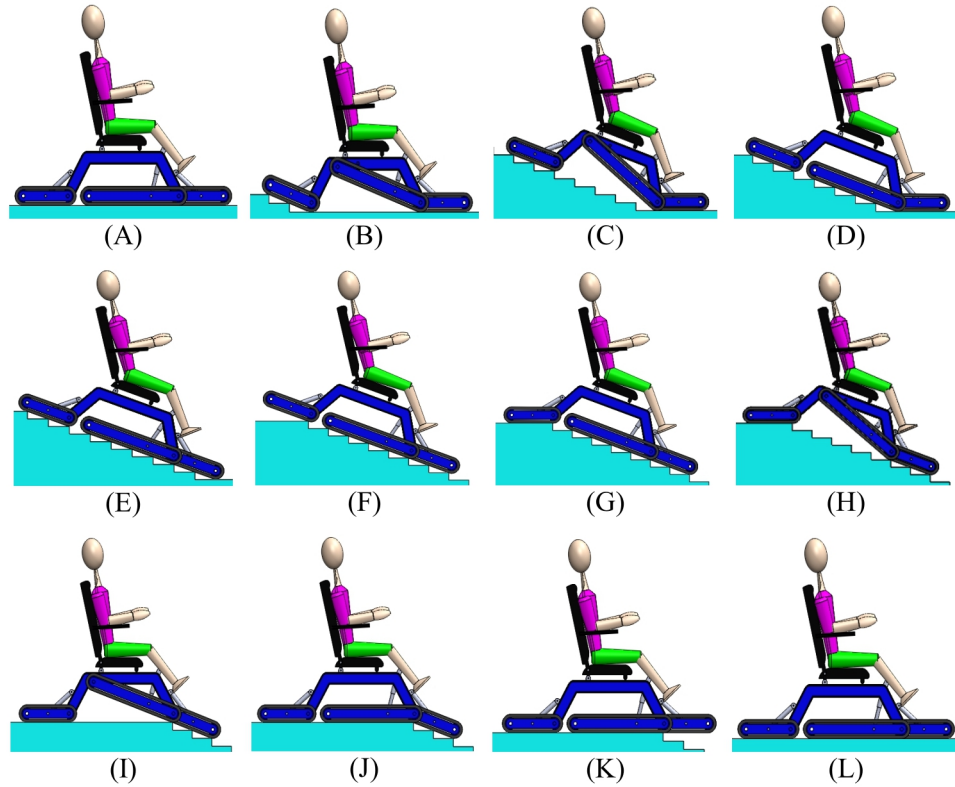


Figure 4.11: Safe motion profile of the mobile platform for stair ascending

There are twelve stages for stair ascending which is same as stair descending as shown in Figure 4.11. Also, when ascending stairs the design is operated reverse direction because of some reasons. One of the most highlighted reason is the safety posture that can provide for the user. Also, based on the user placement, the design can provide minimum height for the seat placement. Thus, ensures a comfortable operation for the user. The other major difference between stair ascending and descending is the arm controlling method based on force and angle. This will be explained in PID controller usage for stair ascending.

Table 4.5: Detail description of stair ascending stages

Stage	Description
A-B	Design is moved reverse at a predefined speed(V_{stair}) while moving middle and rear arms in upwards
B-C	Design is moved reverse at a predefined speed(V_{stair}) while moving front arm upwards by keeping it parallel to ground and keeping the rear arm parallel to stair edges
C-D	Middle arm is operated downwards until it is parallel to staircase
D-E	Design is moved reverse at a predefined speed(V_{stair}) while moving front arm downwards by keeping it parallel to staircase
E-F	Design is moved reverse at a predefined speed(V_{stair}) until top of staircase edge is detected
F-G	Rear arm is operated downwards until it is properly contacted with flat surface
G-H	Middle arm is operated upwards until it is equal to staircase angle
H-I	Design is moved reverse at a predefined speed(V_{stair}) while moving front arm parallel to staircase and keeping the rear arm parallel to flat surface
I-J	Middle arm is operated downwards until it is aligned with rear arm
J-K	Front arm is operated upwards until it is aligned with rear arm
K-L	Design is moved reverse at a predefined speed(V_{stair}) until design leaves the staircase

4.3.2 Motion Planning of Stair Ascending

For stair ascending operation, motion plans for arm operation and design speed control are demonstrated in Table 4.6. These motion plans are executed when conducting the simulation and experimental study. Also, when comparing to the motion plans defined for stair descending are, more similar to this operation as well. The only difference is the defined reference angles are selected as opposite direction.

Table 4.6: Motion plan for angular displacement of arms in stair ascending

Stage	Time Period	Front Arm Angle(α)	Middle Arm Angle(β)	Rear Arm Angle(γ)	Speed
A-B	$0 \leq t \leq t_1$	0	$\frac{\beta(t)}{(t_1)}$	$\frac{\gamma(t)}{(t_1)}$	V_{stair}
B-C	$t_1 \leq t \leq t_2$	$\frac{-\alpha(t-t_1)}{(t_2-t_1)}$	β	$\gamma - \left\{ \frac{\gamma(t-t_1)}{(t_2-t_1)} \right\}$	V_{stair}
C-D	$t_2 \leq t \leq t_3$	$-\alpha$	$\beta - \left\{ \frac{\beta(t-t_2)}{(t_3-t_2)} \right\}$	0	0
D-E	$t_3 \leq t \leq t_4$	$-\alpha + \left\{ \frac{\alpha(t-t_3)}{(t_4-t_3)} \right\}$	0	0	V_{stair}
E-F	$t_4 \leq t \leq t_5$	0	0	0	V_{stair}
F-G	$t_5 \leq t \leq t_6$	0	0	$\frac{-\gamma(t-t_5)}{(t_6-t_5)}$	0
G-H	$t_6 \leq t \leq t_7$	0	$\frac{\beta(t-t_6)}{(t_7-t_6)}$	$-\gamma$	0
H-I	$t_7 \leq t \leq t_8$	$\frac{\alpha(t-t_7)}{(t_8-t_7)}$	β	$-\gamma + \left\{ \frac{\gamma(t-t_7)}{(t_8-t_7)} \right\}$	V_{stair}
I-J	$t_8 \leq t \leq t_9$	α	$\beta - \left\{ \frac{\beta(t-t_8)}{(t_9-t_8)} \right\}$	0	0
J-K	$t_9 \leq t \leq t_{10}$	$\alpha - \left\{ \frac{\alpha(t-t_9)}{(t_{10}-t_9)} \right\}$	0	0	0
K-L	$t_{10} \leq t \leq t_{11}$	0	0	0	V_{stair}

4.3.3 Usage of PID Controller for Stair Ascending

As discussed earlier, usage of four basic PID controllers for stair ascending are shown in Table 4.7. As it is demonstrated, usage of PID controllers for similar stages with compared to stair descending take different PID implementations. Because of the change of the orientation of arm position.

Table 4.7: PID controller usage at different stages of stair ascending

Stage	Front Arm	Middle Arm	Rear Arm	Speed
A-B		PID_{angle}	PID_{angle}	PID_{speed}
B-C	PID_{syn}		PID_{syn}	PID_{speed}
C-D		PID_{angle}		
D-E	PID_{force}			PID_{speed}
E-F				PID_{speed}
F-G			PID_{force}	
G-H		PID_{angle}		
H-I	PID_{syn}		PID_{syn}	PID_{speed}
I-J		PID_{angle}		
J-K	PID_{angle}			
K-L				PID_{speed}

Chapter 5

SIMULATION AND EXPERIMENTAL STUDY

In the previous chapters, detailed descriptions of prototype development were explained. In this chapter, the design operation is further discussed in order to provide clear demonstration of this design operation under different forces in different postures. In order to validate safe and stable operation of the design, experimental study has been carried out. Also, simulation study is used to further study the design operation as well.

5.1 Simulation Study

As discussed earlier, there are some stages where both the front and the rear arm operation should be synchronized properly to maintain stable and safe postures throughout the staircase operation. In order to study further about these stages, both descending and ascending operations are considered separately. Before conducting the experimental study, the simulation study had been carried out by using SolidWorks software. Thus, it could provide a clear demonstration of the design operation in all the stages. In this study, 20 degrees of the staircase with 200mm length of adjacent stair edges was selected, which was similar in dimensions for the staircase used in the experimental study. Also, in this study, gravitational force and solid body contact in between the design and the staircase were defined. By following the motion plans explained in the previous chapter, all the arms and the design speed were controlled based on the stages of the stair descending operation.

In the Solidworks environment, all the arms and the design speed were controlled by using motion analysis feature. In the motion analysis mode, all the stages of operation could be simulated by using the Event-base motion analysis in Solidworks. In order to drive the design and the arms, linear servo motor and rotary servo motors were defined in Event-base motion. Based on the stage of the operation, displacement for each motor could be provided. Based on the de-

defined time interval for each stage, appropriate speeds were defined for each motor by the Event-base motion feature. In this simulation study, the time interval in between two stages were considered as five seconds in order to observe a clear demonstration.

5.1.1 Simulation Study of Stair Descending

In order to provide a clear demonstration of simulation study, the stair descending operation is further simplified. In this study, the basic stages defined in the previous chapter have been further categorized based on the placement of the design on the staircase.

5.1.1.1 Entering the Staircase at the Top (Stage A-G)

In stage $A - B$, the design was moved forward until it reached to the top of the stair edge. In this stage, design speed was controlled based on the defined distance to travel in Event-base motion. Once the design reached to the desired location, it was stopped. Then the front arm was moved downwards until it was parallel to the staircase in stage $B - C$. Based on the given angle for rotary servo motor, the front arm was operated at 20 degrees. In order to create a parallel arrangement with the staircase, the middle arm was operated upwards. In stage $D - E$, the design was moved forward at a pre-defined speed. Meanwhile, in this stage, the front and the rear arms were operated to follow the desired angular positions. Throughout this stage, the front and the rear arms maintained parallel arrangements with particular surfaces. Due to the simulation environment, all the arm operation could be controlled based on the angular positions to observe the desired postures. But, in the experimental study, contact forces should be used to observe the desired arrangements. In stage $E - F$ and $F - G$, the middle and the rear arms were operated parallel to the staircase. The angular displacements of all the arms when entering to the staircase are demonstrated in Figure 5.1 by following the stages of operation.

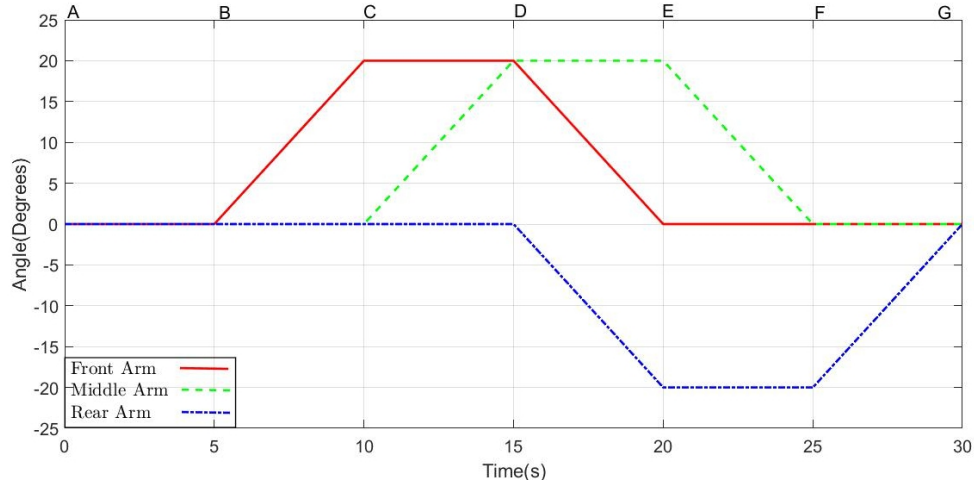


Figure 5.1: Angular displacement of the arms in entering the staircase at the top in stair descending

5.1.1.2 Middle of the Staircase (Stage G-H)

In this stage, the design was moved at a pre-defined speed to reach the bottom of the staircase. In this stage, all the arms were parallel to each other. Only the design speed was controlled.

5.1.1.3 Leaving the Staircase at the Bottom (Stage H-L)

When the design reached the bottom of the staircase, the front arm was operated to upwards to create a parallel arrangement with floor. In this case, the design was also moved at a pre-defined speed as specified in the Event-base motion. In stage $I - J$, the middle arm was operated upwards to reach 20 degrees. In next stage, the design was moved according to the Event-base motion while moving the front and the rear arms to the desired angle positions. Finally, the middle and the rear arms were operated downwards parallel to the surface. The angular displacements of all the arms when leaving the staircase are demonstrated in Figure 5.2 by following the stages of operation.

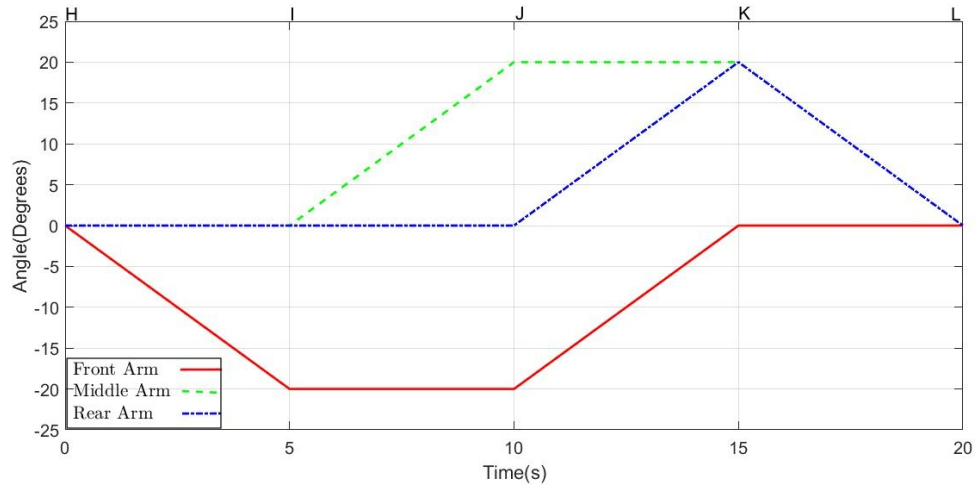


Figure 5.2: Angular displacement of the arms in leaving the staircase at the bottom in stair descending

If the operation of all the arms and the speed of the design were controlled properly, then the design could be able to maintain stable posture specially at the top and the bottom of the the staircase. In order to maintain these stable postures, the front and the rear arms operation must be synchronized properly. As discussed in Figure 2.20, if both the front and the rear arms were synchronized properly, then the total absolute angle of the front and the rear arms must be equal to the staircase angle. This can be easily verified by referring the angular displacement of the front and the rear arms in stage $D - E$ and $J - K$ as shown in Figure 5.3.

