IZMIR KATIP CELEBI UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DESIGN AND DEVELOPMENT OF A MULTI DEGREES OF FREEDOM MOBILE PLATFORM TO BE UTILIZED ON ROUGH TERRAIN

M.Sc. THESIS

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Department of Mechanical Engineering

JUNE 2019

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İZMİR KATİP ÇELEBİ ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

ENGEBELİ ARAZİ ÜZERİNDE KULLANILMAK ÜZERE ÇOK SERBESTLİK DERECELİ BİR MOBİL PLATFORM TASARIMI VE GELİŞTİRİLMESİ

YÜKSEK LİSANS TEZİ

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HAZİRAN 2019

Ercan PAÇALI, a **M.Sc.** student of **IKCU Graduate School Of Natural And Applied Sciences**, successfully defended the thesis entitled "**DESIGN AND DEVELOPMENT OF A MULTI DEGREES OF FREEDOM MOBILE PLATFORM TO BE UTILIZED ON ROUGH TERRAIN**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 23.05.2019
Date of Defense : 28.06.2019

to my family,

FOREWORD

First and foremost, I would like to thank my supervisor Assist. Prof. Dr. Erkin Gezgin who taught, supported and believed me.

I would also like to thank each member of Mechatronics Engineering Department to let me study in the laboratories throughout this research.

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28.06.2019 Ercan PAÇALI

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ABSTRACT

Thanks to the technological advances that have been continuously improved throughout the last century, applications of robotics have increased in every aspect of our lives. Within all of these various applications, mobile robotics can be given as one of the most common and popular subfield. Utilization of mobile robots emerges in many environments such as, medical applications, military operations, simple household routines, and even space exploration. On the other hand, due to the requirements of different robot designs for individual applications, need for mobile robot designs, which are capable of doing many things by getting equipped with respect to the related task, has also increased. Thus, mobile robots have been started to be replaced by more versatile mobile platform designs.

In light of this, throughout the thesis, a multi degrees of freedom mobile platform design that can be used in various terrain conditions was proposed. The main aim of the study is to carry out the structural design of a mobile platform that can adapt different terrain conditions and avoid obstacles within its path by changing its structural configuration. Proposed design allows the implementation of various modules to the top of the platform so that it can be utilized for different task scnerios. During the thesis, constraints of the proposed mobile platform, such as maximum speed, payload, operation conditions and etc. were determined by considering the properties of the existing commercial mobile platform designs in the literature including their advantages and disadvantages in different terrain conditions. Locomotion of the proposed design was fulfilled by utilizing six independent tracked triangular wheels that are attached to the main body by suspension systems. In order to increase the ability to overcome obstacles each wheel has capable of two independent motions as rotation around their geometrical central axis and track motion on triangular circumference. Also for the sake of adaptability, overall mobile platform was designed in such a way that the distance and the heights between the individual wheels can be changed to adapt various terrain conditions such as asphalt, muddy and rocky terrain.

During the thesis structural and dimensional design of necessary transmission systems were designed along with the mechanisms that were required for adaptability. At the end of the study modelling of the system was finished in simulation environment and scaled prototype was manufactured.

ENGEBELİ ARAZİ ÜZERİNDE KULLANILMAK ÜZERE ÇOK SERBESTLİK DERECELİ BİR MOBİL PLATFORM TASARIMI VE GELİŞTİRİLMESİ

ÖZET

Son yüzyılda gerçekleşen ve sürekli gelişen teknolojik ilerlemeler sayesinde robotik uygulamalar güncel yaşantımızın her alanında yer almaya başlamışlardır. Bu uygulamalar içerisinde mobil robotik en popüler alt alanlardan birini oluşturmaktadır. Mobil robotların kullanımı, tıbbi alanlar, askeri uygulamalar, rutin ev işleri ve hatta uzay araştırmaları da dahil olmak üzere bir çok farklı alanda gerçekleşmektedir. Ancak uygulama gereksinimlerine ve çeşitliliğine bağlı olarak bağımsız bir çok işi farklı modüller kullanarak gerçekleştirebilecek mobil robotlara olan ihtiyaç gün geçtikçe artmaktadır. Bu doğrultuda mobil robot tasarımları yerlerini daha kullanışlı ve çok yönlü mobil platform tasarımlarına bırakmaya başlamışlardır.

Bu tez kapsamında farklı arazi şartlarında yol alabilecek çok serbestlik dereceli bir mobil platform tasarımı gerçekleştirilmiştir. Çalışmanın en önemli amacı farklı yol ve arazi şartlarına kendi yapısal konfigürasyonunu değiştirerek uyum sağlayabilen ve kısıtlamaları dahilinde olmak koşulu ile engel benzeri unsurları aşabilen bir mobil robot platformun yapısal tasarımının gerçekleştirilmesidir. Çalışma çerçevesinde önerilen tasarım, sistem platformunun üzerine farklı modüller eklenmesine olanak sağlamaktadır. Bu sayede mobil platformun bir çok farklı alan içerisinde kullanılabilmesi kolaylaştırılmıştır. Tez kapsamında mobil platformun yapısal tasarımı için gereken kısıt ve hedefler, literatürde bulunan bir çok ticari maksatlı mobil platformun incelenmesinden elde edilen veriler (maksimum hız, taşıma kapasitesi, operasyon koşulları vb.), farklı yol koşullarında sahip oldukları avantaj ve dezavantajlar değerlendirilerek şekillendirilmiştir. Mobil platformun seyir hareketleri, palet yapısına sahip ve gövdeye süspansiyon sistemi ile montajlanmış toplam altı adet üçgen geometride tekerlek ile sağlanmaktadır. Mobil platformun engel aşma kabiliyetini arttırmak için ilgili tekerlekler geometrik merkezleri etrafında dönme kabiliyetine sahip olarak sisteme entegre edilmişlerdir. Ayrıca tasarımın sahip olduğu değişebilir yapısal konfigürasyon sayesinde tekerlek geometrik merkezleri arasında bulunan uzaklık ve yükseklik mesafeleri farklı yol koşullarına uyum sağlayabilmek için değişebilmektedir.

Tez kapsamında ilgili kısıtlamalar dahilinde gerekli hareket aktarım sistemlerinin ve konfigürasyon değişimine olanak sağlayan mekanizmaların yapısal ve boyutsal tasarımı gerçekleştirilmiştir. Çalışma sonunda yapısal tasarımı tamamlanan mobil platformun doğrulama çalışmaları, sistemin üç boyutlu modellenmesi tamamlanarak simülasyon ortamında gerçekleştirilmiştir. Ayrıca sistemin ölçekli bir prototipi de tez kapsamında üretilmiştir.

1. INTRODUCTION

1.1 Mobile Robots

Mobile robots can be defined as systems with electromechanical components that can be utilized for various applications. These applications mostly require locomotion from one point to another point in various environments. With respect to their locomotion types, mobile robots can be categorized as wheeled robots, legged robots and robots that include tracks. Due to the operational requirements mobile robots are capable of free movement without the need for fixed ground as the industrial robots, so they may require more complex controls, higher performance and many types of sensors depending on the tasks, functions and environmental conditions in which they are being operated.

Mobile robots are designed primarily to perform tasks that are difficult, dangerous and tedious for people. Those are the tasks including but not limited to making explorations in the oceans or on another planets, cleaning unreachable environments, collecting samples from hazardous environments, patrolling in critical zones etc.

Mobile robots can be controlled either autonomously or remotely by the support of the sensory systems in order to detect environmental conditions and actions around the robot. Thoughout the literature, mobile robots for underwater exploration, space exploration, entertainment, education, military and security purposes can be seen as the examples of the most common mobile robots.

1.2 Locomotion Types

Mobile robots require locomotion sytems that enable them to cruise throughout their environment. Owing to the fact that there exist a great variety of possible ways to move, selection of the locomotion characteristic is an important aspect of mobile robot design. Throughout the literature, there are many robots that can walk, jump, run, slide, skate, swim, fly and even roll. Locomotion designs in most of these mecanisms have been inspired by their biological counterparts. However in open environment, the most common locomotion choices include wheels, tracks, and linkage mechanism as legs.

1.2.1 Wheeled locomotion

Due to the fact that their implementation is easy and they are versatile for various conditions, usage of wheels for locomotion on mobile robotics is very popular. Wheeled robots can carry out lots of tasks with good efficiencies by having less mechanical requirements. Moreover as the wheels are always designed to have contact with the ground, balancing issues of wheeled mobile robots are relatively easy when compared with other locomotion types. In order to maintain ground contact in case of uneven rough terrain, suspension systems are usually used in conjunction with the wheels.

Although using wheels on mobile robots are less complex and requires minimal effort than using other locomotion types in terms of configuration, maintenance, manufacturing, and control, some hindrances exist. Wheeled robots can not explore at well-finished snags, as rough terrains, sharp decreases, or terrains with the low grating. As a result wheeled robots are most prevalent among the customer market that needs effortlessness during cruising. The simplest locomotion configuration of the wheeled mobile robots can be given as the differential drive system that uses dual actuated wheels.

1.2.1.1 Differential drive

Differential drive is the most common locomotion type used in wheeled mobile robots for mostly indoor environments as it’s the simplest and easiest locomotion system to be implemented. As seen in Figure 1.1 differential drive utilizes two main wheeles that are driven by individual actuators. In order to achieve balance without additional control another passive wheel can be attached to the system that prevents robot from falling over.

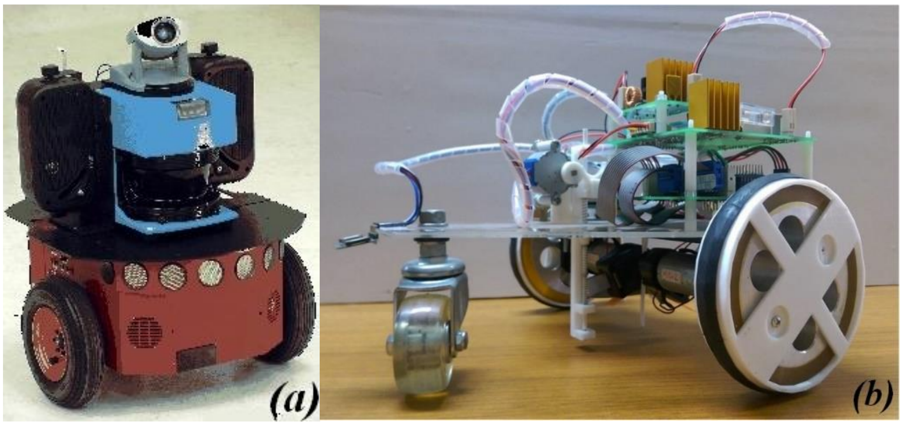

Figure 1.1: a) Diffrential Drive on the Pioneer 3-DX8 [1] **b)** Differential Drive Mobile Robot Platform with a Drawing Pen to Generate Picture from an Image [2].

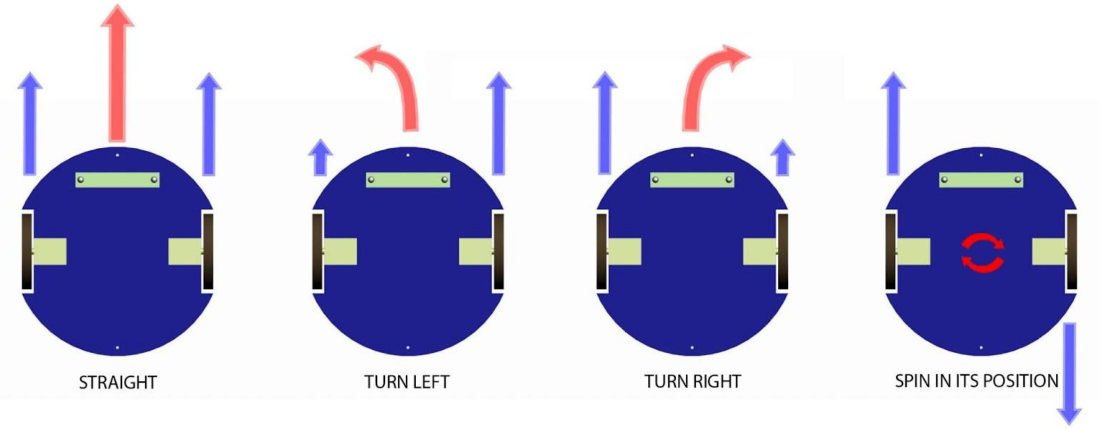

Figure 1.2: Actuators and Wheel Connections [3]

Table 1.1: Actuators Sequences

MOTION	LEFT WHEEL	RIGHT WHEEL
Right Turn	Counter Clockwise	Clockwise
Left Turn	Clockwise	Counter Clockwise
Forward	Clockwise	Clockwise
Backward	Counter Clockwise	Counter Clockwise

In order to achieve various types of motions each active wheels should be independently driven. Figure 1.2 and Table 1.1 shows the sequences for different kind of motions for the mobile robots with a differential drive.

1.2.2 Legged locomotion

Locomotion with legs can be carried out by utilizing multiple point contacts between the robot and the fixed ground. These point contacts with the legs allow wide range of adaptability and maneuverability for rough terrains. Due to the fact that only a set of point contacts are required between the legs and the ground, quality of the terrain between those points does not matter as long as the robot can maintain adequate ground clearance. Most of the mobile robot designs that are using legs for locomotion include six legs to achieve static balancing on three legs during walking. Decreasing the number of legs renders robot balancing task complicated. Thus, complex control algorithms are required. Throughout the literature there exist many robot designs with single leg (Figure 1.3), dual legs (Figure 1.4), four legs (Figure 1.5) and six legs (Figure 1.6).