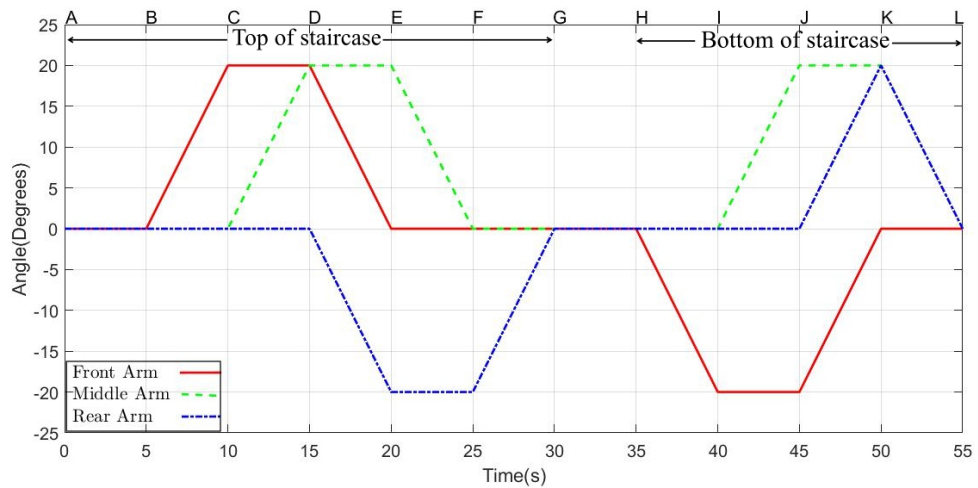


Figure 5.3: Angular displacement of the arms in stair descending in simulation

According to the above graph, the front and the rear arms maintained desired postures in stage $D - E$ and $J - K$. As a result, the user position should follow a smooth path in order to maintain a comfortable operation throughout all the operations. This can be demonstrated in Figure 5.4. As it is demonstrated in Figure 5.4, there did not exist any sudden movements specially at top and bottom of the staircase. As a result, it could provide stable and safe operation. At the experimental study the design behaviour at the top and the bottom of the staircase should be discussed in detail to validate stable and safe operation.

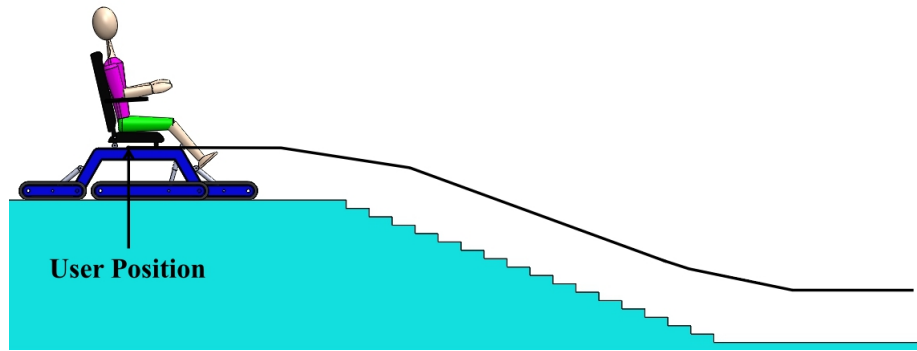


Figure 5.4: Traced path of the user position

Furthermore, the user's comfort can be verified by further analyzing the change of the user's position and orientation. In order to study the user's position behaviour, the user's position was measured with respect to the ground. Also, the orientation of the user's seat placement was measured in the clockwise direction as shown in Figure 2.20. By using these parameters, the rate of change of the user's height and the orientation are demonstrated in Figure 5.5. Based on these results, it clearly demonstrated that there did not exist any sudden variation in the user's position. This should be further verified at the experimental study.

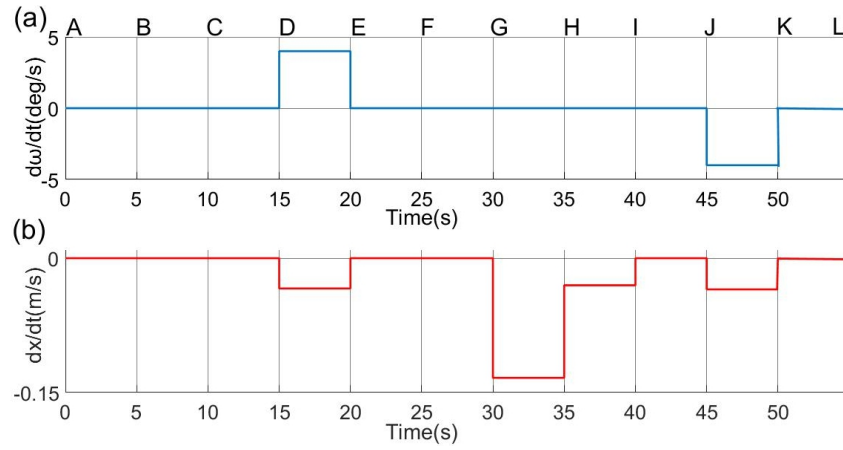


Figure 5.5: Behaviour of the user's position (a)rate of change of orientation (b)rate of change of height

5.1.2 Simulation Study of Stair Ascending

In this simulation, also the same mobile platform and staircase which were used in the previous study, was used. Also, by using the motion plans discussed in the last chapter, the design operation was controlled. In this study, also the simulation study was categorized into three sections to simplify the results.

5.1.2.1 Entering the Staircase at the Bottom (Stage A-E)

In these stages also, the design speed was controlled by following the motion plans. By following defined angles for each arm based on the stage, arm operations were controlled. The angular displacement of arms at the bottom of the staircase is demonstrated in Figure 5.6

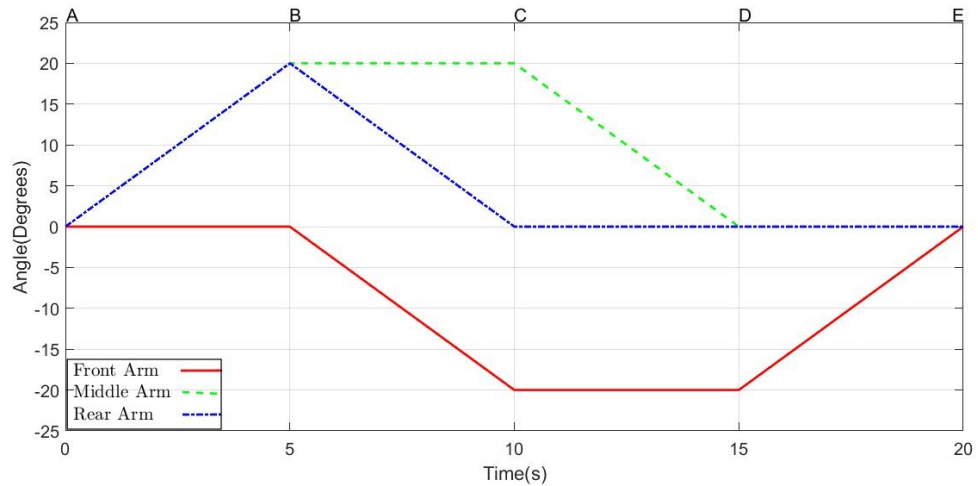


Figure 5.6: Angular displacement of arms in entering the staircase at the bottom in stair ascending

5.1.2.2 Middle of the Staircase (Stage E-F)

This is a similar operation as discussed in stair descending. In this case, all the arms were parallel to each other. Only the design speed was controlled. In Event-base motion, the desired speed could be selected by including the distance to travel and time to reach the top of the staircase.

5.1.2.3 Leaving the Staircase at the Top (Stage F-L)

When the design was on the top, the front and the rear arm operation should be synchronized properly to obtain the desired path for the user position as discussed earlier. In stage $H - I$, the front arm moved to 20 degrees downwards and the rear arm moved upwards to keep it parallel to flat surface. Based on the motion plans, the angular displacement of all the arms are demonstrated in Figure 5.7

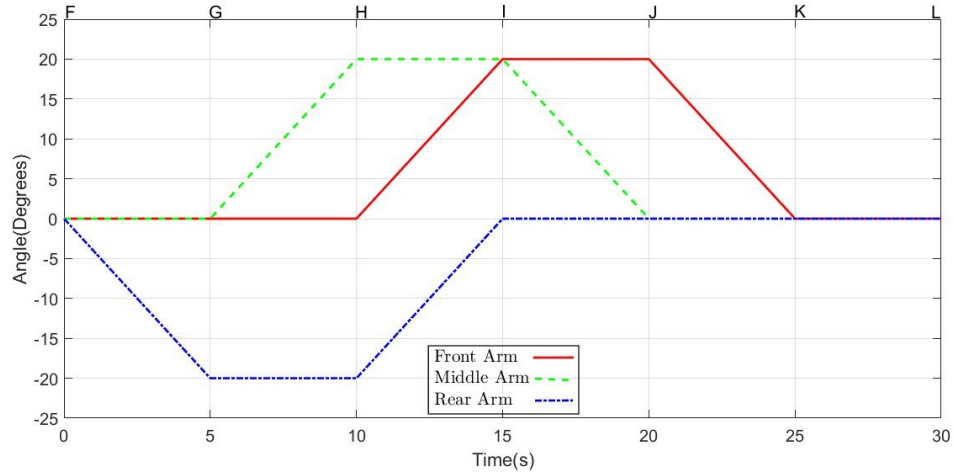


Figure 5.7: Angular displacement of the arms in leaving the staircase at the top in stair ascending

In this operation also, the stable postures could be observed by considering the front and the rear arm operation in stage $B - C$ and $H - I$. This can be easily verified by referring the Figure 5.8 as discussed in stair descending operation. According to the angular displacements of arms, a similar user's position could be observed as same as in stair descending operation as shown in Figure 5.4.

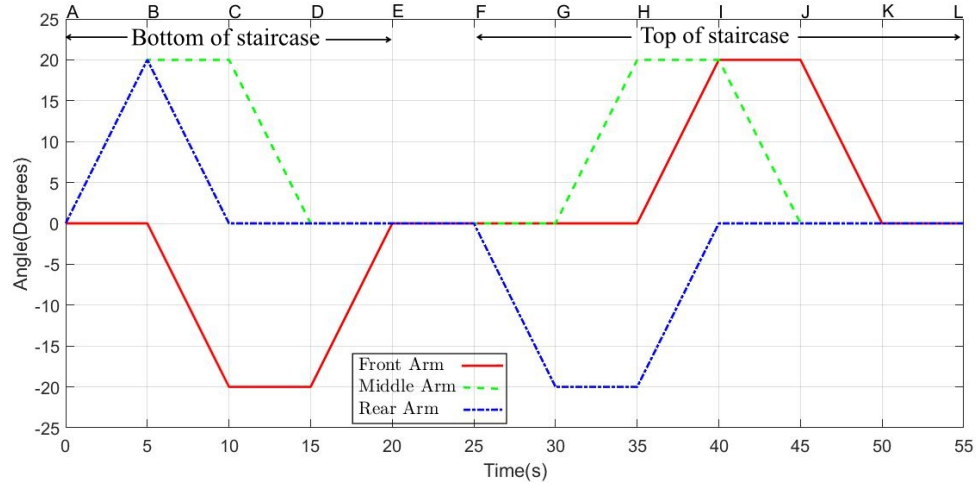


Figure 5.8: Angular displacement of arms in stair ascending in simulation

5.2 Experimental Study

Based on the simulation study, it had provided a clear demonstration of the behaviour of the user's position for both stair ascending and descending. Also, execution of motion plans for each stage of operation was also explained in detail. This was very helpful when conducting the experimental study. In this study also, both ascending and descending operations were considered separately for further analyze of the design posture at the top and the bottom of the staircase. Also, based on the experimental results, safety operation of the design was further discussed.

In the experimental study, the design was tested on a 20 degrees of staircase with a 200mm length of adjacent stair edges, which was the same staircase dimension considered in the simulation study. This helped to conduct a comparison in between the simulation and the experimental study. Due to some issues, the slope of the staircase was around 19.8 degrees. By using the same method as explained in the simulation study, the design operation was controlled according to the motion plans as discussed in the previous chapter. In the simulation study, only angles were controlled in all the operations to observe the desired postures. But, in the experimental study, the contact force and the angular positions were considered to control the arms in order to observe the required postures. When executing the motion plan for each arm, PID controllers were implemented separately as discussed in the previous chapter. Also, throughout the operation, the design speed was controlled to maintain a lowest constant speed.

The main purpose of this experimental study was to analyze the user position behaviour specially at the top and the bottom of the staircase because at those stages, the front and the rear arm operation should be synchronized properly to maintain the stable and safe posture. When operating the design in the experimental study, the user interface was used as discussed in the previous chapter. In each and every stage, the controller received commands from the user interface to acknowledge the stage of the operation. As it was a prototype, automatic detection of steps, identification of each stage and alignment were not considered in the development. By using the user interface, all these features were adjusted manually. Once the system controller received the command to start the operation for a particular stage, the controller took necessary actions to control the design and arm operation automatically. Also, in the controller interface, an additional stage was defined to provide accessibility to control each arm manually. This was very useful when executing the experimental study. In all the stages of the operation, all the processing data in the controller design was sent to a laptop via USB port. This data was used to analyze the experimental study.

Before testing this design on the 20 degrees of staircase, an adjustable staircase of 17.8 degrees was used. As it was constructed by using steel and wood, there were many issues when the design was operated. The main purpose of that experiment was to clearly identify the suitable controller design to control the arm operation. After finalizing the appropriate controller, the experimental study was carried-out on the 20 degrees of the staircase. In this case, the gains for each arms were fine tuned by conducting several experiments. When selecting the gains for each controller, mainly the safety of the design was considered. Specially at the top and the bottom of the staircase, oscillation should be minimized as much as possible. Meanwhile, appropriate gains were selected for the design speed control to maintain the lowest speed as well. By conducting several experiments, summarized results were presented in this the experimental study.

5.2.1 Experimental Study of Stair Descending

In order to demonstrate the angular displacement and force for each arm, the experimental study was further divided into three sections. Thus, it can provide a clear demonstration for each arm operation.

5.2.1.1 Entering the Staircase at the Top

Before starting the stair descending, the system controller received an update through the user interface regarding the stage of the operation. Based on the stage of the operation, the arms and the design speed were controlled. In stage $A - B$, the design was moved forward until it reached the top of the stair edge. In this stage, a joystick command was fed to the system to start the design operation. Here, a joystick command was used only to give commands to start or stop the design operation. Based on the defined speed, the design speed was controlled by using the PID_{speed} controller. Once the design reached the desired position, it was stopped manually. Then the controller system again received an update to start the next step, which was stage $B - C$. This command was fed to the controller by using the joystick manually. In this stage, the front arm was moved downwards automatically until it properly contacted with stair edges. In order to control the front arm, the PID_{force} controller was executed. When it reached the defined contact force range as shown in Figure 5.9, the front arm operation was stopped by the controller.

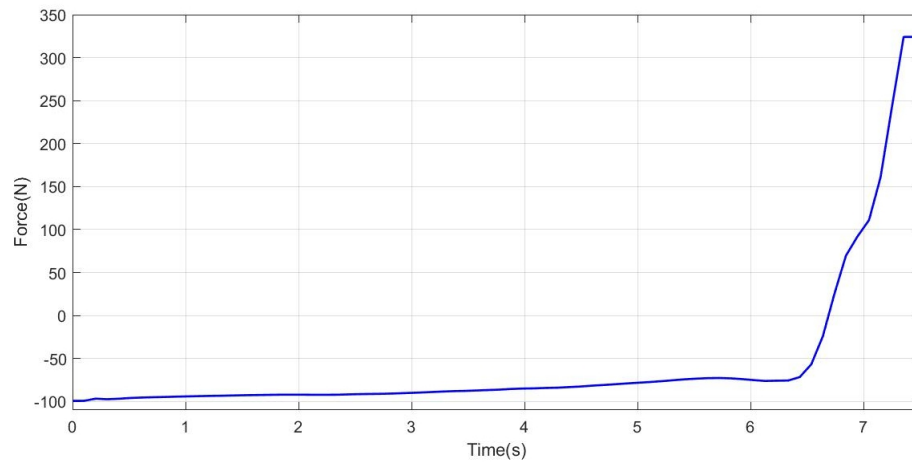


Figure 5.9: Contact force of the front arm in stage B-C

Then the middle arm was operated upwards by implementing the PID_{angle} controller in stage $C - D$. In this stage, the middle arm was operated to follow the front arm angle automatically. In this stage, the front arm angle was used as the reference angle to control the middle arm. In the next stage, $D - E$, design speed and arms operation were controlled simultaneously. In this stage, the PID_{syn} and the PID_{speed} controllers were used to control the front and the rear arms and design speed respectively. By using the user interface, the design

was moved until the rear driving wheel reached the top of the stair edge. When it reached the desired location, the design was stopped manually. When the stage $E - F$ was fed to the controller using the user interface, the middle arm was operated downwards until it was parallel to the staircase. Finally, the rear arm was operated upwards to align with other arms. Based on the stage of operation, the angular displacement of all the arms when entering to the staircase at the top are shown in Figure 5.10. Also, based on the stage of the operation, the design speed was controlled to a constant value. When compared to the simulation study, the time duration in between stages were varied based on the operation of the arms.

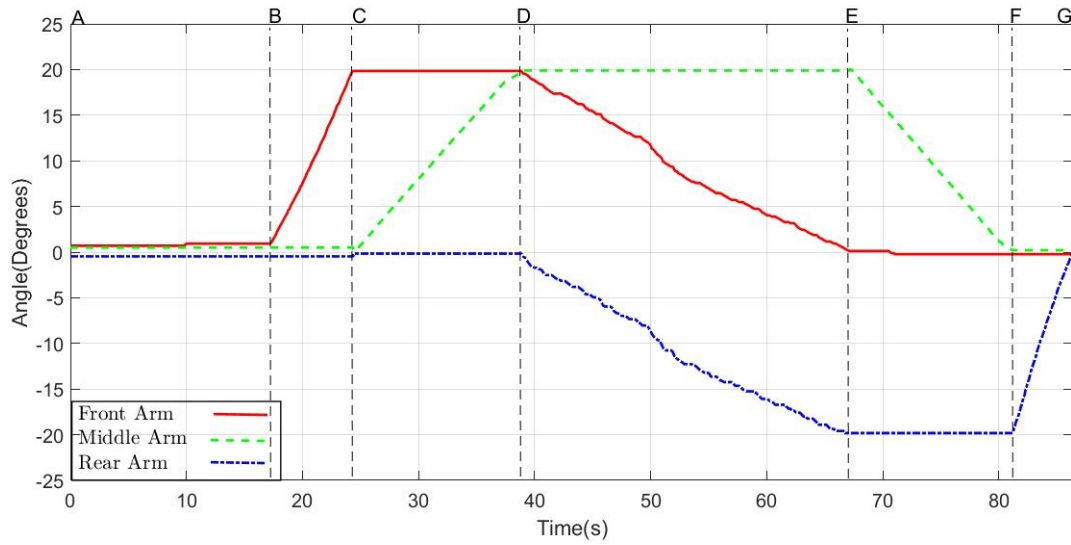


Figure 5.10: Angular displacement of the arms in entering the staircase at the top in stair descending

In this experimental study also, a similar graph can be observed as discussed in the simulation study. But, it does not guarantee stable posture, especially at the top of the staircase. Design operation at this stage should be further analyzed in order to validate design safety. As discussed in the previous chapters, if both front and rear arms were synchronized properly, then the total absolute angle of front and rear arms should follow the staircase angle. In order to maintain this condition, both arms should be parallel to a particular surface. At the top, the front and the rear arms should be parallel to stair edges and the flat surface respectively. In any case if one or both arms were unable to maintain this arrangement, then it caused issues to maintain stable operation. As a result, it could create problems in user's position behaviour as discussed in the simulation study. In order to validate the safety of the design, the absolute total angular

displacement of both front and rear arms at the top of the staircase was observed as shown in Figure 5.11.

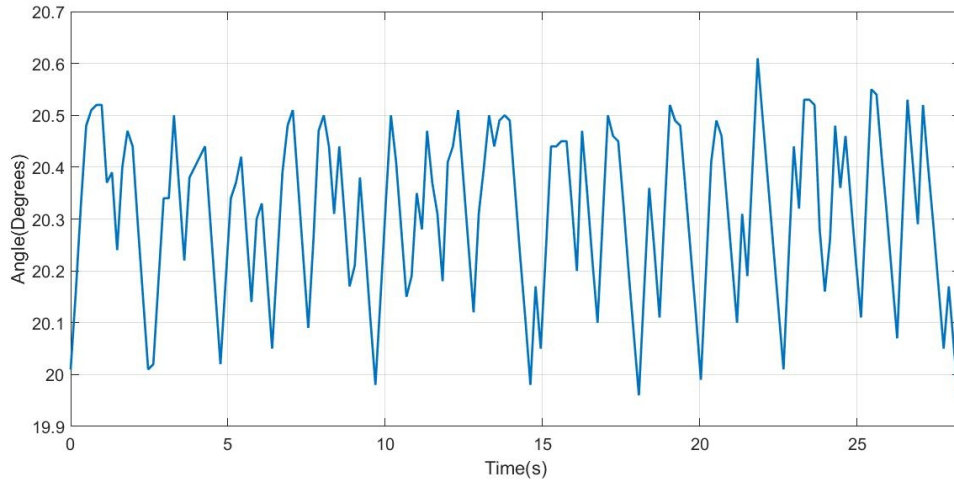


Figure 5.11: Absolute total angular displacement of front and rear arms in stage D-E in stair descending

As it is demonstrated on the Figure 5.11, the absolute total angular displacement at stage $D - E$ followed the staircase angle. Also, based on the selected reference contact force range for both front and rear arms as discussed in previous chapter, there could exist some oscillation in angular displacement of arms. Based on the selected force range, the marginal value was defined as 0.7 degrees. This marginal value was observed when the particular arm started to create non-parallel arrangement with a flat surface. In this observation, the particular arm was under the maximum reference contact force value. As a result, it caused to compress most of the parts of the arm. Thus, it could directly affect the angular displacement measuring method as discussed earlier. Thus, it caused to define the marginal values for angular displacement. According to the defined marginal values, the absolute total angular displacement could be in between 20.5 to 19.1 as shown in Figure 5.11. Furthermore, to demonstrate the parallel arrangement of the rear arm with a flat surface, the linear actuator force reading for the rear arm is demonstrated in Figure 5.12. In this case, the rear arm should maintain a parallel arrangement with a flat surface when the design is on stage $D - E$.

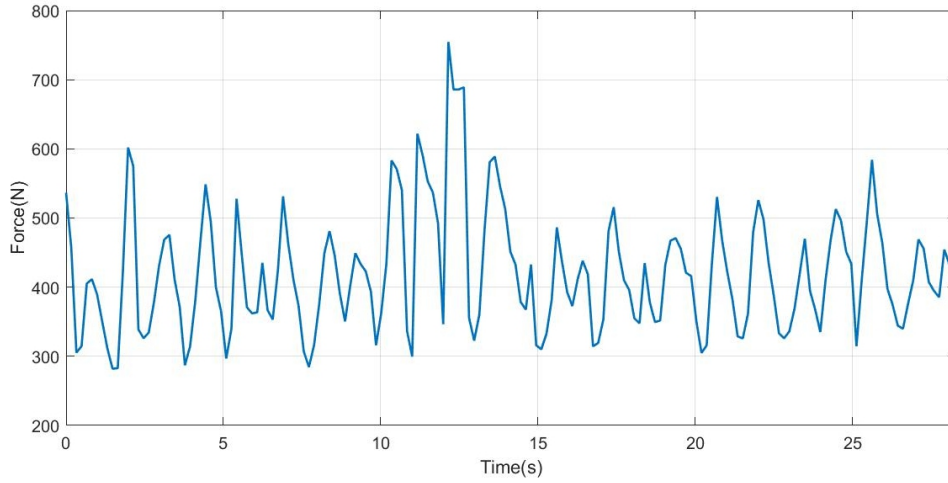


Figure 5.12: Contact force of the rear arm with a flat surface in stage D-E in stair descending

As it is demonstrated in Figure 5.12, the rear arm maintained the contact force within the defined reference contact force range. It ensured that the rear arm maintained a parallel arrangement throughout the operation. On the other hand, it also ensured that the rear arm maintained proper contact with the surface as well.

In all the experimental results discussed earlier, explained about the operation of arms when entering the staircase at the top in stair descending. In order to further justify the actual behaviour in user's position at those stages, it is better to have visual illustrations for the experimental study. In order to observe the visual illustration of user's position behaviour at stage $D - E$, a video clip was used. By using this video clip, it was able to plot the actual operating path of design operation. In order to plot the operating along the staircase, a Tracker software was used. In this visual illustration, it was hard to locate the actual user's position as demonstrated on the simulation study. As a result, in this illustration, a point was selected on the chassis which was very closer to the center of the chassis. On the other hand, when selecting a point for tracing the operating path, the point should have a different colour when compared to the background. By considering these facts, tracing point was selected for stage $D - E$. By using the Tracker software the operating path of design in stage $D - E$ is demonstrated in Figure 5.13.

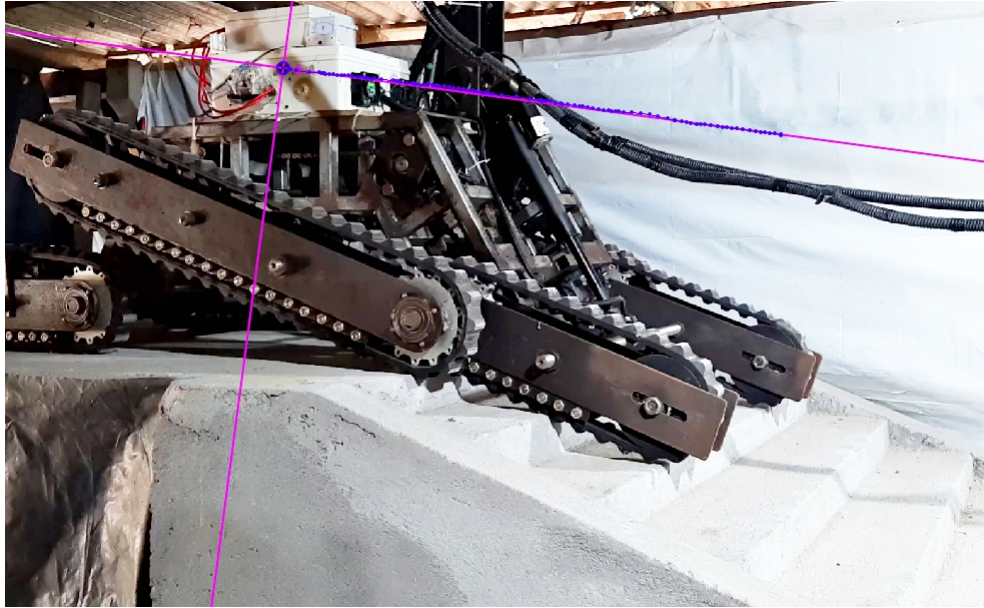


Figure 5.13: Trace path of design operation in stage D-E in stair descending

As it is demonstrated in Figure 5.13, the operating path at the top followed a straight line, which displayed a similar behaviour as demonstrated in the simulation study. In order to further illustrate the trace path behaviour, the displacement of the traced path was observed. In this observation, the axes of plot in the video were defined by considering the beginning and the end of the operation, because at the beginning and end of the operation the design was aligned with particular surface. Thus, it provided a clear demonstration of the actual behaviour when compared to the defined operating path. In order to further validate user's position behaviour, change of velocity and acceleration are demonstrated in Figure 5.14.