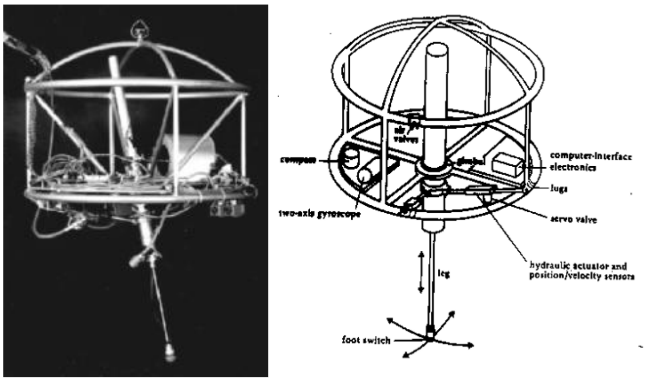

Figure 1.3: Raibert Hopper [4]

Figure 1.4: Humanoid robot P2 from Honda, Japan. © Honda Motor Corporation. [5]

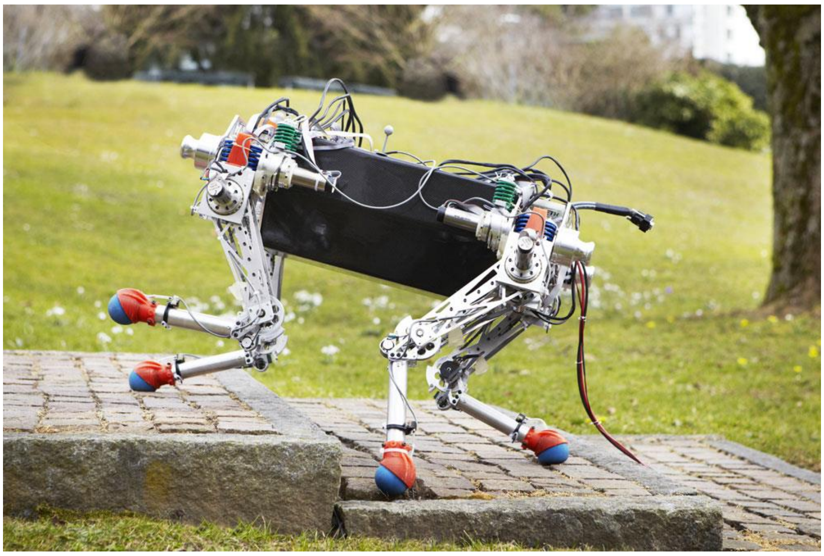

Figure 1.5: StarlETH four Legged Mobile Robot [6]

Figure 1.6: Capers II, a Hexapod Robot [7]

The main disadvantages of legged locomotion include power requirements and mechanical complexities. In order to achieve required overall mobility of the system, individual degrees of freedom of the legs should be higher with many actuated joints. These joints should be designed in such a way that, they should carry the weight of the system during locomotion as well as they should have high maneuverability with a sufficient number of degrees of freedom to impart forces in a number of different directions. As a result of these requirements mobile systems with legged locomotions have higher cost requirements to be produced.

1.2.3 Tracked locomotion

Tracked drives are best for mobile robots that are designed to be used on soft terrain. Tracks on these robots help both reducing the amount of slip and allows the distribution of the weight equally due to their large surface contact area, making them useful for soft and rocky terrains. Robots that utilizez tracks have much larger ground contact patches, and this significantly improves maneuverability on loose terrain compared to conventional wheeled designs. These types of systems are widely used in rough terrain conditions (Figure 1.7). However, due to this large ground contact patches, changing the orientation of the robot usually requires a skidding turn, and a large portion of the track must slide on the terrain.

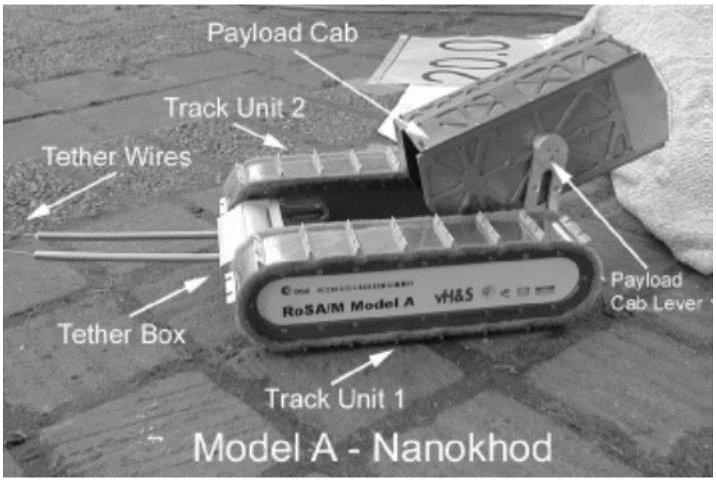

Figure 1.7: Microrover Nanokhod [8]

During the motion of the tracked system there exists lateral force acting on the ground that can damage the surface of the tracks and cause them to wear faster. Also using tracked locomotion increases mechanical and connection complexity. Three kinds of tracked locomotion systems can be found in literatures as,

- Line Type Tracked Systems
- Triangular Type Tracked Systems
- Combination Type Tracked Systems

1.2.3.1 Line type tracked systems

In these tracked systems the drive and idler are located on the same plane (Figure 1.8). Because of this configuration pallets are always stay parallel to each other.

Figure 1.8: Line Type Tracked System [9]

1.2.3.2 Trigular type tracked systems

In these tracked systems, pallets form a triangular shape (Figure 1.9). Thus, this configuration allows the driving gear to be located above from the ground.

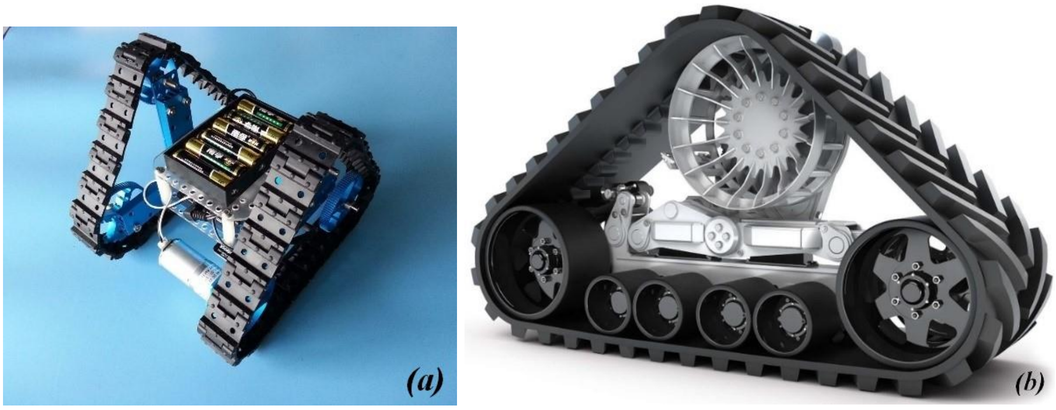

Figure 1.9: Triangular Type Tracked System [10]

1.2.3.3 Combination type tracked systems

In these systems, triangle and line systems are used together in combination as locomotion systems (Figure 1.10). It is easier to overcome obstacles with these type of the systems.

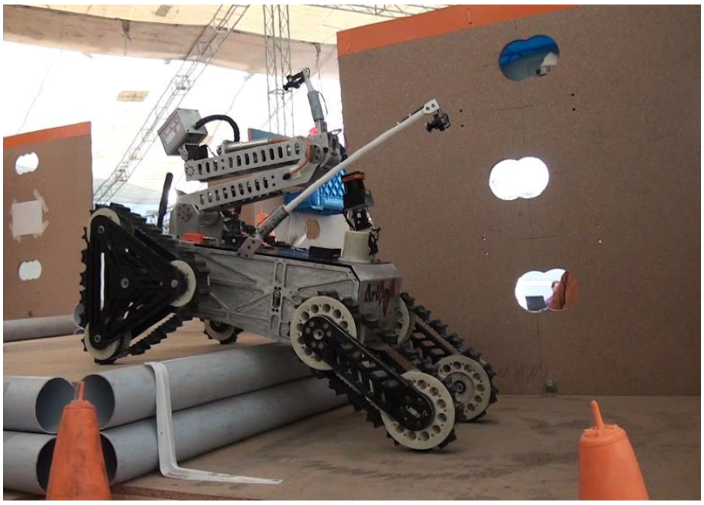

Figure 1.10: Combine Tracked System [11]

1.2.4 Hybrid type locomotions

Most of the biological systems in nature are adapted legged locomotion due to the environmental issues where the terrains are totally rough. On the other hand current environments for humans mostly include engineered and smooth surfaces. As a result most of the industrial and personal applications of mobile robotics chose wheeled locomotion. On the other hand recently, for more natural outdoor adaptation, there have been some advances towards hybrid and legged industrial robots such as the forestry robot shown in Figure 1.11.

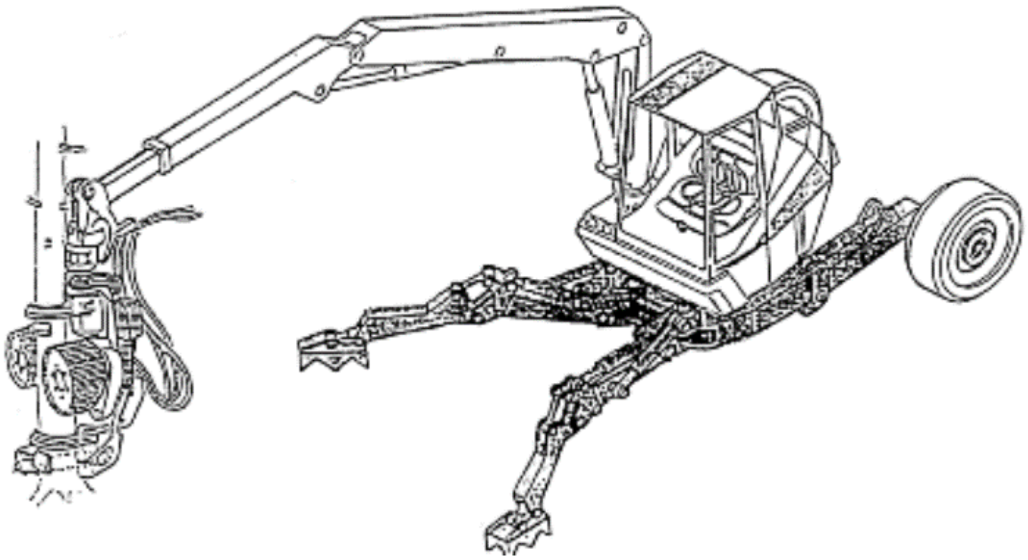

Figure 1.11: RoboTrac, a hybrid wheel-leg vehicle for rough terrain [12]

The most important advantages of these hybrid type mechanisms are the fact that they can be designed and built to meet specific needs for various enviroments that renders them to have increased functionality and versatility. On the other hand requirements of custom parts, increased complexity and costs make them difficult to be commercialized.

1.3 Utilization Areas

Robots and application areas, along with technological advances, have made a progressive interaction with people. In these days, utilization of robots in various areas is becoming increasingly widespread, and this expansion creates new job opportunities for some of the segments of the industry.

1.3.1 Industrial robotics

As the complexity of the robots increases, their usage areas in industry also expand regularly. The most basic function of the industrial robots is the automation of massive production industry, where the defined routines are repeated in the same way and continuously. Automotive industry is the most obvious example of where these large and complex robots are working. For instance an automated guided vehicle (AGV) (Figure 1.12) is a convenient robot that cruises after markers or wires in the floor, or uses vision, magnets, or lidars for route mapping. They are frequently utilized in mechanical applications to move materials around an assembling office or distribution center. Utilization of these programmed guided vehicles has expanded through the late twentieth century.

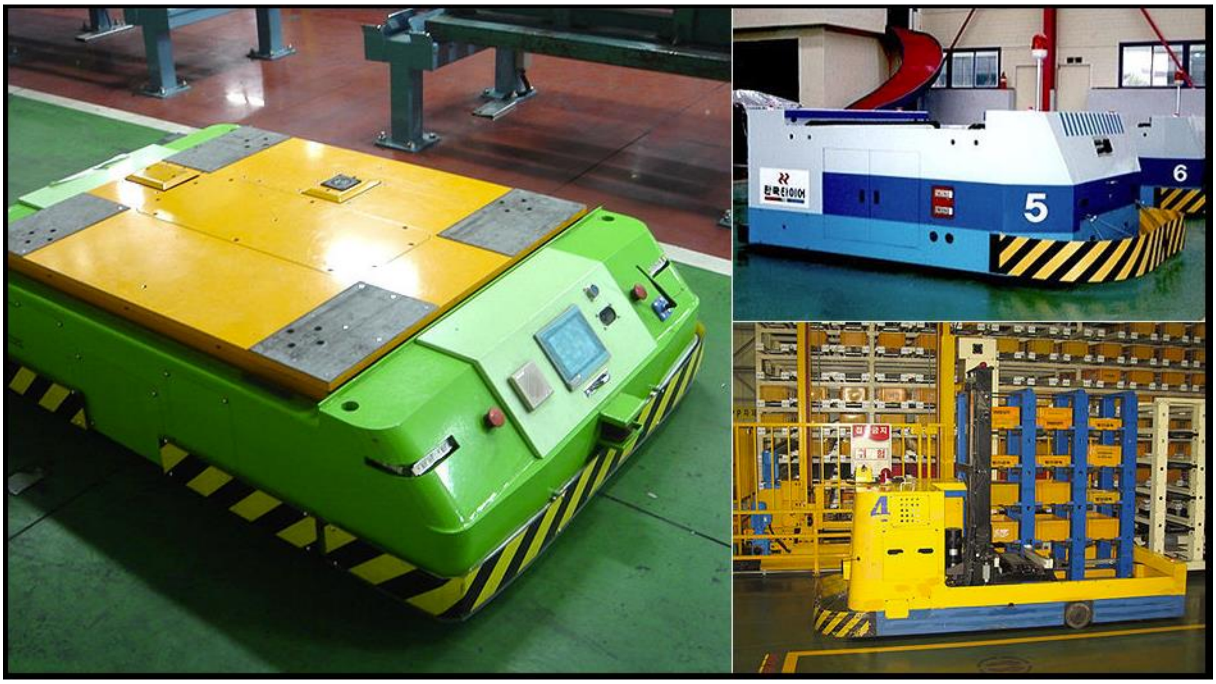

Figure 1.12: Handling of Goods with Automatic Guided Vehicle [13]

1.3.2 Operational robotics

Operational robotic systems have been developed to operate in environments that are unsuitable for human life as submersed environments, volcano craters, outer space locations, environments with toxic wast, mining plants and etc. These systems are mostly remote controlled rather than self-running. They require high technology and their working principles are reasonably specific.