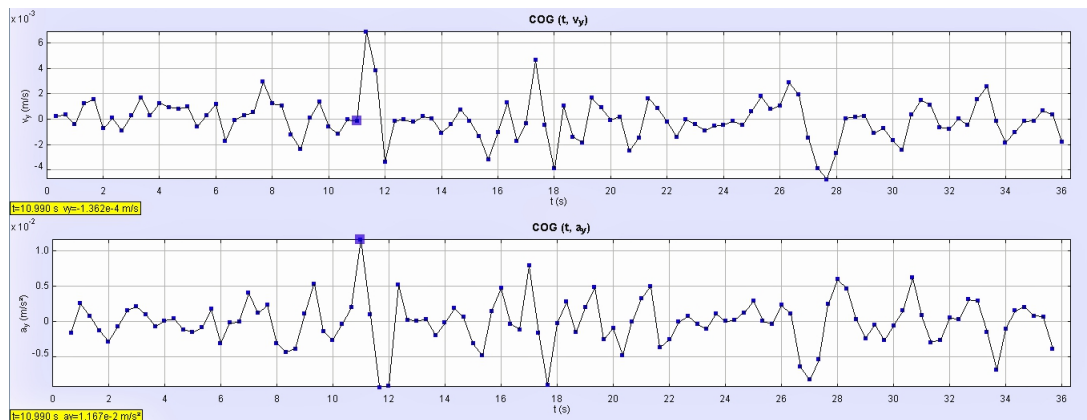


Figure 5.14: Change of velocity and acceleration of user's position in stage D-E in stair descending

According to Figure 5.14, it clearly demonstrated that the maximum change of velocity and acceleration for the traced path were around $7ms^{-1}$ and $10ms^{-2}$ respectively. Due to this small oscillation, it can be considered that the actual traced path almost followed the desired profile. Also, it can provide clear demonstration that user's position behaviour when entering the staircase in stair descending was lack of sudden movements. As it was not discussed about user case study, it was not able to conclude the comfortable operation for the user. But, based on the geometrical posture, this can be further validated by considering the existing designs in the market.

5.2.1.2 Middle of the Staircase (Stage G-H)

In this stage, all the arms were in parallel arrangement with each other. When moving from stage $G - H$, only the design speed was controlled by using the PID_{speed} . By using the joystick operation, the controller received a command to start the design operation. Based on the defined speed, the design was controlled to move downwards.

5.2.1.3 Leaving the Staircase at the Bottom (Stage H-L)

When reached the stage H , the controller received an update to start the particular operation. In this stage, the PID_{force} and the PID_{speed} controllers were used to control the front arm and the design speed respectively. Once the front driving wheel contacted with the floor, stage $H - I$ was stopped manually. After that, the middle arm was operated upwards until it reached the staircase angle automatically. In this case, the PID_{angle} controller was used. In next stage $J - K$, the PID_{syn} and the PID_{speed} controllers were used to control both the front and the rear arms and design speed respectively. In order to start the operation, a user interface was used to acknowledge the controller to start the stage $J - K$. This process was continued until the rear driving wheels contacted the floor. When it contacted the floor, design was stopped manually. In the last stage, design was moved forward while moving both middle and rear arms downwards until they were parallel to floor. In order to demonstrate the all the angular displacements, a clear illustration has been presented in Figure 5.15.

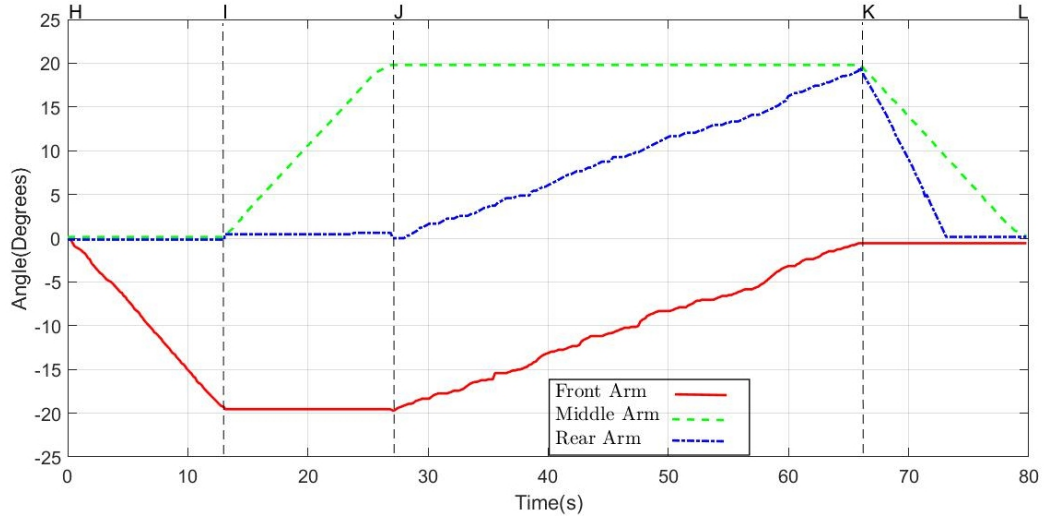


Figure 5.15: Angular displacement of the arms in leaving the staircase at the bottom in stair descending

In this case also, the front and the rear arm operation should be synchronized properly to maintain a stable posture at the bottom of the staircase. As discussed earlier, in this case also, the total absolute angle of the front and the rear arms was observed to analyze the arm synchronization. As it is demonstrated in Figure 5.16, the absolute total angular displacement at stage $J - K$, followed the staircase angle within the defined marginal values as defined earlier. Also, in this stage, the front arm maintained proper contact with the floor to ensure a parallel arrangement. As it is illustrated in Figure 5.17, the front arm maintained contact force within the defined reference range.

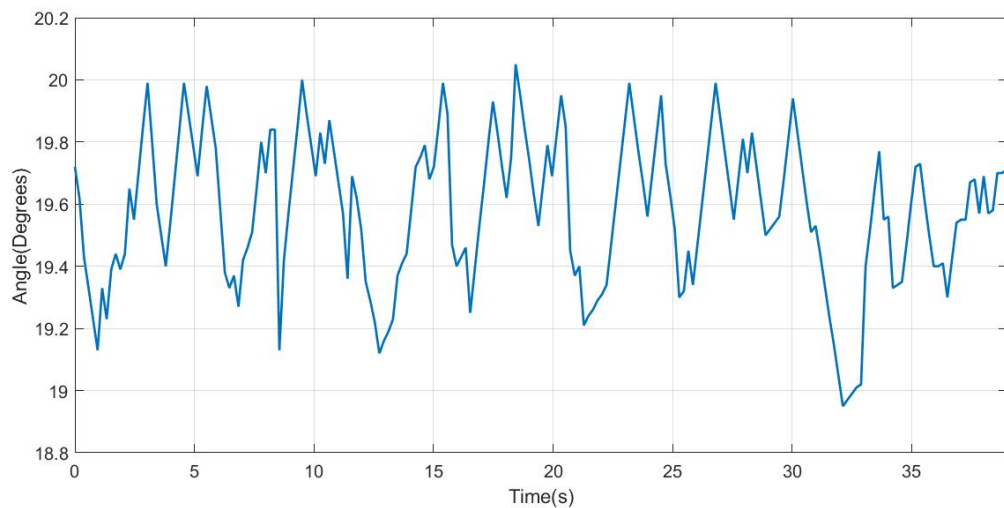


Figure 5.16: Absolute total angular displacement of the front and the rear arms in stage J-K in stair descending

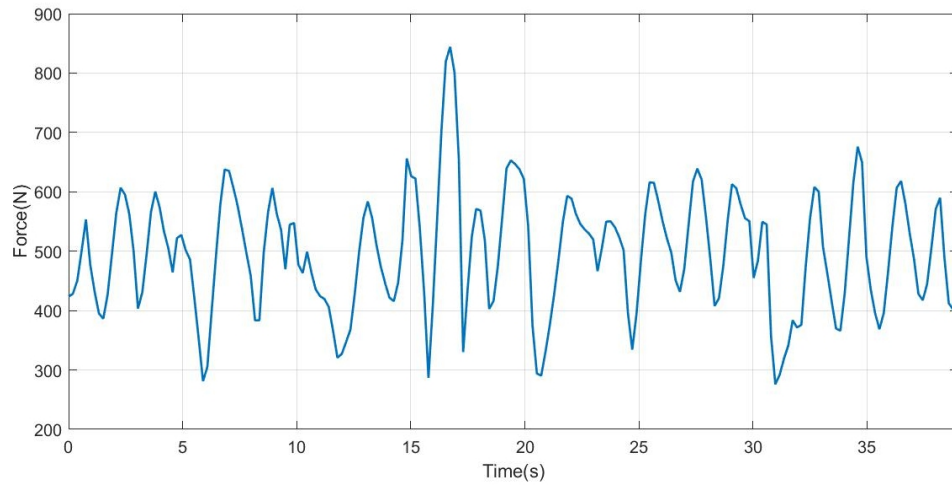


Figure 5.17: Contact force of the front arm with the floor in stage J-K in stair descending

In order to further illustrate the actual behaviour of the design operation, a video clip was used. By using the video, the operating path of user's position was observed by using the Tracker software which was discussed earlier. Due to some technical issues, it was hard to locate the same point which was used in stage $D - E$. On the other hand, even if the selected point was not exactly the same, the operating path should have a similar behaviour. As illustrated in Figure 5.18, the traced path followed a straight line, which was a similar behaviour as in stage $D - E$.

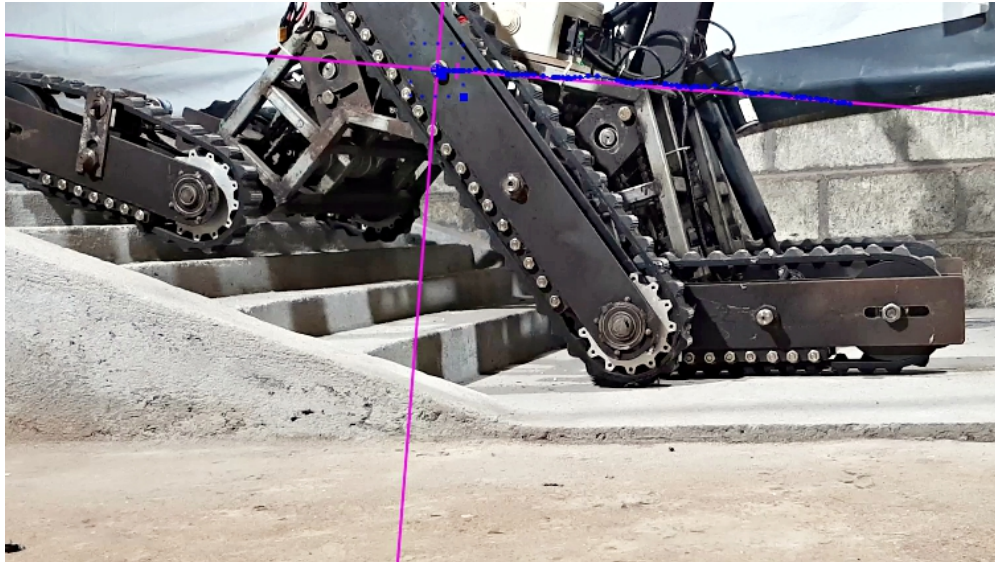


Figure 5.18: Trace path of design operation stage J-K in stair descending

In order to further illustrate user's position behaviour, change of velocity and acceleration are demonstrated in Figure 5.19. According to the Figure 5.19, it clearly demonstrated that change of velocity and acceleration were very small. When compared to the existing designs as discussed earlier, the design operation when leaving the staircase at the bottom was almost free of sudden variations.

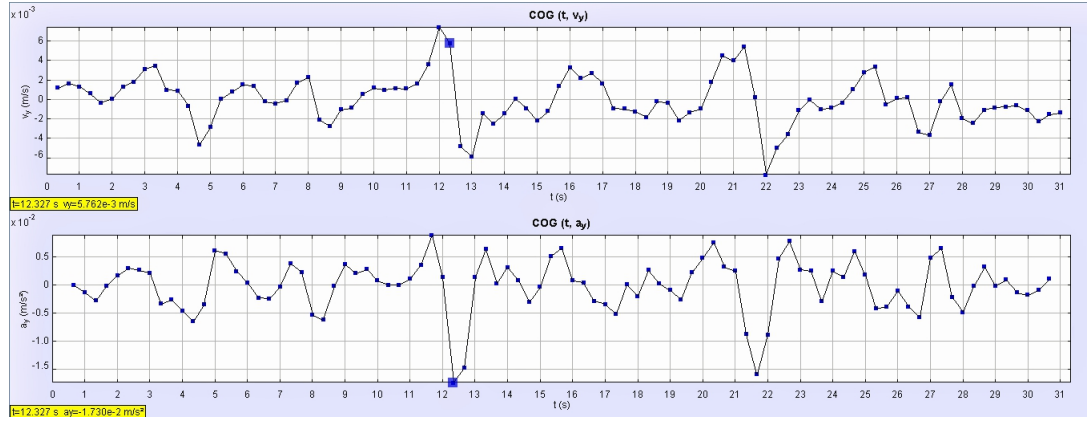


Figure 5.19: Change of velocity and acceleration of user's position in stage J-K in stair descending

5.2.2 Experimental Study of Stair Ascending

In this experimental study also, the same methods used for stair descending were applied. In order to control the arm operation, the motion plans explained in the previous chapter were used. In this study, all the stages used for stair ascending were further categorized.

5.2.2.1 Entering the Staircase at the Bottom

In this stage, the design speed and both middle and rear arms were controlled by using the PID_{speed} and the PID_{angle} controllers respectively. As this was a prototype development, there was not any method to detect the staircase angle automatically. By using the user interface, the staircase angle was fed to the controller to control the arm operation. Based on the defined staircase angle, both middle and rear arms were controlled by using the PID_{angle} controller. This stage of operation was continued until the rear arm contacted the staircase. After that, in stage $B - C$, both front and rear arms and design speed were controlled by using the PID_{syn} and the PID_{speed} controllers respectively. This process was continued until the front arm followed the staircase angle. When the front arm reached the staircase angle, the design was stopped by using the user interface. After that, in stage $C - D$, the middle arm was operated downwards until it was

parallel to the staircase. Here, the PID_{angle} controller was used to operate the middle arm. In the last stage $D - E$, the design was moved over the staircase while maintaining contact with the floor by the front arm. In this case also, the PID_{speed} and the PID_{force} controllers were used to control the design and the arm operation. Based on the stage of the operation, the angular displacement of all the arms when entering the staircase at the bottom are shown in Figure 5.20.

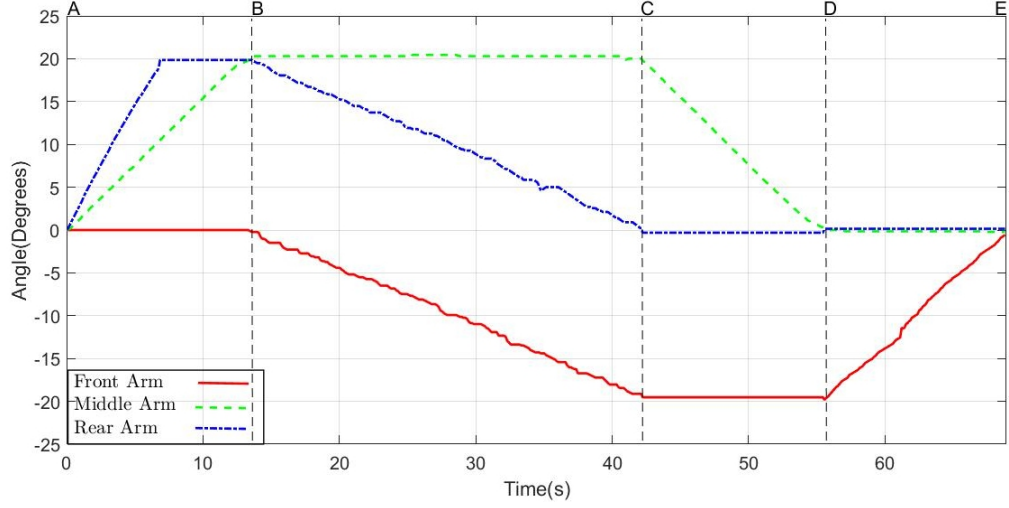


Figure 5.20: Angular displacement of arms in entering the staircase at the bottom in stair ascending

In order to further validate the stable postures of design at stage $B - C$, it is better to observe the absolute total angular displacement of both arms. As shown in Figure 5.21, the values were oscillated in between 19.1 to 20.5, which were the defined marginal values as discussed earlier. Within this marginal values, the front and the rear arm could be able maintain a parallel arrangement with the particular surface. As a result, the design could be able to maintain stable postures at the bottom of the staircase.

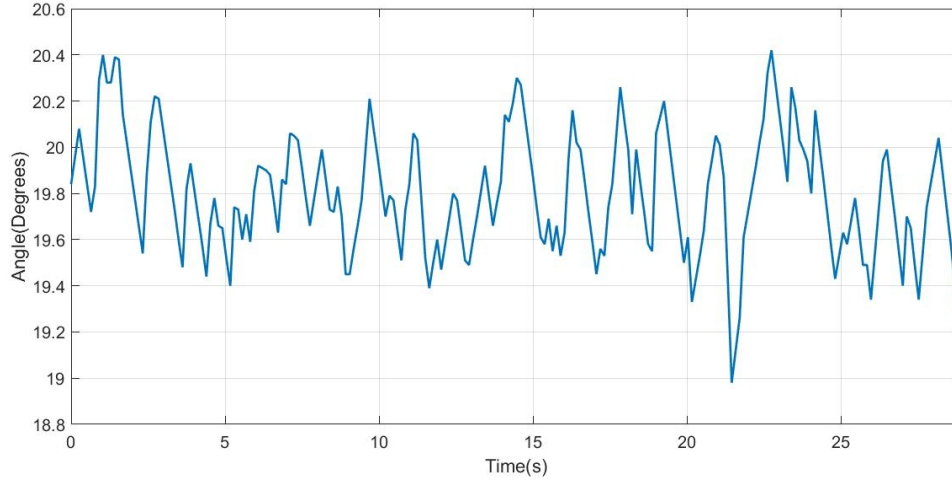


Figure 5.21: Absolute total angular displacement of both front and rear arms in stage B-C in stair ascending

In order to further confirmed the parallel arrangement of the front arm in stage $B - C$, the contact force is demonstrated in Figure 5.22. Based on the experimental results, it demonstrated that front arm was able to maintain the contact force within the defined reference contact force range. Thus, it ensured a parallel arrangement with the particular surface. As a result, the design could be able to maintain proper contact with the surface to ensure stable posture.

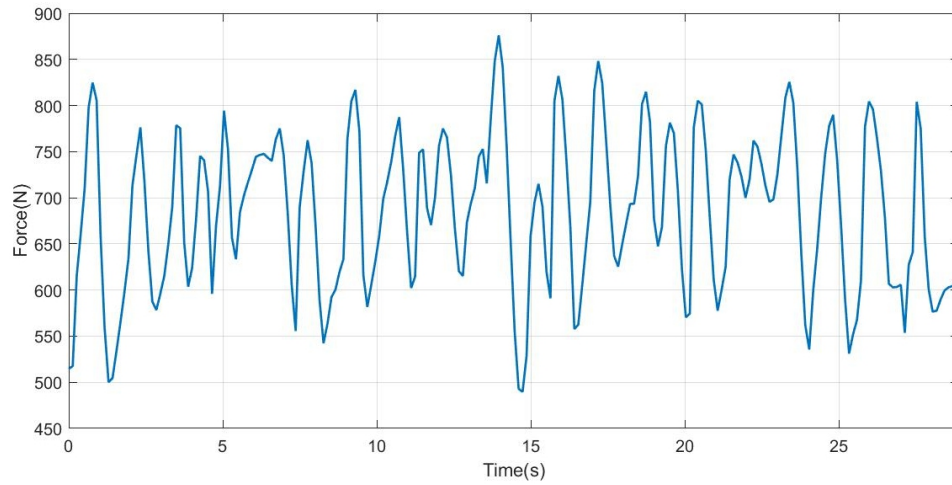


Figure 5.22: Contact force of the front arm in stage B-C in stair ascending

In order to further justify the design safety, it is better to illustrate the operating path in stair ascending as well. In this case also, the same point which was used for stage $J - K$ in stair descending was used for the tracing. By using the

auto tracker features of the Tracker software, the operating path of selected point was traced as shown in Figure 5.23. As it is demonstrated, the operating path followed a straight line which was similar behaviour as discussed in the simulation study.

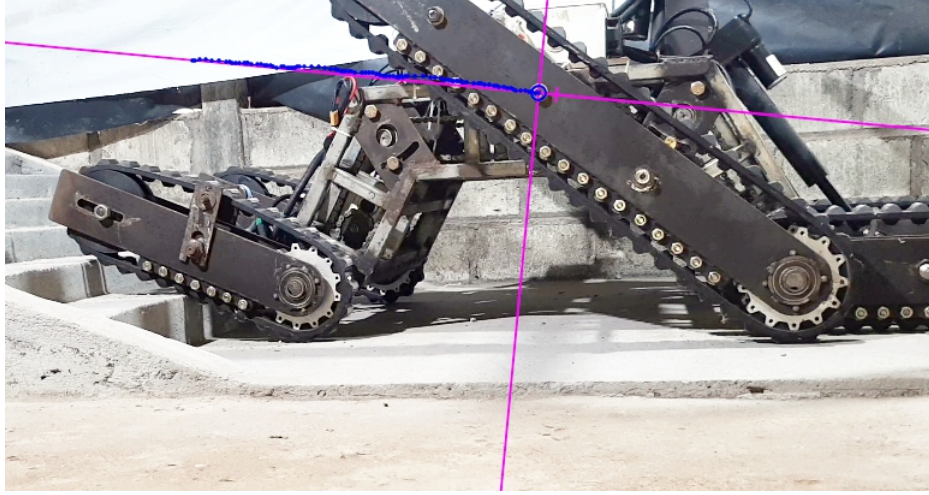


Figure 5.23: Trace path of design operation in stage B-C in stair ascending

In order to observe the displacement of the traced points, the axes of plot in the video were defined as same as in stair descending. Based on the beginning and end of the stage of operation, the traced path followed a straight path with some oscillation. In order to further illustrate user's position behaviour, change of velocity and acceleration are illustrated in Figure 5.24.

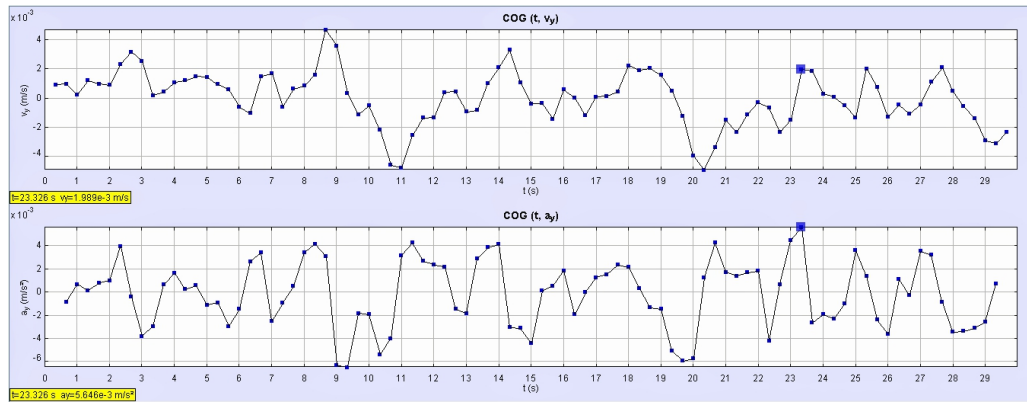


Figure 5.24: Change of velocity and acceleration of user's position in stage B-C in stair ascending

In this case, a similar behaviour could observe for user's position, as illustrated for stair descending when leaving the staircase. Due to the small oscillation

of velocity and acceleration, user's position almost followed the desired path. Furthermore, due to these negligible values, the sudden oscillation on the platform was prevented.

5.2.2.2 Middle of the Staircase (Stage E-F)

In stage $E - F$, all the arms were in parallel arrangement with the staircase. In this stage, only the PID_{speed} controller was used to control the design speed. This operation was continued until the rear driving wheel contact the top stair edge. When it reached the desired location, the design was stopped by using the user interface.

5.2.2.3 Leaving the Staircase at the Top (Stage F-L)

Once the design reached the desired location, the controller received an update through the joystick to start the operation for stage $F - G$. In this case, the rear arm was operated downwards until it contacted with the flat surface. Here, the PID_{force} controller was used. As illustrated in Figure 5.25, the rear arm maintained the contact force within the reference contact force range. Thus, it ensured that the rear arm maintained a parallel arrangement with the flat surface as well.

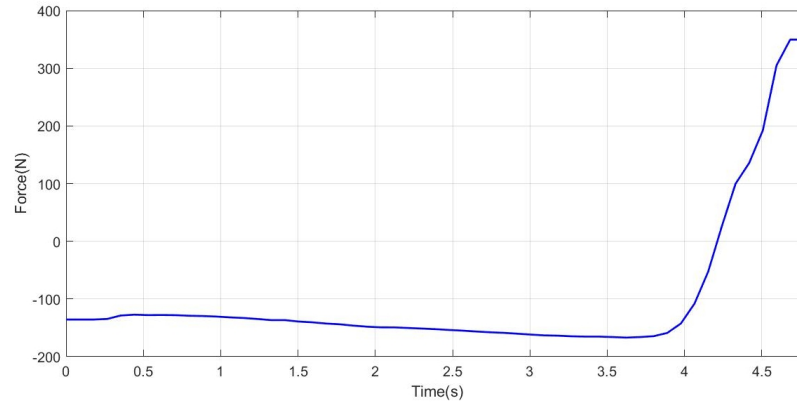


Figure 5.25: Contact force of the rear arm in stage F-G in stair ascending

In stage $G - H$, the middle arm was operated upwards until it followed the staircase angle. Here, the PID_{angle} controller was used to control the arm. Once the above step was completed, the controller received an update to start the stage $H - I$. In this stage, the design was moved upwards by using the PID_{speed} controller. Meanwhile, the front and the rear arms were controlled by using the

PID_{syn} controller. When the front driving wheel reached the top of the stair edge, this stage of operation was stopped through the user interface. After that, in stage $I - J$, the middle arm was operated downwards until it was parallel to a flat surface by using the PID_{angle} controller. Also, by using the same controller, the front arm was operated upwards until it was parallel to the flat surface in stage $J - K$. At the final stage, design was moved by using the PID_{speed} controller until it left the staircase. All the angular displacements of the arms are illustrated in Figure 5.26.

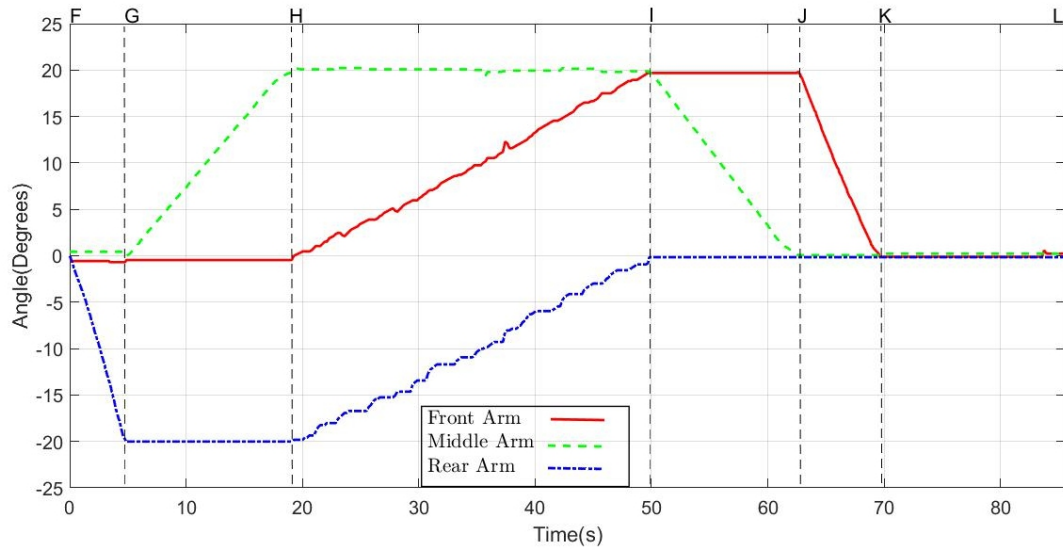


Figure 5.26: Angular displacement of arms in leaving the staircase at the top in stair ascending

In these stages of operation, design should maintain proper arrangement in stage $H - I$. Because at this stage, the front and the rear arm operation should be synchronized properly to maintain the desired posture. In order to analyze the arm operation, the absolute total angular displacement of both front and rear arms at the top of the staircase is observed as shown in Figure 5.27. As it is demonstrated in Figure 5.27, the absolute total angular displacement at stage $H - I$, followed the staircase angle within the defined marginal values.