Today many operational robots can be investigated at their fields such as Pathfinder robot (Figure 1.13) that was designed to cruise around the surface of Mars and PackBot that is currently used for mine clearance operations. There are also mobile platforms used to take samples from active volcanoes suchas Robovolc that is a robotic system for volcano exploration (Figure 1.14).

Figure 1.13: Mars Pathfinder Rover Analyzes the Yogi Rock on the Surface of Mars [14]

Figure 1.14: Robovolc System in Operation [15]

1.3.3 Robotics in medicine and health

In medical environments, mobile robots can also be utilized for various tasks. An example can be given as a transport platform that is an autonomous robot designed to transport logistics inside a hospital (Figure 1.15). The software of platform includes simulation and control packages for different work environments, map generation, localization and route definitions. These mobile platforms are currently implemented in some European hospitals, where they help staff members in transportation tasks that result in time and resource optimization for the hospitals.

Figure 1.15: AGVS: Mobile Platforms for Intrahospital Logistics [16]

1.3.4 Military robotics

Military has dependably been at the forefront of innovation, so many different kinds of robots on the literature have been firstly revealed during the studies of military applications. Military field mobile robots are widely used throughout the world especially in unmanned vehicle experiments for various missions.

Figure 1.16: KAPLAN Unmanned Ground Vehicle Family and KAPLAN Explosive Ordnance Disposal Robot [17]

KAPLAN (Figure 1.16) Unmanned Ground Vehicle (UGV) Family includes new generation mobile systems with modular Control Console where different special loads can be installed to their platforms.

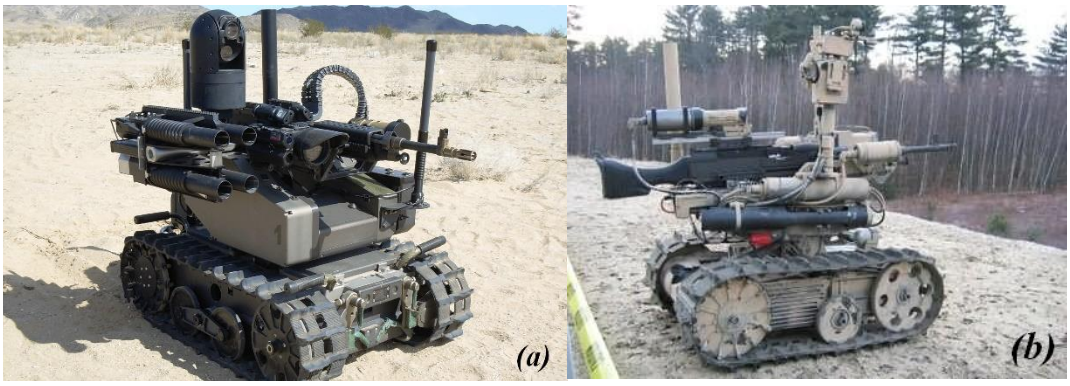

Figure 1.17: MAARS (Modular Advanced Armed Robotic System) and SWORDS [18]

Modular design of the MAARS (Modular Advanced Armed Robotic System) (Figure 1.17.a) allows its controllers to equip it with variety of armaments, ranging from non lethal lasers (designed to blind foes) to tear gas and grenade launchers. MAARS is a follow-up to an earlier model of robot called SWORDS (Figure 1.17.b) that was used in real scenarios.

Figure 1.18: XM1216 Small Unmanned Ground Vehicle (SUGV) [19]

XM1216 Small Unmanned Ground Vehicle (Figure 1.18) is also a lightweight mobile robot that can be used for military operations such as surveillance and rescue tasks.

1.4 Literature Survey

Considering technological advancements, vital contributions of the mobile platforms for the field of robotic science cannot be unseen. As these systems formed by many different structural sections including the mobile platform itself, specific equipments for the platform, control mechanisms and the locomotion system, each improvement on these sections contribute to the overall efficiency.

Throughout the literature, different researchers have contemplated on the parameter streamlining and execution assessment of mobile platform designs for various applications. Mobile platforms that are frequently used in transportation applications have very high impact on the structural designs for the new studies. Therefore, improvements on the suspension systems of mobile platforms, facilitation of controllability in the mechanical systems, easiness of locomotion system integration, and many other issues are continuously investigated throughout the literature.

Soygüder et al. [20] designed a mobile robot with versatile Sweedish mechanical wheels that can be utilized for different scnerios. Sun et al. [21] proposed the design of a mobile robot with a locomotion system that can be transformed between wheel and feet configurations. This transformability helps mobile system to pass through different obstacles. Belter et al. [22] proposed a new integrated motion planning procedure for a rough terrain in order to utilize a hexapod robot. Zırh et al. [23] worked on the design of a mobile robot that uses six curved legs for the locomotion. Throughout their study structural and electronic design procedures for the proposed system were given along with the experimental studies. Labenda et al. [24] studied on the kinematically redundant locomotion models on mobile robots. In their paper authors gave examples of conceptual mobile systems that can be connected physically to each other in order to adapt different terrain types. Appala et al. [25] designed a torus-shaped wheel to prevent wheel slippage in rough terrain. Authors integrated these wheels into the mobile platform by using two degrees of freedom suspension system that enables lateral and vertical tilting. Mobile platforms three wheel integrated design showed that it can pass over rough terrain with low wheel slip. Gören et al [26] proposed a mobile system design that accomplishes the task of overcoming obstacles through mechanical design, without any additional sensor. It has the ability to overcome an obstacle with pre-determined height. Thanks to the wheels positioned in parallel arms above the mobile platform, it has the ability to exceed certain heights and climb a standard ladder. The robot is designed in such a way that minimum slip occurs between the wheels and the floor. Edlund et al. [27] designed a mobile platform where the wheels can be used in soft and hard-ground forest areas. Utilizing a large wheel that is attached to the main axis of the bogie and connected to the body, proposed system is able to exceed major obstacles and ditches. Design also includes dual wheels with free swiveling that are placed to the front and rear of this large wheel to provide high mobility. Simulations have shown that authors design is less damaging to soil in forest conditions (Figure 1.19).

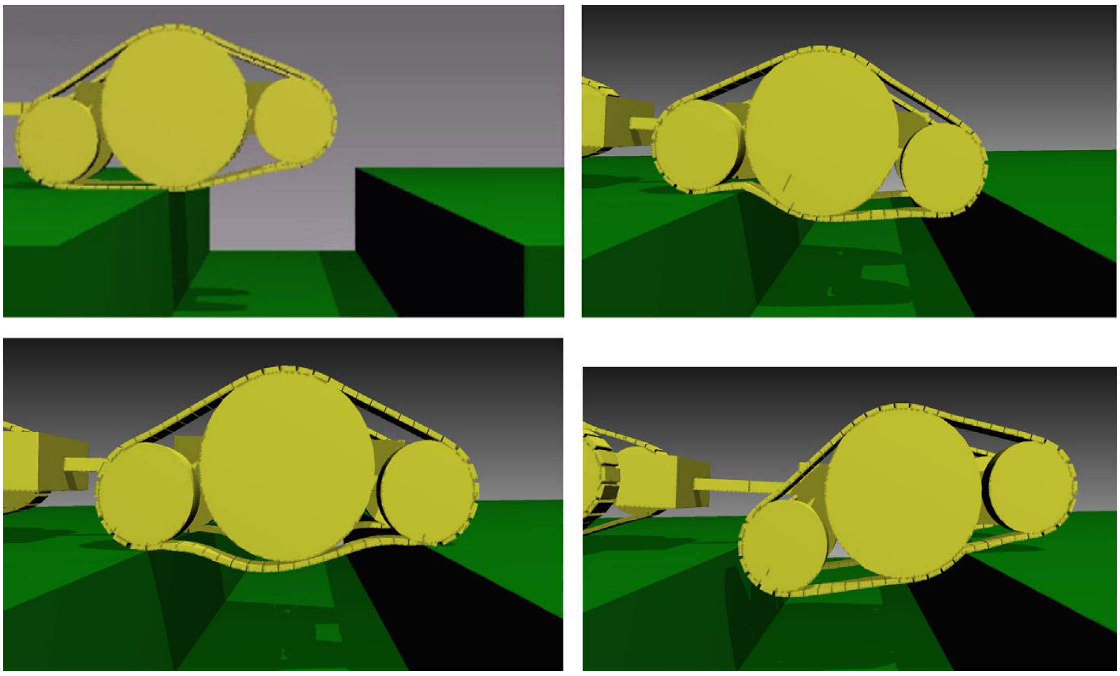

Figure 1.19: Mobile Platforum Wheel Design [27]

Ghotbi et al. [28] studied the effect of force distributions between wheel and soft ground to the mobility. They investigated related target interaction using both multi-body dynamic simulation and a six-wheel mobile platform that can be seen in Figure 1.20

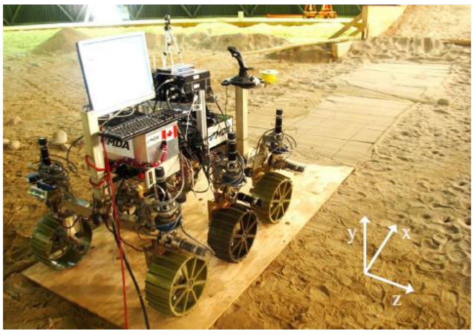

Figure 1.20: Six-Wheel Mobile Platform [28]

Loc et al. [29] researched on the development of a mobile platform that will be used in 3D rough terrain. As seen in the Figure 1.21, the system has crab-like movable four legs. Proposed mobile robot was thought to be superior to with respect to a wheeled robot on rough terrain. An algorithm was created on the optimum distances that four legs could reach. Effectiveness of the mobile platform was verified by simulations and experiments.

Figure 1.21: Mobile Robot with Four Legs [29]

Moubarac et al. [30] have focused on a mobile platform that can be interlocked, autonomously mobile and can be reconfigured. Authors conducted a comprehensive literature review on robots that were smart, mobile, autonomous and modular. As it can be seen in Figure 1.22, such mobile robots can be reconfigured differently with respect to the areas in which they are used.

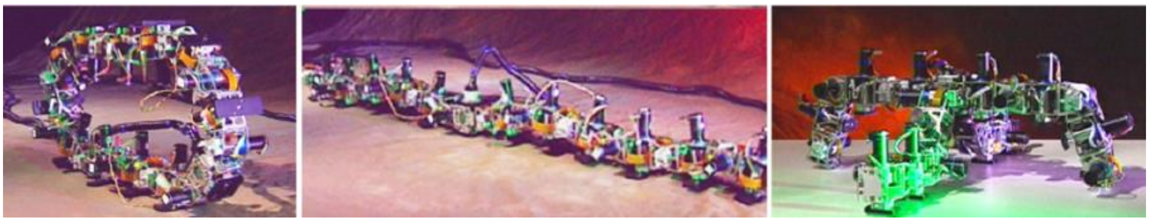

Figure 1.22: The Mobile Platform That Can Be Interlocked [30]

Raja et al. [31] worked on the algorithm of route determination and planning of a 6-wheel mobile platform with 10 degrees of freedom. Although the motion planning algorithm is new, simulations and the results of the experiments showed proposed potential field method gives better results. Hichri et al. [32] proposed the design of cooperative mobile robots to be used for the transportation tasks. In their design the system composed of multiple mobile robots. Their numbers and positions can be adjusted with respect to the target load that should be carried by them. Proposed mobile robots can be used for payload prehension, payload lifting and payload transport as shown in Figure.1.23.

Figure 1.23: Mobile Platforms to be Used for the Cargo Transfer (Prehension, Lifting, Transport) [32]

Hacene et al. [33] designed a mobile platform that could follow a dynamic target. This robot design avoids obstacles thanks to the ultrasonic sensors that are equipped on it. Proposed design has both three wheels and versatile wheels. Simulation results of this robot, which is controlled by two fuzzy behaviors including target tracking and avoidance of obstacles, are positive and open to improvement. Wang et al. [34] worked on the design of control parameters of mobile robots with a non-holonomic wheel and a new controller system. The effect of this controller on the mobile robot in different variations was confirmed by experiments and simulations. Levratti et al. [35] studied on a mobile platform called Tirebot and its software implemantation that could work in a tire workshop and perceive operators body movements. As shown in Figure 1.24, this robot utilizes an Omniwheel wheel and can be used as a lift and wheel-changer for the operators. Verification of the mobile platform were carried out in a real tire workshop and proved to be effective. Improved version of the robot is intended to lift loads that are heavier than a tire. Thus, it can be utilized as an independent lift.