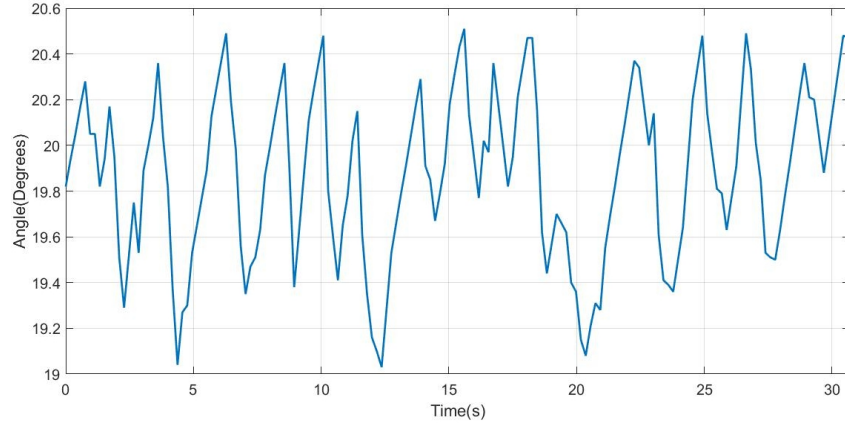


Figure 5.27: Absolute total angular displacement of front and rear arms in stage H-I in stair ascending

In order to further illustrate the behaviour of the rear arm, the contact force of the rear arm is illustrated in Figure 5.28. According to Figure 5.28, the rear arm maintained the contact force within the defined contact force range. Thus, it ensured that the rear arm maintained a parallel arrangement with the flat surface.

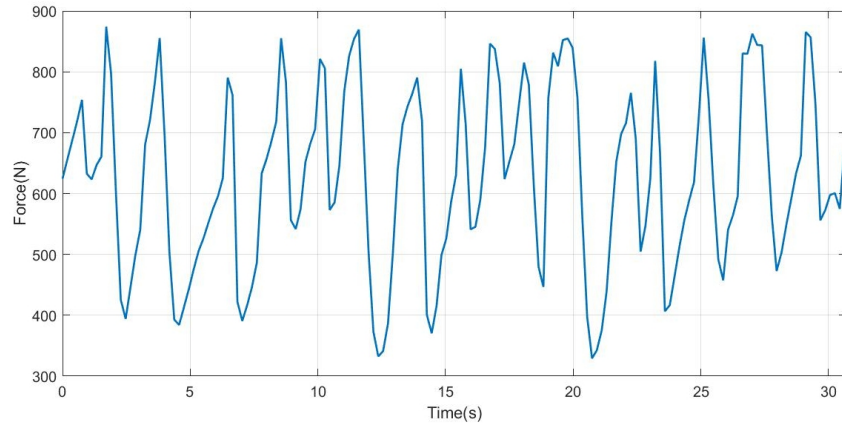


Figure 5.28: Contact force of the rear arm with flat surface in stage H-I in stair ascending

By using a video clip, the traced path of the user position was analyzed for stage $H - I$. In this case also, the same point which was used for stage $D - E$ in stair descending was used for the tracing. By using the auto tracker feature in the software, the operating path of selected point was traced as shown in Figure 5.29. In this stage also, the traced path followed a similar behaviour as discussed in stair descending operation.

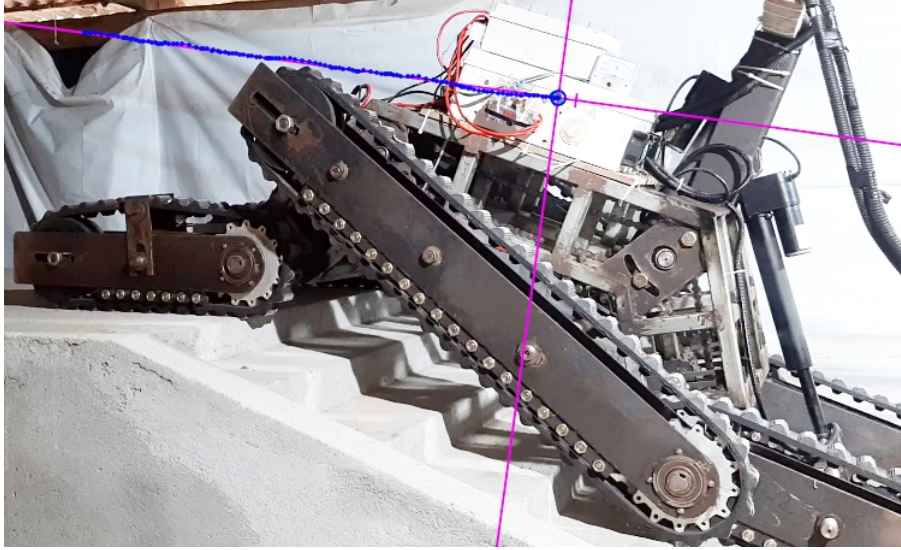


Figure 5.29: Trace path of design operation stage H-I in stair ascending

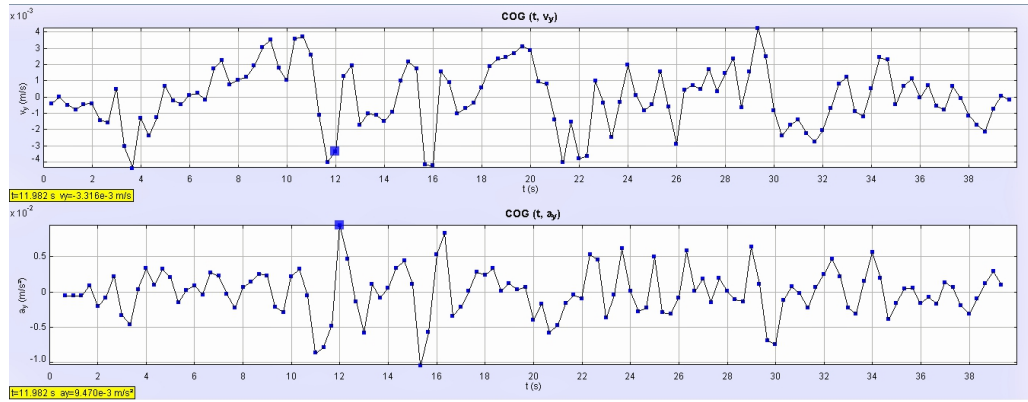


Figure 5.30: Change of velocity and acceleration of user's position in stage H-I in stair ascending

Based on the fixed-track mechanisms as discussed earlier, the maximum oscillation was executed when the design was at the top of the staircase. This was because of the lack of adaptability as explained earlier. But, in this novel design it was correctly addressed to solve the adaptability issue. Due to the stable posture specially at the top, the design was operated with acceptable low oscillation as illustrated in Figure 5.30. Due to this small change of velocity and acceleration, the design could operate at the top of the staircase by following the desired path.

Interpretation of Results against the Research Objectives

In wheel based stair-climbers, there existed many disturbances on the platform when operating over stairs. As discussed in Figure 2.1, when operating over stairs,

there existed sudden disturbances for the user based on the geometry of staircase and dimension of wheel cluster arrangement [35]. Because in each and every step, the wheel based arrangement should be adjusted to maintain the desired posture. Also, when the wheelchair was at the top and the bottom of the staircase, it created unstable postures as well. Due to these reasons, it could not provide stable and safe motion profile as discussed in Figure 5.4. Similar behaviour could be observed in leg-based arrangement as demonstrated in Figure 2.5. In this case also, leg based arrangement should be adjusted for each and every step. As a result, a wheelchair user experienced some uncomfortable. But, in existing fixed track mechanisms, such oscillations were avoided due to the operating path over the staircase. But, due to the lack of adaptability, there existed sudden oscillations at the top and the bottom of the staircase [36]. Specially at the top of the staircase, there existed a sudden rotation on the top stair edge. Thus, it could not able to provide stable and safe motion profile as illustrated in Figure 5.4.

As this is a novel design, there did not exist any similar design or benchmark to discuss the results of user's position behaviour. But, when compared to the existing designs, the oscillation was very negligible as it was very small. But, in existing designs, there existed sudden oscillations specially at the top of the staircase which created unstable operation. When compared to the operating path of existing designs, this stair-climbing mobile platform can provide more stable and safe operation in all the stages of stair-climbing operation. Thus, it helped to maintain the desired profile for user's position.

Based on a general comparison of existing designs, research objectives of this thesis can be summarized. In order to fulfill the first objective, a novel stair-climbing mobile platform was presented in this thesis. Based on the geometrical design, it had a better adaptable arrangement to the staircase specially at the top and the bottom. When compared to variable track mechanisms, this design was able to maintain the most appropriate posture throughout the staircase operation. In order to maintain adaptable postures based on the stage of operation, the kinematic controller structure was presented as discussed in the second objective. Based on the motion plans, different controllers were executed to operate design and arms operation. Based on the stage of the operation, design operation was further analyzed to demonstrate the stable and safe operation. By demonstrating the actual traced path of user's position behaviour, it further illustrated that

the design operation was lack of sudden disturbances. According to the third objective, force and angle sensors were used to control the arm operation. Based on each stage of operation, absolute total angular displacements and reference contact forces were observed in the experimental study to analyze the design operation. Based on the experimental results, it confirmed that the arms maintained the desired postures as discussed in the motion plans.

Generalizability of Results

Based on the objectives of the research study, a novel variable track mechanism was designed and developed. According to the experimental study, it verified that this novel design had an adaptable arrangement to the staircase throughout the operation. But, almost all the designs existed in the market did not have such adaptability in all the operations as discussed in the Chapter 1. Due this adaptable feature, this mobile platform can provide stable and safe operations in stair-climbing. In stair-climbing wheelchair application, this mechanism can provide practical solution to overcome from the lack of stable and safe operation of existing mobile platforms.

On the other hand, this mechanism could maintain proper contact with the floor and the staircase throughout the operation. Thus, it can provide safety to the design when it is in emergency state. For instance, assume that, a track based wheelchair is entering to a staircase at the top. Due to some issues on the staircase such as wet surface, oily surface, there could exist some problems to maintain proper contact with stair edges, especially when a track based stair-climber rotate around the top of the stair edge as illustrated in Figure 2.7. In such a situation, design safety could not be able to continue anymore. But, in such situations there should be a solution to get rid of such incidents. In order to overcome from such issues, this novel design uses proper contact with both floor and stair edges. As a result, in such an emergency situation, this design can provide facilities to abort the operation at the beginning without continuing it further. On the other hand, as a novel mobility platform, this design can be used in other applications such as robotics. Based on the application, appropriate arrangements can be implemented as explained in in Appendix C. Based on the stability, safety and speed, several type of arrangements are applicable with this novel design, which is another advantage of this design.

Chapter 6

CONCLUSION AND FUTURE WORKS

In this research, a novel stair-climbing mobile platform with better stability and safety was designed and developed. This new design was able to avoid any sudden disturbances on the platform in order to make it more comfortable for the user. A 3D model of the design was used in the simulation to analyze the design operation. In this simulation study, separate motion plans were executed to control arm and design operation. According to the simulation study, it confirmed that the user's position behaviour along the the staircase followed a smooth path by following the staircase profile. Furthermore, in the rate of change of the user's position and orientation, it confirmed that this design did not create any sudden disturbances on the platform and it ensured that this design could provide a more comfortable operation for the user.

By following the same method as explained for the simulation study, a similar behaviour was clearly observed in the experimental study as well. According to the safety study of the design, front and rear arms maintained parallel arrangements with a particular surface based on the stage of operation. According to the experimental study it confirmed that the absolute total angular displacement followed the staircase angle with acceptable marginal value. Also according to the contact forces of front and rear arms, it further confirmed that the design maintained the defined postures. By using the autotracker feature of the video tracking software, the actual operating paths were observed for all the operations. Based on the traced path, it further confirmed that the design was able to minimize disturbances on the platform at crucial stages.

Based on the first objective stated in this thesis, a novel track based stair-climbing mobile platform was designed and developed. Based on the experimental study, stable and safe operation of the design was verified based on the crucial stages of operation. This was further illustrated by demonstrating the actual

user's position behaviour at the top and the bottom of the staircase. Furthermore, a kinematic controller was designed and developed to control the arms and design operation. Based on the location of the staircase, twelve stages were defined to control the design operation. For each stage of operation, different controllers were executed in order to obtain the required stable postures. To control the arms, angular sensors and force sensors were used based on each stage of operation. Based on the implementation of these sensors, it provided facilities to control the arm position as defined in the motion plans. Thus, it was provided to maintain the required postures throughout the stair-climbing operation.

After referring the benefits and drawbacks of the existing designs, a novel stair-climbing mobile platform was presented in this study. As it was a novel design, it was hard to compare the adaptability of this design with existing designs as there did not exist any benchmark. Because most of the existing stair-climbing wheelchair products in the market did not present much information regarding their design adaptability. As a result, stable and safe operations were discussed based on the actual user's position behaviour. According to the traced path, it provided a clear illustration that the design operation over a staircase was free of sudden disturbances. Thus, it could provide better experience for the wheelchair user.

One of the main challenges experienced throughout the experimental study was the lack of facilities available for the testing. Due to the physical constraint, it was difficult to conduct the testing at outdoor places. At the first stage of the experiment, this design was tested on a temporary constructed staircase. Due to the constructional issues, it was very hard to operate the design on that staircase. As a result, the same experiments were repeated several times to finalize the controller design. The other challenge was that this design was tested only on one staircase due to available facilities. But, in order to further analyze the design operation, this design should be tested on different staircases.

Future Works

- In order to further analyze the stable and safe operation of the design, it is better to conduct a user case study for different staircases.
- To identify each stage of operation, different types of sensors should be included in the final product.

- There should be an error detection and correction method in the design to detect the errors beforehand.
- In an emergency state, there should be enough facilities to control the design to prevent accidents.
- There should be some supporting communication devices to operate the design.
- The design should be compacted to operate on limited space areas.
- A seat with angle adjustment should be attached to the design.
- Based on the appearance, it is better to have collapsible features for arms to compact the design in flat surface operation.
- A Joystick based user interface should be designed in order to receive commands from the user quickly and easily.
- With some additional modification to the prototype and patent rights (pending) , this will be commercialized soon.

Appendices

Appendix A

Specifications of Staircases

A.1 Different Types of Steps

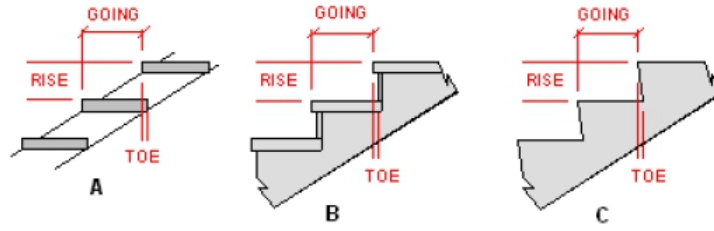


Figure A.1: Dimensions of different types of steps

A.2 International Standards for Staircase Construction

Table A.1: Staircase specifications based on standards

Standard	Rise(mm)		Going(mm)		Max Hypotenuse (mm)	Max Angle (Deg)
	Min	Max	Min	Max		
UK	135	180	280	340	385	33
AUS	115	190	240	355	403	38
IRC		196	254		321	37.7

As shown in Table A.1, in UK, the recommended dimensions for staircase construction for institutional and assembly stair (serving a place where many people gather) is explained [40]. Also based on the Building Code of Australia (BCA) Volume 2, the recommended dimension for rise and going for private stairways are also included in the table [41]. As published on the 2006 International Residential Code, Virginia, USA under the section of R311.5.3, stair treads and risers, dimensions of riser height and tread depth are also included in the same table [42].