Figure 1.24: Tirebot [35]

Della corte et al. [36] studied on motion-based calibration of a mobile platform equipped with different heterogeneous sensors. They used both kinematic parameters and sensor data to provide calibration and presented an open-source version of this study to the community. Oliveira et al. [37] studied the algorithms of mobile robots that are capable of performing their functions by avoiding moving and stationary obstacles in a known environment. Thanks to this algorithm, robots with a limited number of sensors and processing capabilities were aimed to gain the ability of avoiding obstacles and performing their functions in the most appropriate way. This algorithm requires simple tasks that have shown successful results in mapping and obstacle avoidance issues. However, proposed system needs to be developed further to be used in complex and different environments.

Cleaning robots, which are one of the most common mobile platform examples, are generally designed to be close to the ground and flat. Therefore, when performing simultaneous localization and mapping, equipped camera can only detect a part of the objects that appear in front of it. Chae et al. [38] worked on a new object surface recognition algorithm focusing on this problem. Throughout the study, it is aimed to be able to detect objects from the geometric shapes of the surfaces of unknown obstacles that are encountered by the robot. Kowalczyk et al. [39] studied on the navigation function of two-wheel mobile platforms with differential control as shown in Figure 1.25. Navigation function algorithm that they proposed offers a quick mapping method from any starting point to the end point.

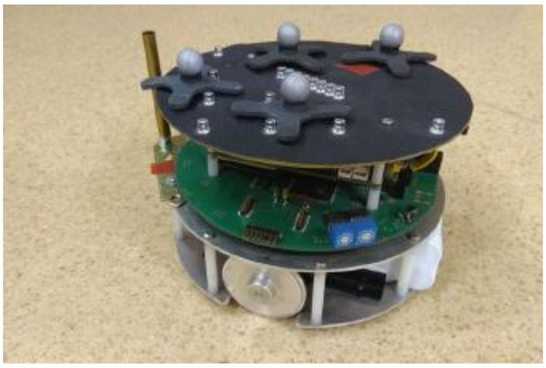

Figure 1.25: Two-Wheel Mobile Platforms [39]

Huang et al. [40] focused on a path planning of multiple cooperative mobile robots by using hybrid artificial fish swarm algorithm (HAFSA) that is inspired by the flocks of fish. Thanks to this algorithm, more than one mobile robot is able to avoid obstacles by determining their own path. Tiwari et al. [41] conducted studies for the optimization and efficient use of energy resources of mobile platforms used for various tasks Figure 1.26. Authors aim to reach efficient energy usage by the mobile platforms used on land, in air and on water surface in order to complete the tasks and return to the desired place before they run out of batteries. By optimizing the amount of energy required for the tasks of various mobile platforms, proposed method optimizes a more efficient way of operation. At the end of the study combined energy consumption was confirmed by field tests and yielded positive results.

Figure 1.26: Different Working Conditions: Land, Air and Water Surface [41]

Yang et al. [42] studied to improve the present ORB-SLAM2 algorithm. Proposed methodology includes dual word storage method and word training algorithm to increase tracking accuracy and loading speed. Authors also supported proposed methodology by creating a secondary offline mapping algorithm. After the verification steps authors have demonstrated the success and effectiveness of recognizing and positioning objects. Fang et al. [43] worked on the behavioral control of legged robots and the intelligent control system including the data-driven layer, the robot behavior layer, and the robot execution layer. They experimented with hexapod robots. Results showed that as illustrated in Figure 1.27, control system of long-legged mobile robots that are intended to be used in a variety of tasks needs to be developed and improved further for the future works.

Figure 1.27: Long-Legged Mobile Robots [43]

Hongling et al. [44] proposed a new algorithm for mobile platform robots working together on simultaneous localization and mapping (SLAM) in search and rescue operations. Authors proposed an algorithm in which each robot creates its own local map and communicates with other robots for the search and rescue task. This communication result in generated maps combined and controlled by the main robot. Positive effects of the proposed algorithm by real experiments and simulations were also presented in this study. Li et al. [45] worked on a mobile platform with 3 modes of movement with 7 different types of walking, which could cruise through obstacles in different road conditions. These movement modes include tracked mode, wheeled mode and legged mode. Proposed system can walk with 4 legs (Figure 1.28). Throughout the study experiment studies were also performed. With respect to the results of these experiments, in order to make legged mode more efficient, authors planned to increase the weight, reduce the travel distance, improve the contact surfaces and reduce the friction. For different movement modes, it was foreseen to analyze the walking planning of the robot. In order for the robot to provide more secure service, it is envisaged to perform dynamic analyzes and experiments for a more advanced prototype that can switch automatically between modes. In order to use the robot in real life and in a functional way, it is foreseen that all these movement modes will be designed smoothly, quickly, stable and with an implemented automatic control system.

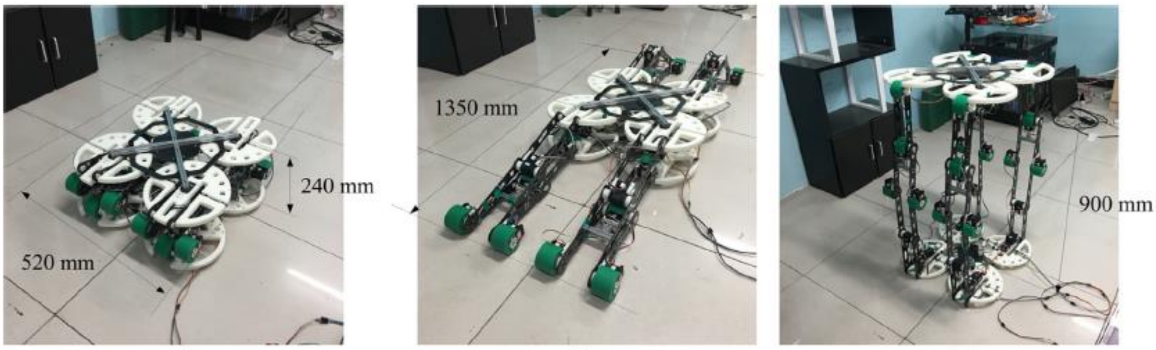

Figure 1.28: Mobile Platform With 3 Modes Of Movement With 7 Different Types Of Walking [45]

Long et al. [46] have attempted to enable low-cost environmental modeling of a mobile robot. They proposed minimum distance of point (MDP) algorithm and fuzzy model. Cylinders, flat surfaces and angular surfaces were used as environmental features to determine the classification. Yao et al. [47] proposed a reconfigurable mobile robot with eight modes. This robot includes the kinematic properties of sphere robots, squirt robots, crawler robots, wheel robots and biped robots. As it can easily be seen in Figure 1.29, mobile robot can overcome obstacles up to a certain height, walk and climb. This robot can adapt to different environments by utilizing its multiple movement modes.

The effectiveness of the proposed mobile robot that is equipped with micro-cameras and sensors was confirmed by using simulations and experiments on the manufactured prototype.

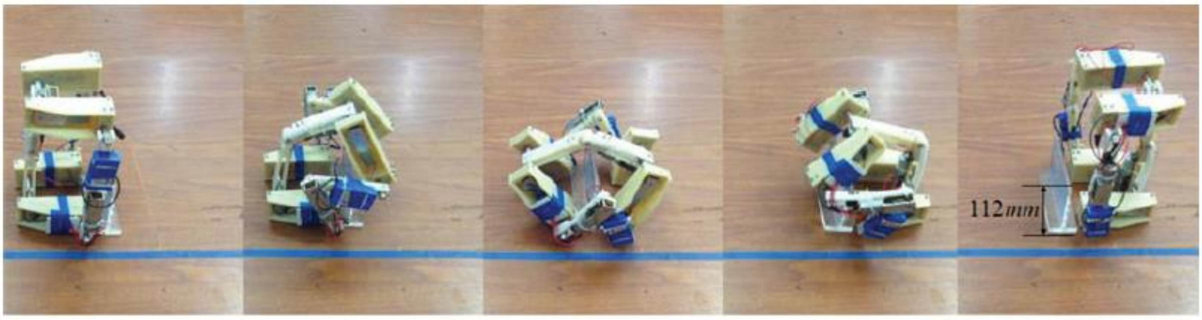

Figure 1.29: Mobile Robot with Eight Modes [47]

Zhu et al. [48] studied on a hybrid robot with four driving mechanisms, four independent pallet devices, two support legs and one wheel lifting mechanism. Prototype of the proposed system can be seen in Figure 1.30. It can adapt to rough and regular terrain with high obstacles. As a result of analysis, simulation and experimental validations, it has been proven that the robot even remain stable during its climbing activity.

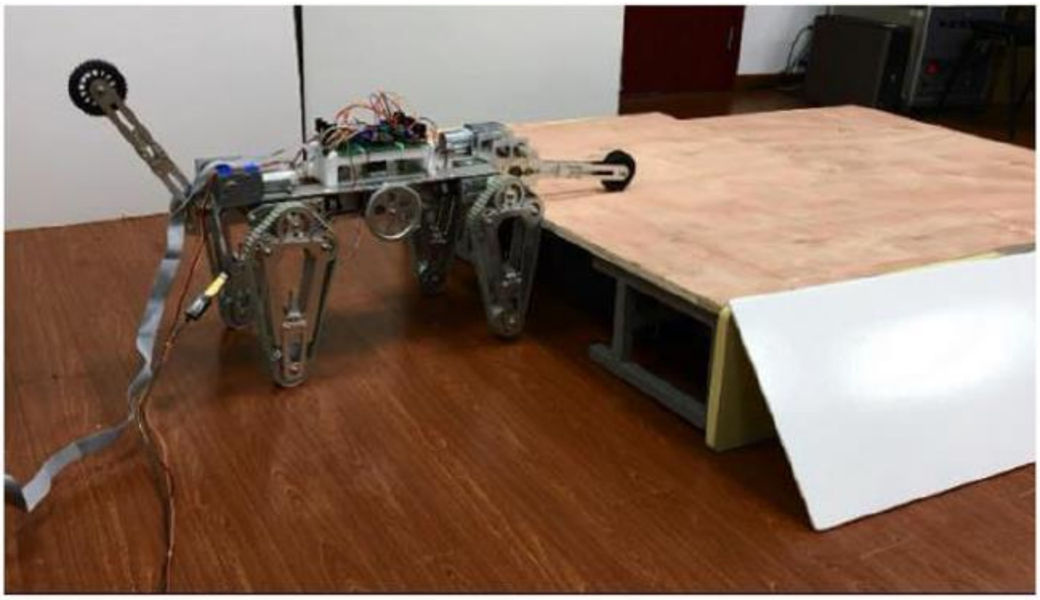

Figure 1.30: Hybrid Robot [48]

Sharifi et al. [49] studied the simulation and modeling of a system called MARIO "Mobile Autonomous Rover for Intelligent Operations". Authors designed the system as non-holonomic by using omniwheels and analyzed offline programming along with system performance by using gazebo simulator and robot operating system. Kinematic model of this robot was successfully tested in real and simulation environments. Sahoo et al. [50] developed a bond graph model to create the dynamic model of the four-wheeled omnidirectional Mecanum wheel robot. Authors created mathematical model from the proposed bond graph and proved the level of this model. Based on the proposal, they also developed a flatness based controller. Simulations showed that accuracy of the dynamic model and the flatness based controller have proven to be superior to the backstop controller. Bai et al. [51] proposed a mobile robot design with transformable locomotion system that can be used for search and rescue tasks in complex terrain. Land Devil Ray (LDR) is able to convert its locomotion system to wheeled driving or legged walking mode with respect to the conditions of the terrain. As seen in Figure.1.31, when the robot encounters an obstacle, transformation occurs. Throughout the study hardware verification was carriedout by using manufactured prototype.

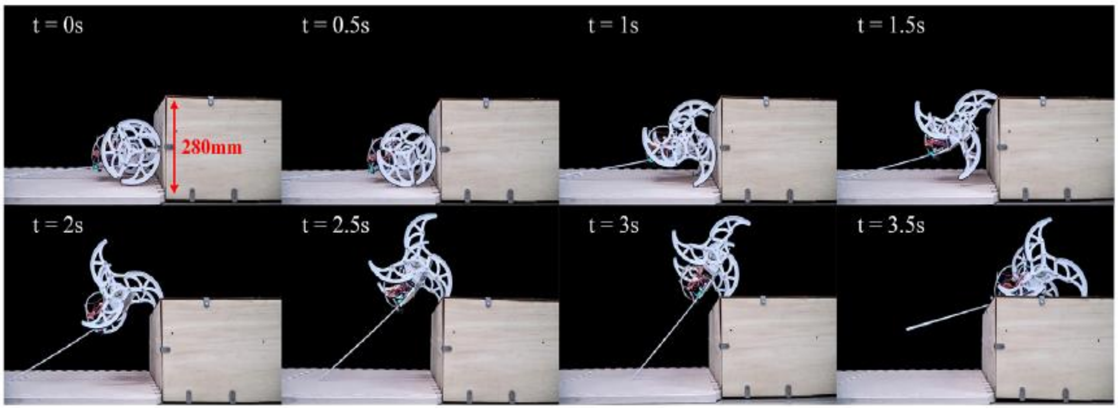

Figure 1.31: Land Devil Ray (LDR) [51]

Chung et al. [52] presented a method for terrain classification of mobile robots that are used for surveillance or delivery in urban environments. Proposed method proposes lidar utilization for terrain detection. In order to handle measurement errors and uncertainties of the lidar, classification criteria of the fields are taught to the mobile robot by a controlled learning method. Training data was obtained through manual driving on land. Ganganath et al. [53] studied an algorithm for mobile platforms powered by portable energy sources to utilize limited energy sources in a most efficient way by deciding the shortest possible path between two locations. Authors validated the applicability of the algorithm for the shortest path planning for energy-constrained mobile platforms on rugged terrain using real terrain data. Yan et al. [54] studied data of traction performance of a crawler mobile robot. Througout the study parameters that are affecting the system such as drawbar pull, slip ratio, blockage and deformation of parts were investigated in order to improve overall performance.

In light of advancements and existing studies in the literature related with mobile robotics, this thesis aims to carry out the structural design of a novel reconfigurable mobile platform that can adapt different terrain conditions and avoid obstacles within its path by changing its structural configuration. In order to have wide area of usage, the system was designed in such a way that its structure allows the implementation of various modules to the top of the platform so that it can be utilized for different task scnerios. Considering the properties of the existing commercial mobile platform designs in the literature, including their advantages and disadvantages in different terrain conditions, main design constraints of the system was decided and listed below.

- Weight of the system should not exceed 200 kg.
- Proposed system should overcome obstacles with a maximum height of 130 mm.
- Maximum speed of the system should lie between 5 to10 km/h.
- Proposed system should carry an additional maximum payload of its own weight.

2. STRUCTURAL DESIGN OF THE MOBILE PLATFORM

In light of fast technological improvements in late history, there has been an expansion in mobile robot usage in various fields. As there are wide ranges of areas for mobile robots, mobile platforms can be given as one of the most versatile options that can be implamented easily to different aplications by only changing the platform equipments. Considering this, current thesis concentrated on the design of a multi-degree of freedom mobile platform that can be utilized for different task scnerios.

2.1 Design Constraints

Prior to the structural design, contraints of the mobile platform were decided. Primary objective of the mobile platform was selected as the maneuvarability over different terrain conditions and overcoming obstacles through its cruising. For this purpose, proposed mobile platform should be adaptable to various terrain conditions by reconfiguration without any external intervention. Moreover the system should be designed as fault tolerant and able to continue its operation in case of a failure in one or many transmission elements. As mentioned before, top plate of the mobile platform will also be left available for the desired equipment such as rescue, mine exploration and sampling equipments to be attached.

Considering these structural objectives locomotion systems are compared for various terrain types (Table 2.1)

Table 2.1: Wheel Types Comparison

	Asphalt Terrain	Sandy Terrain	Rugged Terrain
Wheel	√	X	X
Tracked	X	√	√

Due to the fact that designed mobile platform should be adaptable to these three types of terrains, it is needed to create a hybrid system by the combination of wheels and tracked systems.

Locomotion systems can be created where different module types combined together to create a hybrid system. Accordingly, the table below (Table 2.2) shows the comparison of possible combinations with design constraints.

Table 2.2: Combination Types Comparison

	Rough Terrain	Overcome Obstacles	Adaptation To Different Ground	Fault Tolerances
Wheel-Wheel	X	X	X	X
Flat Tracked-Flat Tracked	√	√	X	X
Triangular Tracked-Flat Tracked	√	√	X	X
Triangular Tracked-Wheel	√	X	√	√
Triangular Tracked-Triangular Tracked	√	√	X	√

As shown in Table 2.2 there is no perfect combination that is suitable for all terrain constraints. Only two combinations have three qualifications. Triangular tracked-wheel combination has disadvantage in overcoming obstacles. This combination cannot be modified, because the possible modifications to the wheel part will be transformed into an existing combination. Triangular tracked-triangular tracked combination lacks in the adaptation for different grounds. Wheel systems are in linear contact with the ground. However, tracked systems have planar contact with the ground. This combination can be modified to provide linear contact at the same time. For these reasons, triangular tracked-triangular tracked combination is selected to be modified.

The appearance of the regular system according to the selected combination can be seen in Figure 2.1.

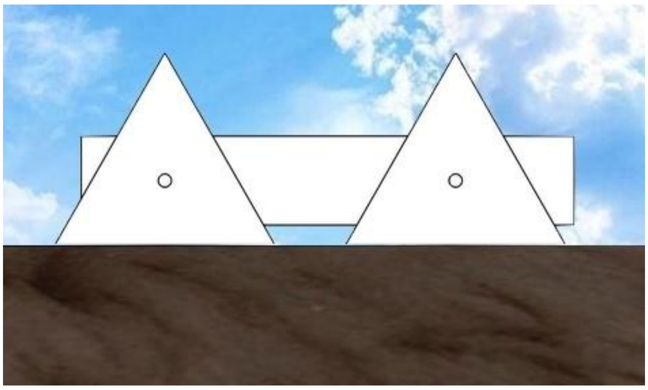

Figure 2.1: Triangular Tracked-Triangular Tracked Combination Basic Representation

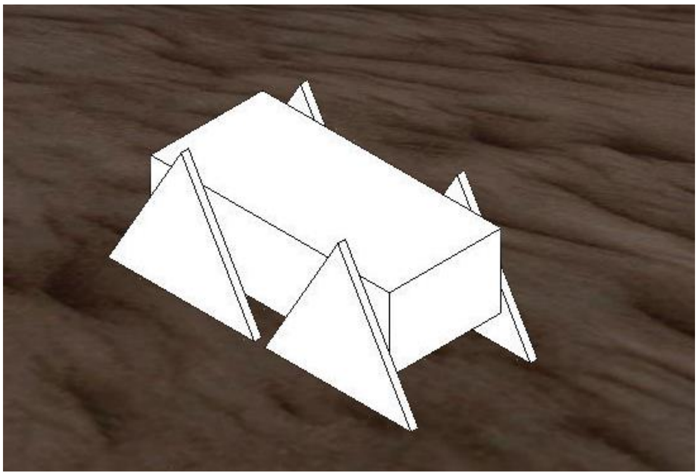

Figure 2.2: Triangular Tracked-Triangular Tracked Combination Isometric Basic Representation

2.2 Design Methodology

Design of the mobile platform will be examined in four main parts as predesign, design of the locomotion system (triangular tracked design), design of the transmisson system and design of the main body

2.2.1 Predesign

In this part general design of the mobile platform will be made. The first design was based on the configuration in Figure 2.2. In order to increase the motion capability of the platform, dual actuators are decided to be used for each module.

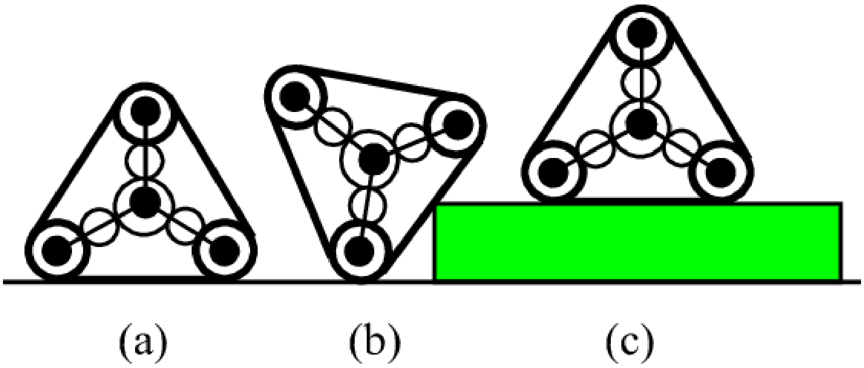

Figure 2.3: Planetary Tracked Wheel And Its Working Phases [55]

As shown in figure 2.3 when the wheel is traveling on a flat surface (Figure 2.3a), it will be cruised by the track actuation. On the other hand when the system encounters with an obstacle (Figure 2.3b) tracked wheel will be rotated from its geometric center by another actuator. After overcoming the obstacle (Figure 2.3c), it will be driven again by the first actuator. Thus a total of eight actuators are required for four wheels to active dual motion wheel design. During this type of cruising, if both of the wheels in front or rear of the mobile platform encounters with an obstacle at the same time the system can overcome the obstacle in a balanced manner (Figure 2.4). But even in this case the upper part of the platform tilts. In order to prevent this, it is necessary to increase the number of point contacts with the ground. In four wheel design, when the wheels are rotating from the geometric center, the height of the platform measurement from the ground will increase and decrease continuously. In order to prevent this, some of the wheels should rise while the remaining will have to be lowered so that the platform will have little oscillation. Yet in this case, four wheel designs will not be sufficient for propoer balancing.

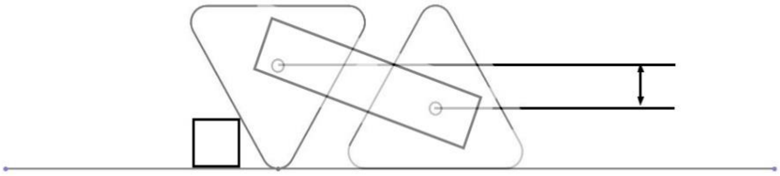

Figure 2.4: Platform Tilt

Additionally when trying to overcome an obstacle with single wheel, the system will not be stable (Figure 2.5). If the obstacle is high enough, it may also cause the platform to overturn.

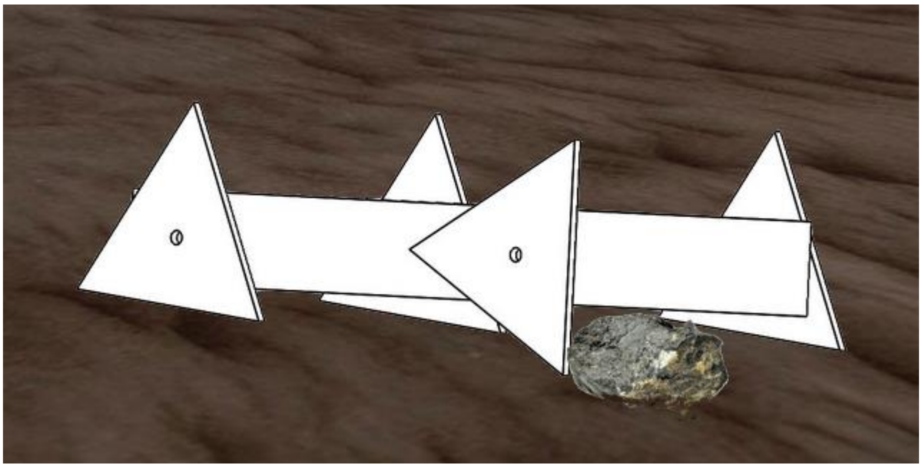

Figure 2.5: Overcoming Obstacles with Single Wheel

In order to solve this situation and increase the number of possible contacts with the ground, number of wheels on the platform was decided to be increased to six and cruising principle has been changed. In this configuration, when the single wheel tries to overcome the obstacle, wheels will rotate diagonally synchronised (Figure 2.6). This scnerio can be seen in Figure 2.7 that shows the system while exceeding the obstacle.

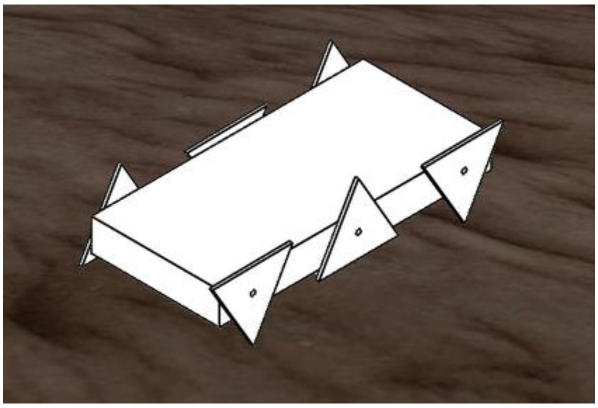

Figure 2.6: Overcoming Obstacles with Single Wheel (Perspective View)

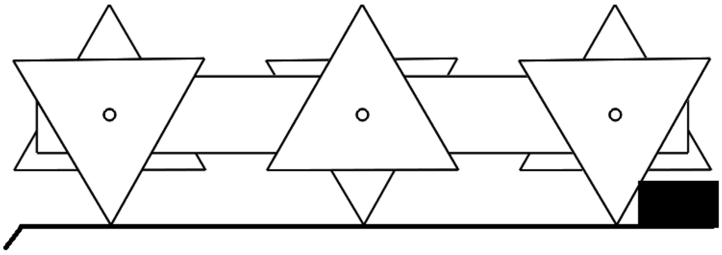

Figure 2.7: Overcoming Obstacles with Single Wheel (Side View)

2.2.2 Locomotion design

Considering the constraints given before, predesign was followed by the locomotion design. There are two types of designs used in triangular tracked wheels. The first type of design is driven from the top of the triangle. The advantage of this is the fact that it keeps the drive point at its maximum level, but in this configuration the triangle cannot be rotated around itself. The other method is to drive the wheel from the geometric center point of the triangle. The advantage of this can be given as the ability to rotate the triangle from the center like a wheel, but the difficulty lies on the motion transfer to the corners from the center. In order to active this transmission two different design can be proposed. The first method includes the usage of timing belt (Figure 2.8) and the second one includes the usage of gears (Figure 2.9). In terms of fault tolerance, the first alternative lacks as the wheels may stop at the moment when the timing belt drive fails. Due to the fact that system with gears is capable of driving three corners from the midpoint at the same time in order to reach system fail all transmission gears should fail at the same time.