Table A.2: Possible range of dimensions for staircases in UK

Rise(<i>mm</i>)	Going(<i>mm</i>)	Angle (<i>Deg</i>)	Hypotenuse (<i>mm</i>)
135	280	26	311
135	340	22	367
180	280	33	333
180	340	28	385

Table A.3: Possible range of dimensions for staircases in Australia

Rise(<i>mm</i>)	Going(<i>mm</i>)	Angle (<i>Deg</i>)	Hypotenuse (<i>mm</i>)
115	240	27	266
115	355	18	373
190	240	38	306
190	355	28	403

Appendix B

Track based Stair-climbing Wheelchairs in the Market

B.1 TopChair-S Wheelchair

Table B.1: Specification of TopChair-S

Total length without footrests	98cm / 38.5 inches
Overall length with footrest	115cm / 45,2 inches
Total height standard seat	107cm / 42,1 inches
Total height of Recaro seat option with headrest	128cm / 50,4 inches
Width	69cm
Empty weight TopChair-S standard seat	145kg
Maximum user weight	110kg
Diameter of rear wheels	35.5cm
Diameter of front wheels	20cm
Radius of gyration	85cm
Maximum speed on wheels	9.2km/h
Maximum speed on tracks	0.7km/h
Autonomy on the flat	35 to 48km
Wheels motors	2 x 350w
Caterpillars engine	2 x 400w
Battery capacity	60Ah
Obstacle height, forward	3cm
Obstacle height, backward	6cm
Obstacle height, forward	20cm
Maximum slope in 'road' mode	6°
Maximum slope in 'Automatic stair' or 'Manual track' mode	33° (65%)

B.2 b-free Wheelchair



Figure B.1: Dimensions of b-free wheelchair

Table B.2: Specification of b-free wheelchair

Maximum incline	35°
Maximum height of Step	20cm
Maximum top Speed	5km/h
Net weight	130kg
User max weight	100kg
Range	27.5km
Battery	Lithium 24V,80Ah
Chassis	Aluminium alloy
Controller	Dynamic DX2

B.3 Scewo Wheelchair

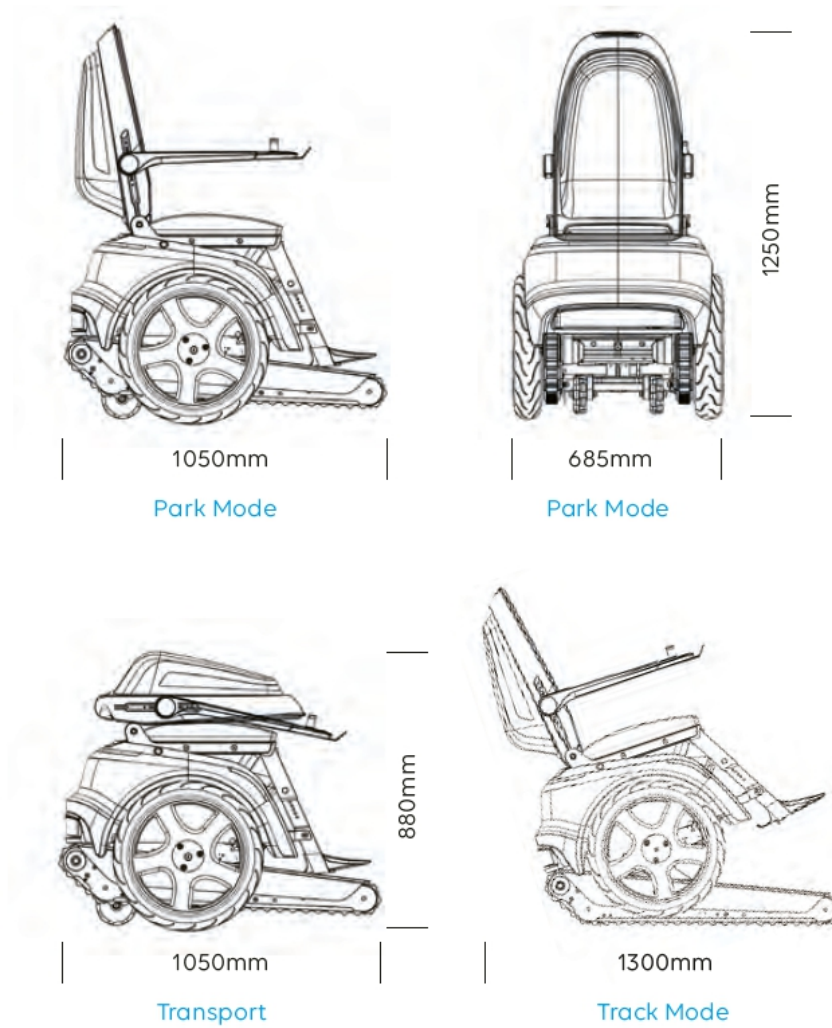


Figure B.2: Dimensions of Scewo wheelchair

Table B.3: Specification of Scewo wheelchair

Incline	min. 20°-36°
Maximum height of step	20cm
Maximum top speed	10km/h
Weight incl. batteries (15Ah)	120kg
User weight	40-120kg
Turning radius (rotation at place)	1200mm
Maximum elevation	6°
Range(20Ah battery)	25km
Battery	Litium-Ion 48V,20Ah

Appendix C

Possibilities of Postures of Stair-climbing Mobile Platform

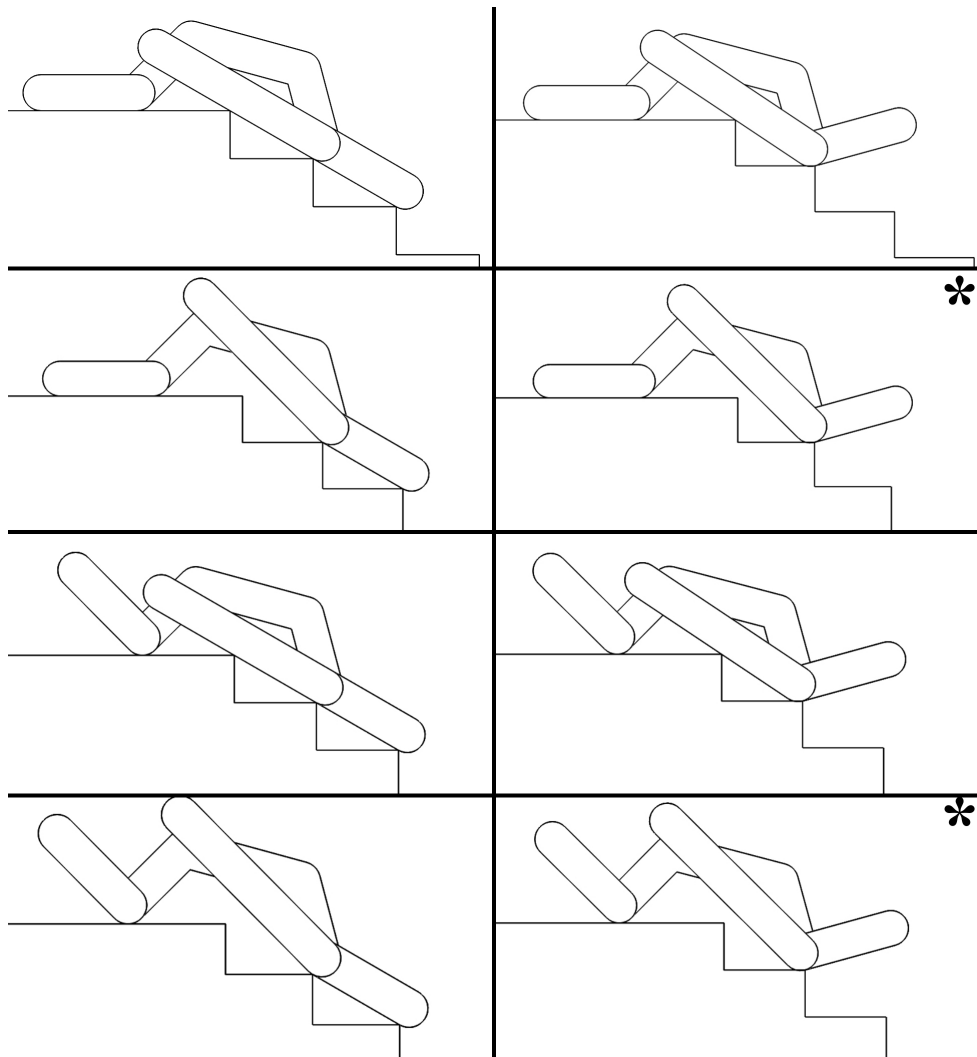


Figure C.1: Geometrical postures of stair-climbing mobile platform when ascending and descending at the top of the staircase

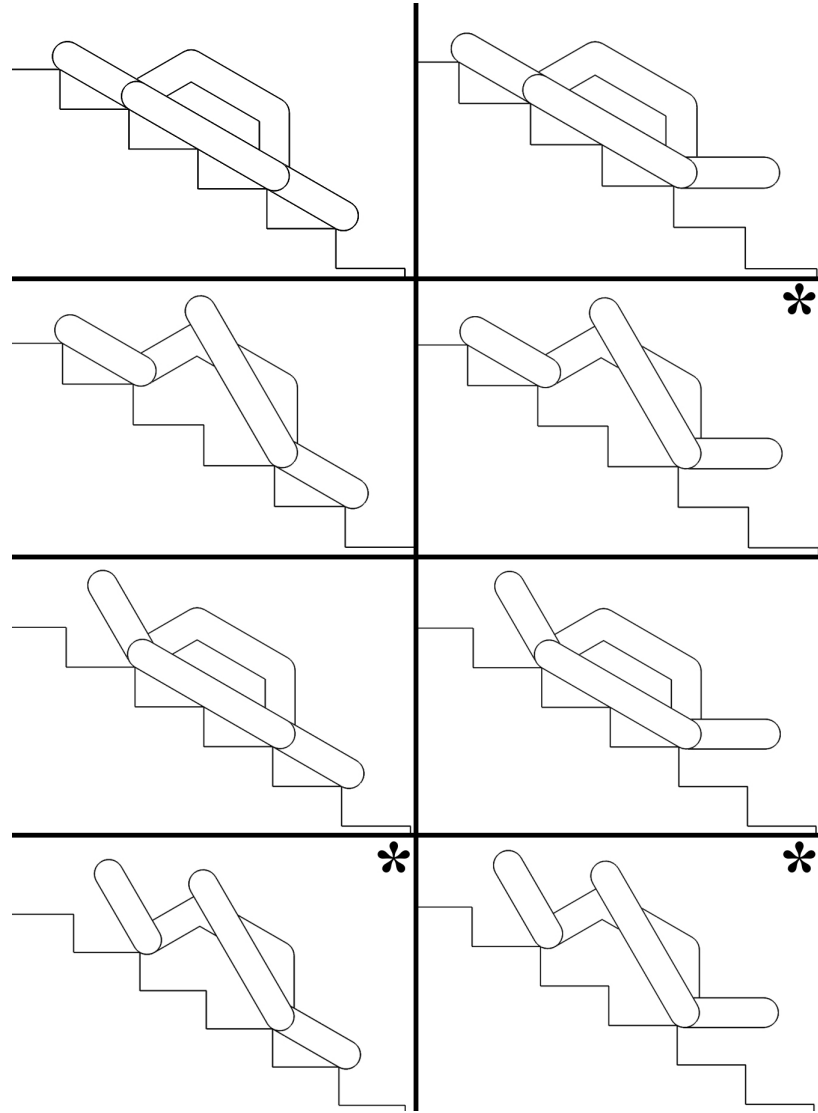


Figure C.2: Geometrical postures of stair-climbing mobile platform when ascending and descending at the middle of the staircase

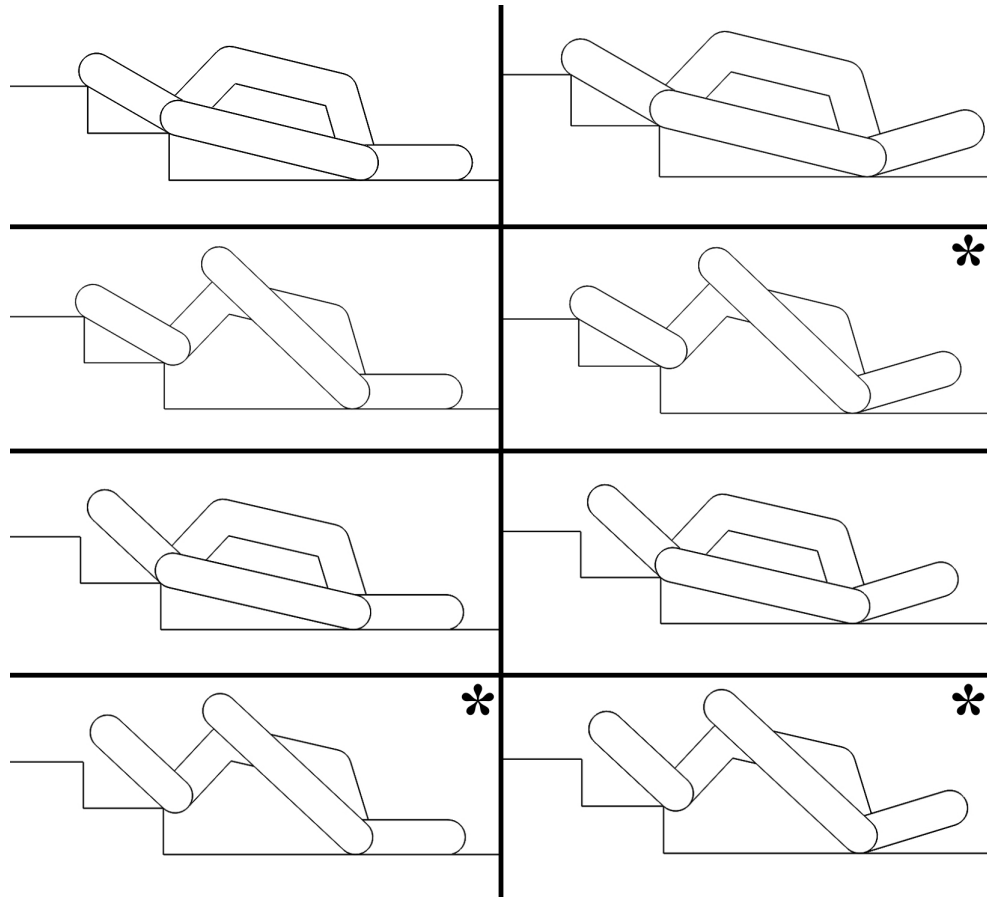


Figure C.3: Geometrical postures of stair-climbing mobile platform when ascending and descending at the bottom of the staircase