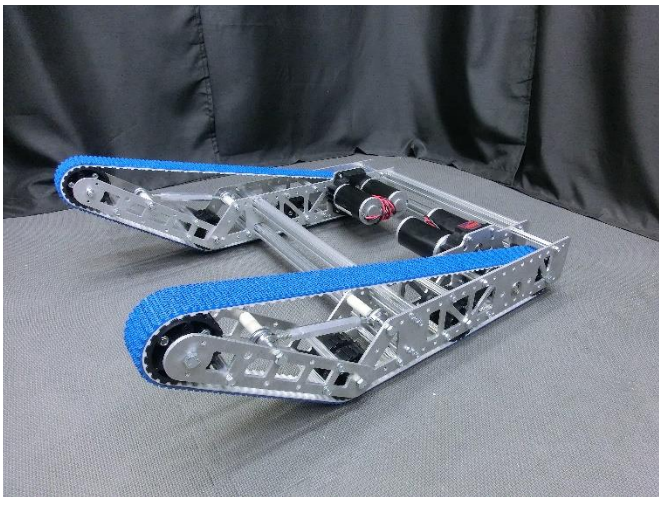

Figure 2.8: The Rhino Track Drive [56]

Figure 2.9: Closeup of Geared Tracks on a bulldozer [57]

In order to carry out mentioned wheel design, geometry should be an equilateral triangle to achieve rotation more conveniently from the center. Timing gears must be used at the ends so that no sweep occurs when the rotation motion stops suddenly. Taking this information into account, the height of the center of the wheel is calculated from the ground. Since the obstacle height contraint is 130 mm, the wheel center must be higher than the obstacle height as seen in Figure 2.10.

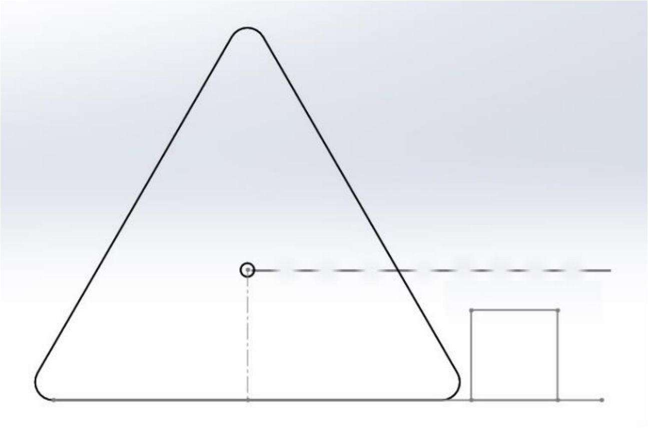

Figure 2.10: Triangular Wheel and Obstacle

With respect to this information, wheel measurements and structure were revealed (Figure 2.11) by also considering timing gears at the corners of the triangle. Also the gear sequence was designed as seen in Figure 2.12

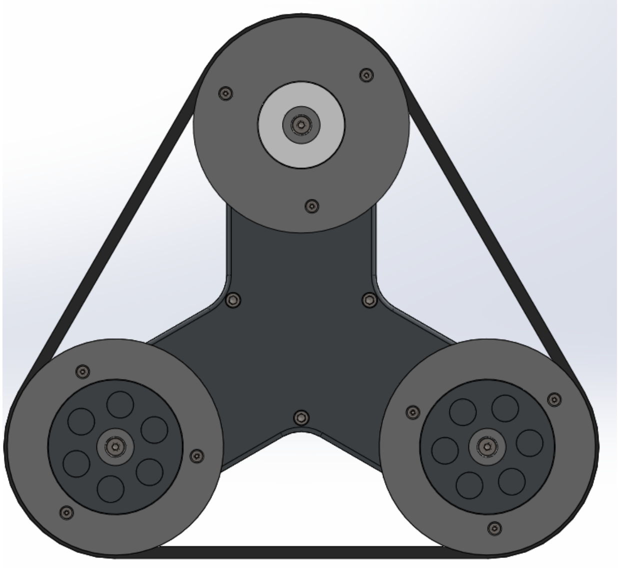

Figure 2.11: Tracked Wheel Design

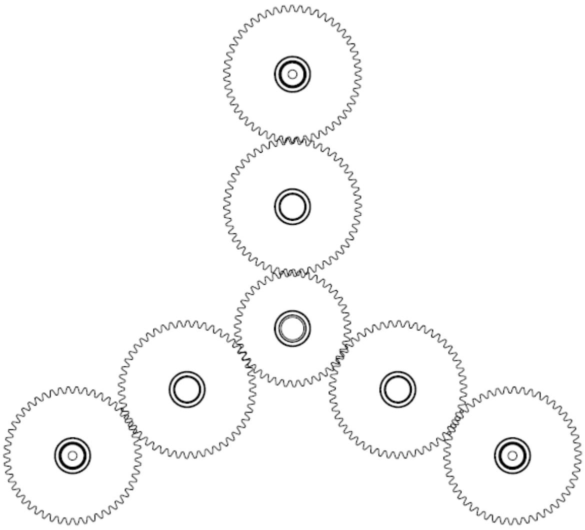

Figure 2.12: Wheel Gear Design

In accordance with decided gear placement, appropriate gear sizes need to be calculated. In order to carry out this calculation following points should be considered as,

- Total transmission rate should be equal to one for ease of design
- Distance between the first and the last gear centers should be 144 mm due to the geometrical constraints.
- Size of the gears should be as small as possible.
- Proper selection of the gear materials should be considered.

Utilizing the given equations below,

$$D_a = D_0 + 2\,m \tag{2.1}$$

$$D_0 = m.z \tag{2.2}$$

$$D_f = D_0 - 2{,}5\,m \tag{2.3}$$

$$h = \frac{D_a - D_f}{2} \tag{2.4}$$

$$E = \frac{m.(z_1 + z_2)}{2} \tag{2.5}$$

calculations were carried out for the gear selections, where in equations 2.1 - 2.5, m = module, z = number of teeths, D_a = major diameter, D_o = pitch diameter, D_f = minor diameter, h = depth of teeth, E = axis between two gears (Figure 2.13). The values that were calculated were shown in Table 2.3.

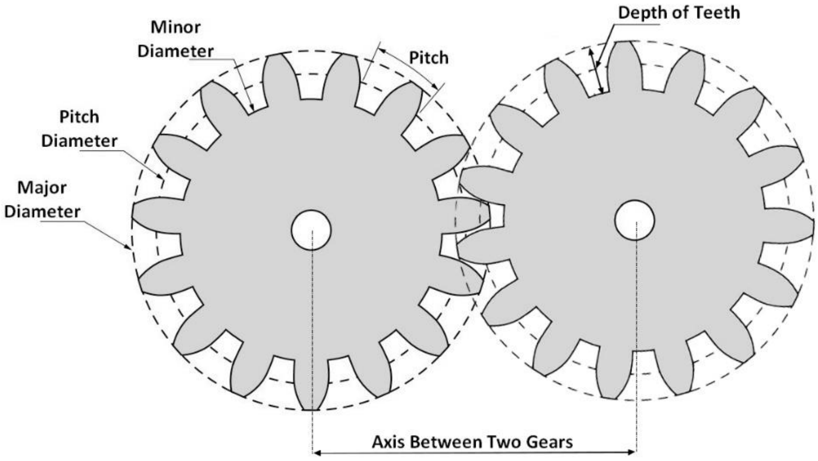

Figure 2.13: Gear Dimensions

Table 2.3: Gears Spesifications

<table>
<tr><th colspan="2">Input Gear Specifications</th><th colspan="2">Idler Gear Specifications</th><th colspan="2">Output Gear Specifications</th></tr>
<tr><td>Gear Module</td><td>1.50</td><td>Gear Module</td><td>1.50</td><td>Gear Module</td><td>1.50</td></tr>
<tr><td>Helical Angle</td><td>0.00</td><td>Helical Angle</td><td>0.00</td><td>Helical Angle</td><td>0.00</td></tr>
<tr><td>Gear Width (mm)</td><td>14.00</td><td>Gear Width (mm)</td><td>14.00</td><td>Gear Width (mm)</td><td>14.00</td></tr>
<tr><td>Active Gear Width (mm)</td><td>14.00</td><td>Active Gear Width (mm)</td><td>14.00</td><td>Active Gear Width (mm)</td><td>14.00</td></tr>
<tr><td>Number Of Teeth</td><td>50.00</td><td>Number Of Teeth</td><td>46.00</td><td>Number Of Teeth</td><td>50.00</td></tr>
<tr><td>Pitch Diameter</td><td>75.00</td><td>Pitch Diameter</td><td>69.00</td><td>Pitch Diameter</td><td>75.00</td></tr>
<tr><td>Major Diameter</td><td>78.00</td><td>Major Diameter</td><td>72.00</td><td>Major Diameter</td><td>78.00</td></tr>
<tr><td>Minor Diameter</td><td>71.25</td><td>Minor Diameter</td><td>65.25</td><td>Minor Diameter</td><td>71.25</td></tr>
<tr><td>Depth Of Teeth</td><td>3.37</td><td>Depth Of Teeth</td><td>3.37</td><td>Depth Of Teeth</td><td>3.37</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="5">Ratio Between Input and Idler Gears</td><td>1.10</td></tr>
<tr><td colspan="5">Ratio Between Idler and Output Gears</td><td>0.90</td></tr>
<tr><td colspan="5">Axis Between Input and Idler Gears</td><td>72.00 mm</td></tr>
<tr><td colspan="5">Axis Between Idler and Output Gears</td><td>72.00 mm</td></tr>
<tr><td colspan="5">Total Axis Between Three Gears</td><td>144.00 mm</td></tr>
</table>

After the wheel gearing calculations, verification of the selected actuators were completed by considering the weight constraint of the mobile platform. As the maximum weight of the mobile platform was decided to be 200 kg and it should carry a maximum payload of its weight. In light of this two different types of actuators have been selected accordingly as D110BLD1500-36A-30S 2 hp Brushless DC Motor (DMKE Motors) for the actuator of tracked mechanism (Figure 2.14) and Maxon 353301 motor and Planetary Gearhead 110413 for the actuators of triangular wheels (Overcoming obstacles) (Figure 2.15).

Figure 2.14: D110BLD1500-36A-30S 2 hp Brushless DC Motor [58]

Figure 2.15: Maxon 353301 Motor And Glenatary Gearhead 110413 [59]

After the actuator selection they were verified in terms of required actuator torque and design constraints of the mobile platform. This procedure was carried out by using simple formulations as,

$$S_{po} = S_m/R_{pg} \tag{2.6}$$

$$T_{po} = T_m/R_{pg} \tag{2.7}$$

$$T_{tg} = T_{po}. R_w \tag{2.8}$$

$$S_{tg} = S_{po} . R_w \tag{2.9}$$

$$F = T_{tg}/R_{tg} \tag{2.10}$$

$$W_t = F. n \tag{2.11}$$

$$R = W_t/ W_s \tag{2.12}$$

$$d_r = R_{tg} . 2. \pi \tag{2.13}$$

$$S = d_r. S_{tg} \tag{2.14}$$

Results of the verification calculations and parameters of equations 6-14 can be seen in Table 2.4. It should be noted that calculated maximum payload capacity and overall speed are within the limits of design constraints. Utilizing the selected actuator, proposed system can cruise at a speed of 7.5 km/h and can carry an approximately 2.2 times of its own weight.

Table 2.4: Verification Results (Wheel Track Motion)

Motor Speed (rpm)	S_m	3000.00
Motor Torque (mNm)	T_m	4780.00
Planetary Gear Ratio	R_{pg}	10.00
Planetary Gear Output Speed (rpm)	S_{po}	300.00
Planetary Gear Output Torque (mNm)	T_{po}	47800.00
Gear Ratio In Wheel	R_w	1.00
Torque On Timing Gear (mNm)	T_{tg}	47800.00
Speed On Timing Gear (rpm)	S_{tg}	300.00
Timing Gear Radius (mm)	R_{tg}	66.84
Force (N)	F	715.14
Force (kgf)		72.89
Number of Wheel	n	6.00
Total Weight (kg)	W_t	437.39
Total Weight of System (kg)	W_s	200.00
Ratio	R	2.18
Displacement/Rotation (mm)	d_r	419.96
Speed (mm/s)	S	125990.40
Speed (km/h)		7.55

After achieving successful verification results, in order to select proper manufacturing material, stresses on the gears at the limits were calculated by using equation 2.15 as

$$\sigma = \frac{F_t}{b.m} Y_f . Y_S . Y_\varepsilon . Y_\beta \tag{2.15}$$

where σ = Gear Stress, F_t = Tangential Force, b = Gear Width, m = Gear Module, Y_f = Form Factor, Y_s = Notch Factor, $Y\varepsilon$ = Load Share Factor, Y_β = Helical Angle Factor. After required necessary factors were checked from the related tables, multiplications were calculated as 2.5. From this point, gear stresses were calculated with the values given in Table 2.5 and shown in Table 2.6.

Table 2.5: Motor And Gearbox Spesifications

Motor Torque (Nm)	5
Planetary Gear Ratio	1/10

Table 2.6: Gear Stress Calculations

Input Gear Specifications		**Idler Gear Specifications**		**Output Gear Specifications**	
Gear Module	1.50	Gear Module	1.50	Gear Module	1.50
Helical Angle	0.00	Helical Angle	0.00	Helical Angle	0.00
Gear Width (mm)	14.00	Gear Width (mm)	14.00	Gear Width (mm)	14.00
Active Gear Width (mm)	14.00	Active Gear Width (mm)	14.00	Active Gear Width (mm)	14.00
Number Of Teeth	50.00	Number Of Teeth	46.00	Number Of Teeth	50.00
Pitch Diameter	75.00	Pitch Diameter	69.00	Pitch Diameter	75.00
Major Diameter	78.00	Major Diameter	72.00	Major Diameter	78.00
Minor Diameter	71.25	Minor Diameter	65.25	Minor Diameter	71.25
Depth Of Teeth	3.37	Depth Of Teeth	3.37	Depth Of Teeth	3.37
Ft (N)	1333.30	Ft (N)	1333,30	Ft (N)	1333,30
Gear Stress (N/mm^2)	158.73	Gear Stress (N/mm^2)	158.73	Gear Stress (N/mm^2)	158.73

As seen in Table 2.6 gear stresses were calculated as 158 N / mm^2. After taking the safety factor as 1.5 in the calculations, light and durable material was selected as 6061 T6, a variant of aluminum that is the most suitable material in terms of strength values. Technical specifications of 6061 T6 can be seen in the Table 2.7.

Table 2.7: Etial 6061 Specifications [19]

Temper	**Yield Strength**	**Tensile Strength**	**Elongation (%50)**	**Stiffness (Brinel)**
	(Mpa) min-max	(Mpa) min-max	min-max	min-max
0	55	125	26	40-30
T4	110-140	180-235	16-21	65
T6	240-275	260-310	8-12	90-95

At the end of calculations, a gear box was designed as a mobile platform wheel from 6061 T6 aluminum material.

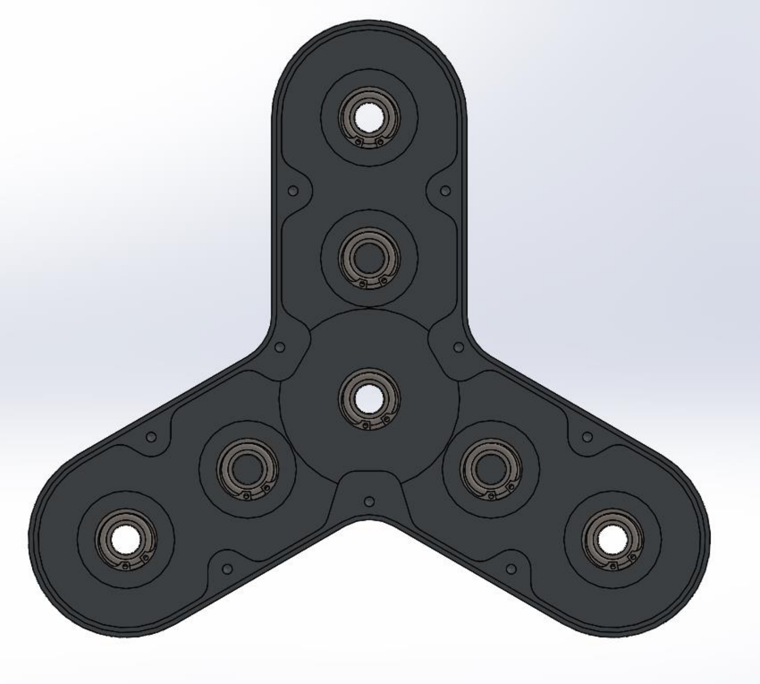

Figure 2.16: Wheel Inside Gear Box Part

As shown in the Figure 2.16 gear bearings shaft seals and oil seals were used as standard parts that are shown in Table 2.8

Table 2.8: Wheel Gear Box Bottom Body Part List

No	Parts Name	Quantity
1	Wheel Gear Box Bottom Body	1
2	40668-V SKT Oil Seal	4
3	DIN 625 - 6002 - Full,SI,NC,Full_68	7
4	Circlip DIN 472 - 32 x 1.2	7
5	Circlip DIN 472 - 24 x 1.2	4

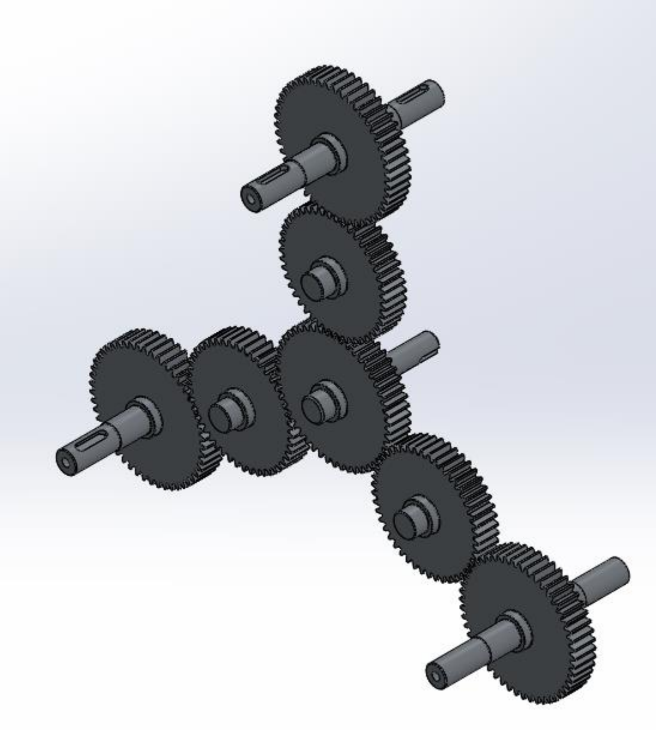

Figure 2.17: Gear Box Assembly Shape

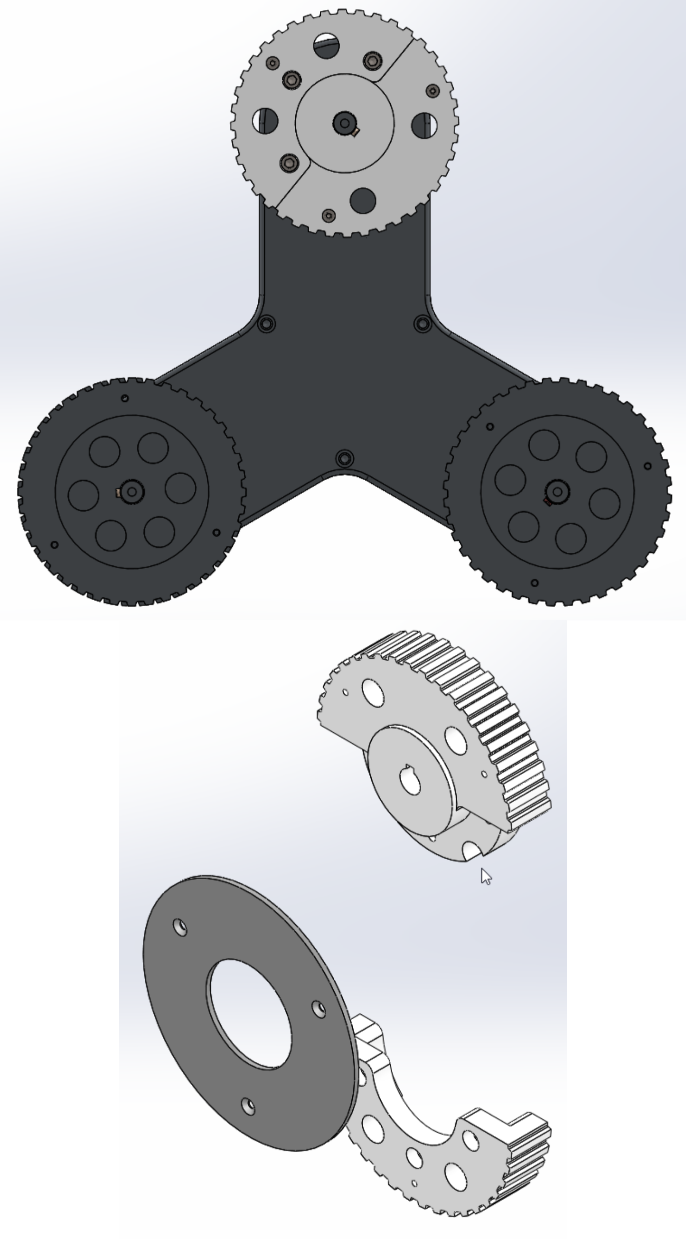

Figure 2.18: Timing Gear Assambly and Timing Belt Tensioning Mechanism

Also a tensioning mechanism for the removal and insertion of the timing belt was designed. As shown in the Figure 2.18, top timing gear was designed as two parts to help the timing belt to be dismantled and mounted. When the timing belt is requested to be changed, the lower part of the gear will be removed and the wheel should be rotated one turn. Thus the timing belt will be loose and can be removed easily. It sould also be noted that as the track is drived from three points on the wheel, the system gains another fault tolerance property. Final design of the triangular wheel can be seen in Figure 2.19.

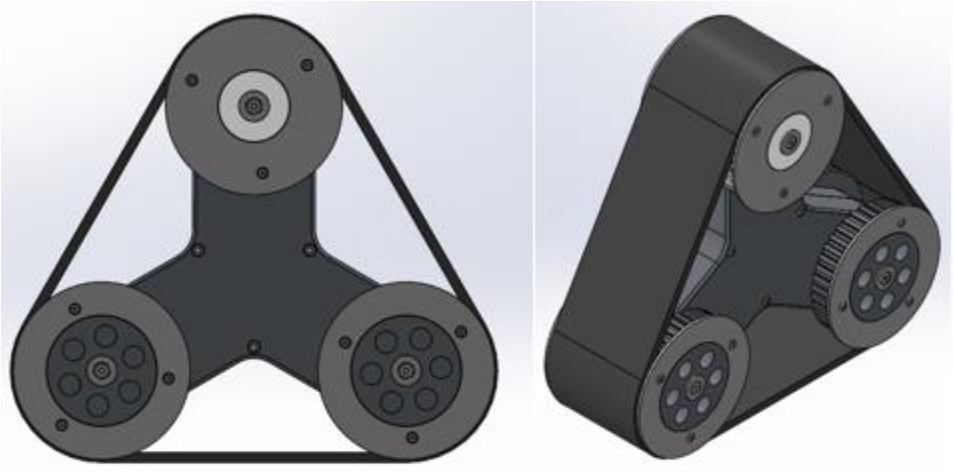

Figure 2.19: Triangle Wheel Design

2.2.3 Transmisson system design

An efficient transmission system design is needed to rotate the triangular wheel and the track system independently. Thus dual actuators should be utilized in the gearbox for both the wheel rotation and the track motion.

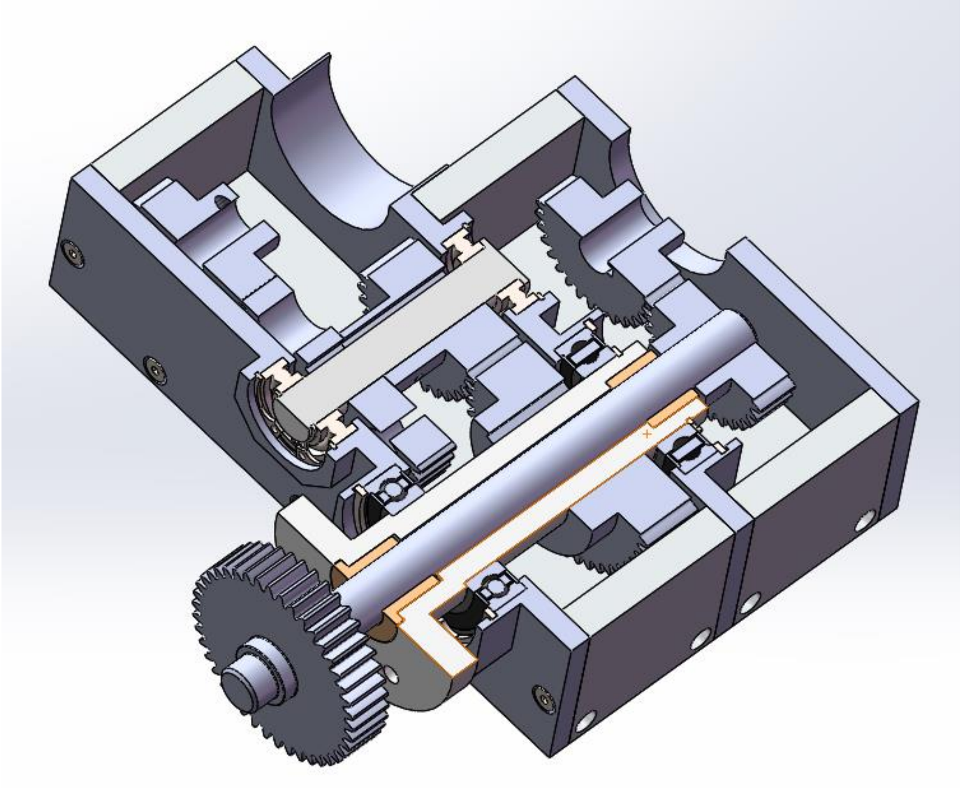

Figure 2.20: Gear Box Design

As shown in Figure 2.20, a gearbox design was prepared for placing two actuators side by side. With this gear box, the movement is transferred from the actuators to the wheel. The first actuator drives the inner gear unit to allow the motion of the track and the second actuator rotates the outer body with the help of gears. In order to calculate the maximum speed of the mobile platform during the rotational motion of the triangular wheels, similar calculations can be carried out by using equations 6-14. Final verification results can be seen in Table 2.9.