Appendix D

Vehicle Dynamics

D.1 Resistance Forces Acting on Moving Object

Rolling Resistance

Rolling resistance is an opposing force acting on a wheel when it is rolling over a surface. Based on the rolling friction coefficient in between the wheel and the surface, the rolling resistance can be varied. Due to the surface behaviour, the rolling friction coefficient can take different values. Also based on the dimensions of the wheel and the tire pressure, the rolling resistance can be varied. The main factors which affect this coefficient are the material of the wheel and surface behaviour. Rolling resistance can be expressed as follow. Here, C_r and R represents the friction coefficient and the normal reaction force respectively.

$$F_r = c_r R \quad (\text{D.1})$$

Some of the friction coefficients of a bicycle tire on different surfaces are shown in Table D.1

Table D.1: Rolling friction coefficients of different surfaces

Material	coefficient
bicycle tire on wooden track	0.001
bicycle tire on concrete	0.002
bicycle tire on asphalt road	0.004
bicycle tire on rough paved road	0.008

Gradient Resistance

When the wheelchair is operating over an inclined surface, the gradient resistance is acting on the wheelchair. When the wheelchair is on stair ascending operation the gradient resistance is acting against the motion. The motors should have enough power to operate against this force. This can be calculated as follows. Here, mg and θ represent weight and angle of the surface respectively.

$$F_g = mg \sin \theta \quad (\text{D.2})$$

Acceleration Force

At the initial point of the wheelchair movement, it needs an acceleration in order to reach a constant speed. Based on the motor performance, the required time to reach the expected speed can be varied. This acceleration force is calculated as follows.

$$F_a = ma \quad (\text{D.3})$$

Aerodynamic Drag Resistance

When an object is moving through a fluid, it experiences a drag against the motion. This is due to shear stress and pressure acting on the surface. In this drag resistance, the speed of the object takes the main contribution for the force. This can be observed as follow. Here, c_d, A, ρ, v represents the aerodynamic drag coefficient, vehicle frontal area, air density and speed respectively.

$$F_d = \frac{1}{2} c_d A \rho v^2 \quad (\text{D.4})$$

Appendix E

Parameters for Simulation Study

E.1 Static Analysis of Chassis

Table E.1: Material selection for the static analysis of chassis

Part	Material
Chassis	Galvanized steel
Driving wheel	Aluminium alloy
Shaft	Mild steel

Table E.2: Details of mesh used for chassis

Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Element size	16.7166 mm
Tolerance	0.835831 mm
Mesh quality	High
Total nodes	134533
Total elements	73724
Maximum Aspect Ratio	566.88
Percentage of elements with Aspect Ratio < 3	22.8
Percentage of elements with Aspect Ratio > 10	59.1
Percentage of distorted elements(Jacobian)	0
Remesh failed parts with incompatible mesh	Off

E.2 Static Analysis of Arm

Table E.3: Material selection for the static analysis of arm

Part	Material
Driving wheel	Aluminium alloy
Idle wheel	HDPE
Axle	Stainless steel
Arm plate	Mild steel

Table E.4: Details of mesh used for chassis

Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Element size	12.5319mm
Tolerance	0.626594mm
Mesh quality	High
Total nodes	83682
Total elements	46173
Maximum Aspect Ratio	60.839
Percentage of elements with Aspect Ratio < 3	61.5
Percentage of elements with Aspect Ratio > 10	3.03
Percentage of distorted elements(Jacobian)	0.00217
Remesh failed parts with incompatible mesh	Off

Appendix F

Experimental Study of Prototype

F.1 Stages of Experimental Study

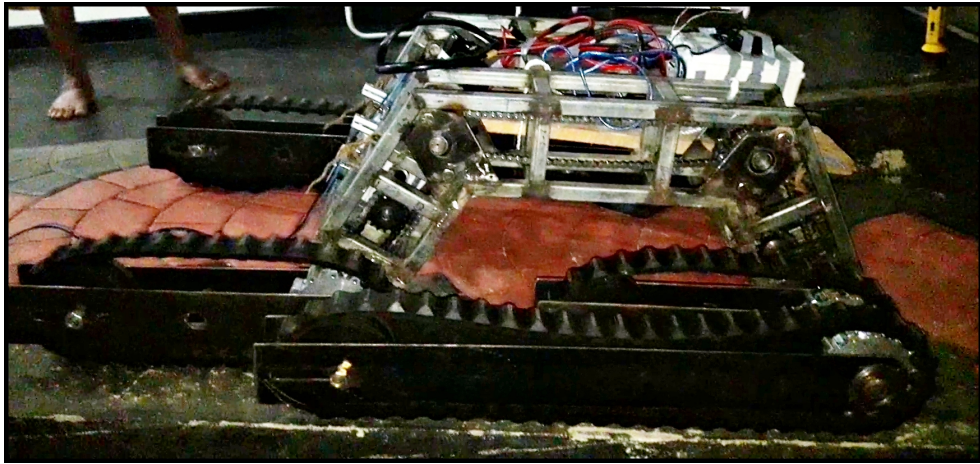


Figure F.1: Design operation over 18 degrees of ramp



Figure F.2: Design operation over adjustable staircase

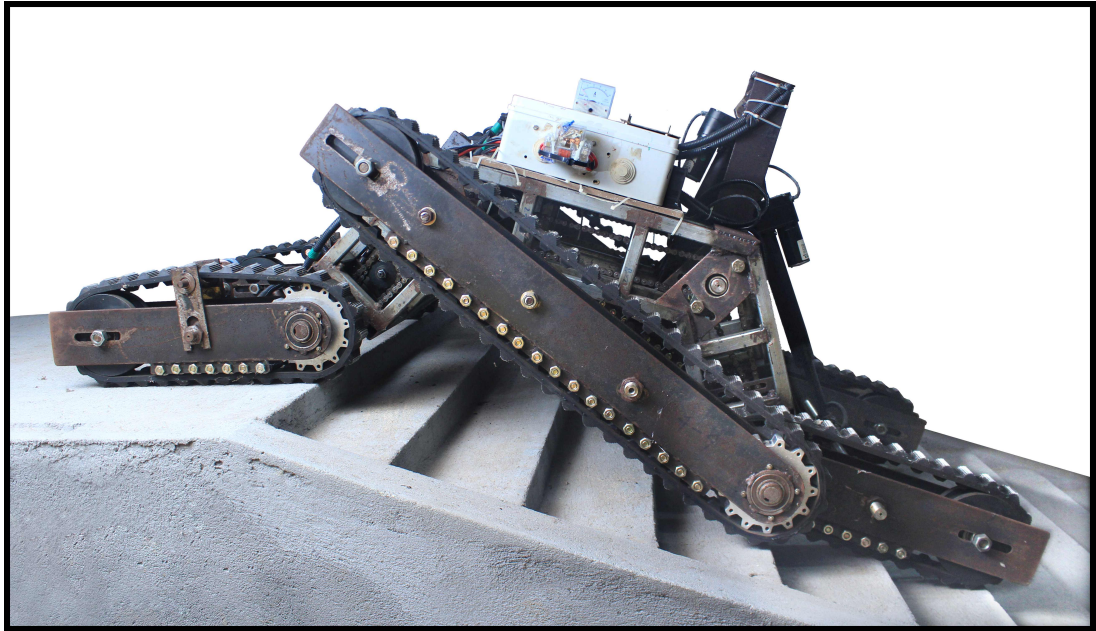


Figure F.3: Design operation over 20 degrees of staircase

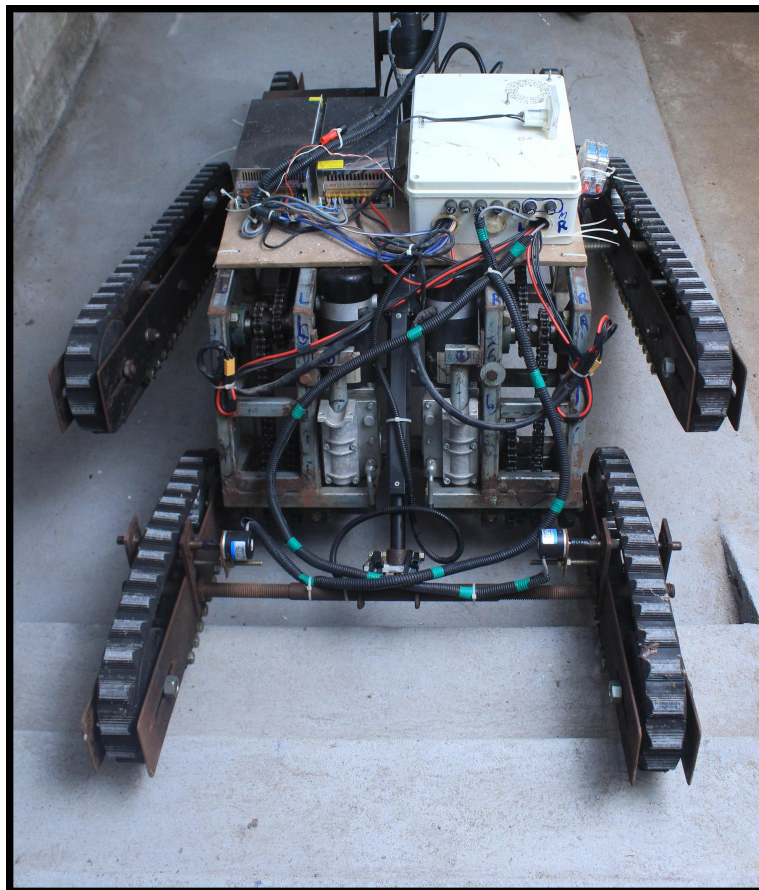


Figure F.4: Top view of prototype

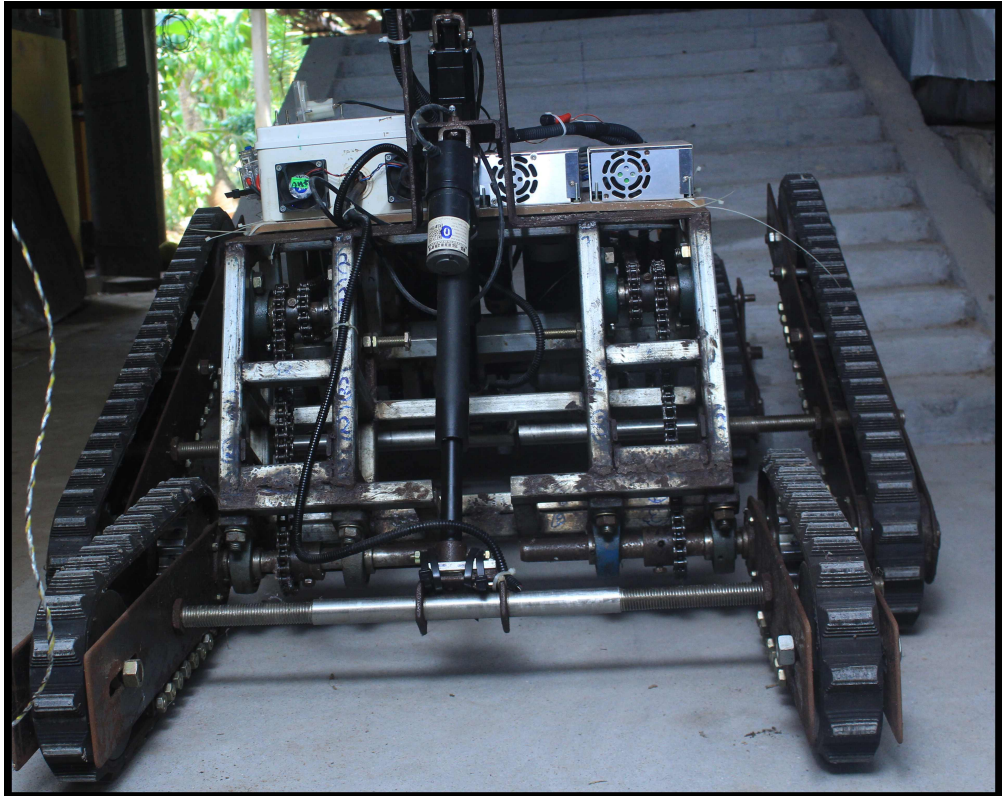


Figure F.5: Front view of prototype

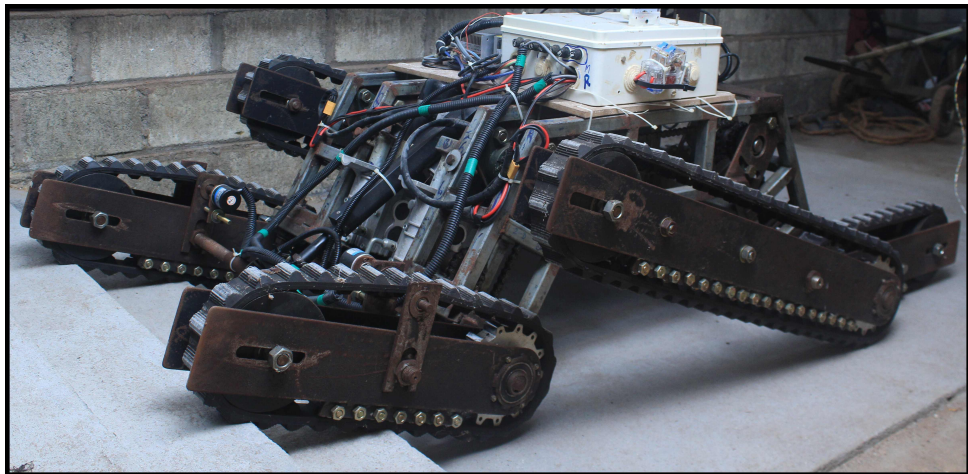


Figure F.6: Isometric view of prototype

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