Table 2.9: Verification Results (Wheel Rotary Motion)

Motor Speed (rpm)	S_m	2570.00
Motor Torque (mNm)	T_m	888.00
Planetary Gear Ratio	R_{pg}	308.00
Planetary Gear Output Speed (prm)	S_{po}	8.34
Planetary Gear Output Torque (mNm)	T_{po}	273504.00
Gear Ratio In Gearbox	R_G	1.00
Torque On Output Gear (mNm)	T_{OG}	273504.00
Speed On Output Gear (rpm)	S_{OG}	8.34
Motion Radius (mm)	R_M	220.00
Force (N)	F	1243.20
Force (kgf)		126.72
Number of Wheel	n	3.00
Total Weight (kg)	W_t	380.18
Total Weight of System (kg)	W_s	200.00
Ratio	R	1.90
Displacement/Rotation (mm)	d_r	1382.30
Speed (mm/s)	S	11534.13
Speed (km/h)		0.69

With the selected actuator, the system can reach speed of 0.7 km/h. This mode will be utilized to overcome the obstacles. Assembly of the gearbox with the triangular wheel can be seen in Figure 2.21.

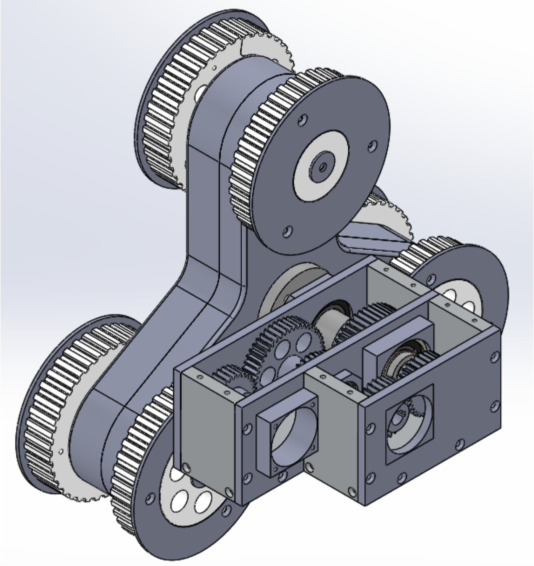

Figure 2.21: Gearbox and Wheel Assembly

When two wheels with the attached gearboxes are conbined side by side, a single motion module will be created (Figure 2.22)

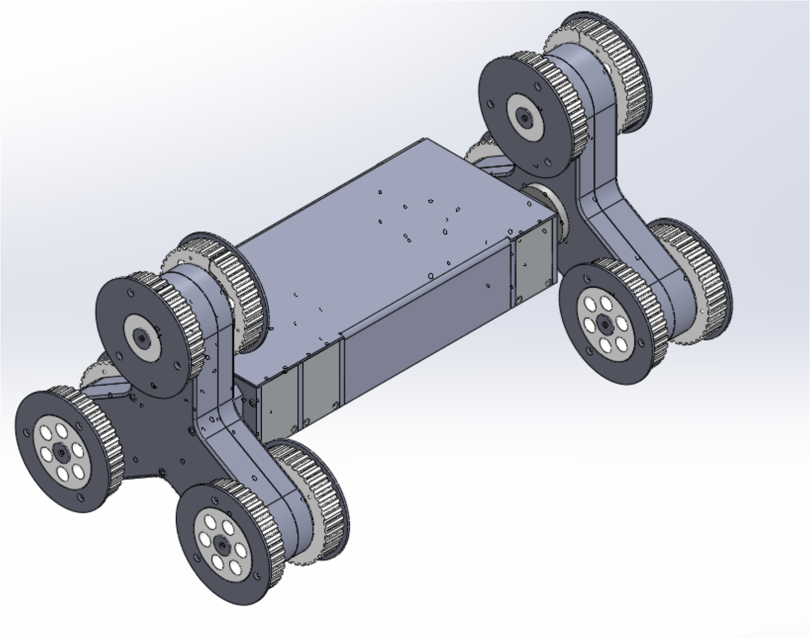

Figure 2.22: Single Motion Module

In order to create reconfigurable mobile platform with respect to the operating conditions of the system, three motion modules were decided to be used in total. This way the system can adapt to different road conditions by configuring the wheel orientations and distances. For instance, if the middle motion module has line contact with the surface, the system moves faster when both front and rear motion modules approaches to the middle motion module. This design allows the creation of a hybrid system. For instance on a muddy road or hard terrain, the system may take different configurations with respect to the environmental constraints. In light of this modular design, proposed system offers three different configurations as,

- All the wheels have surface contact with the terrain (Figure 2.23).
- Front and rear wheels have surface contact with the terrain and the middle wheels have a linear contact (Figure 2.24).
- All the wheels are in linear contact (Figure 2.25).

These configurations will provide different movement conditions on different terrains.

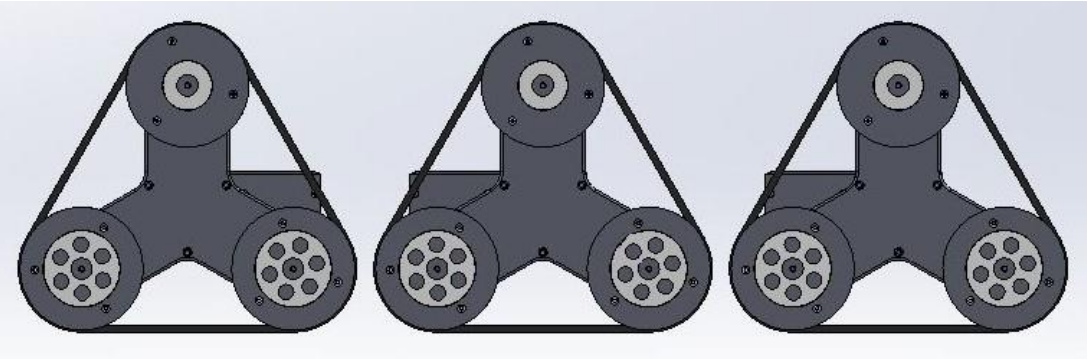

Figure 2.23: First Configuration

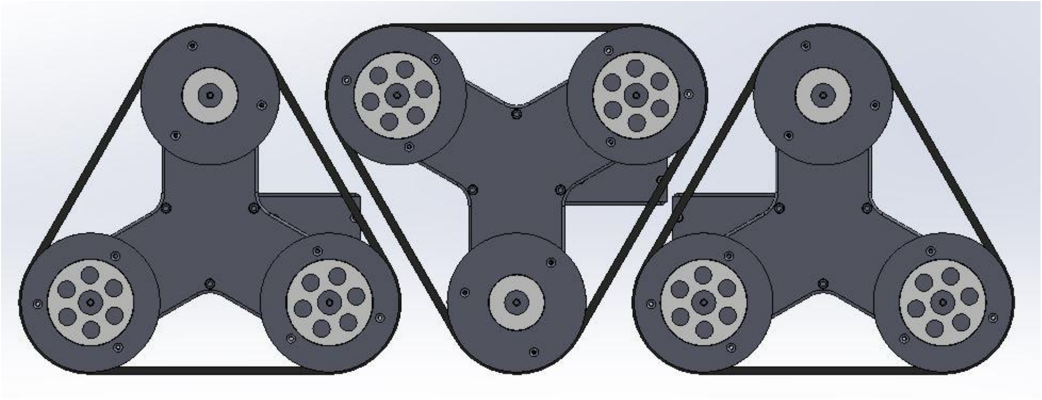

Figure 2.24: Second Configuration

Figure 2.25: Third Configuration

It should be noted that although there will be no configuration change in the system for the first and third configutions, locomotion system should undergo a structural reconfiguration as the geometric center of the middle wheel should change position. Due to the triangular wheel design, geometric center of the wheel should displace 72 mm in order to provide smooth ground contact with the other front and rear wheels. Thus another reconfiguration mechanism is needed to be designed for the middle motion module.

2.2.4 Body design

As mentioned in the previous section, in order to convert into the second configuration, the middle motion module must rise by 72 mm (Figure 2.26) that can be provided by a prismatic actuation.

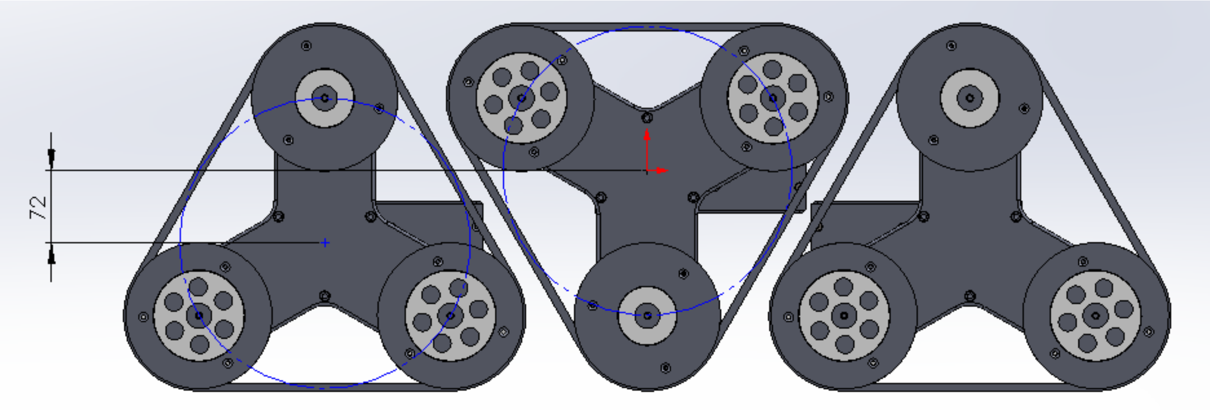

Figure 2.26: Distance Between Wheel Centers

On the other hand front and rear motion cells should also approach at the same time to a closer distance during this motion. In order to avoid usage of excessive actuators, this configuration change was decided to be carried out by a single degree of freedom mechanism that can be seen in figure 2.27.

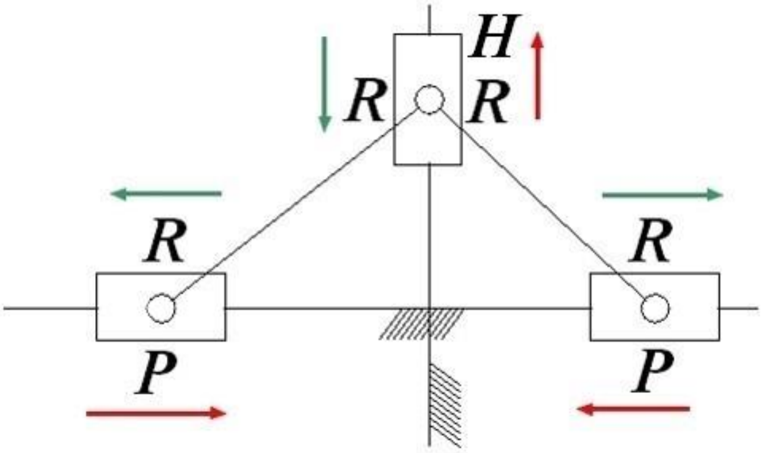

Figure 2.27: Kinematic Drawing

In order to find the construction parameters of the proposed mechanism, firstly the maximum necessary approach distance between front and rear motion modules were measured as 58.79 mm. In order to be able to move two modules at the same time during the middle modules rise motion, dual loop single degree of freedom mechanism was decided to be designed and implemented to the system. The distances between the motion modules are not the same because of their shapes. But when the middle module moves, the other modules must move at the same rate. Therefore, the same loop structure must be used on both sides. In order to use the symmetrical loop structure, the locations of the connection points on the modules were designed as different. The reconfiguration system has two different positions as shown in Figures 2.28 and Figure 2.29.

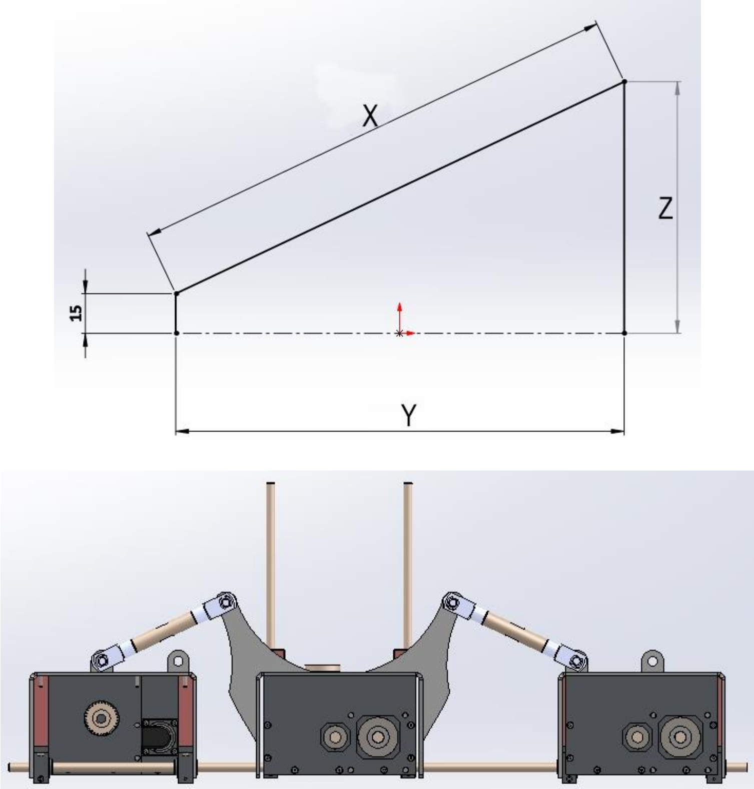

Figure 2.28: Arm Position in the First Position

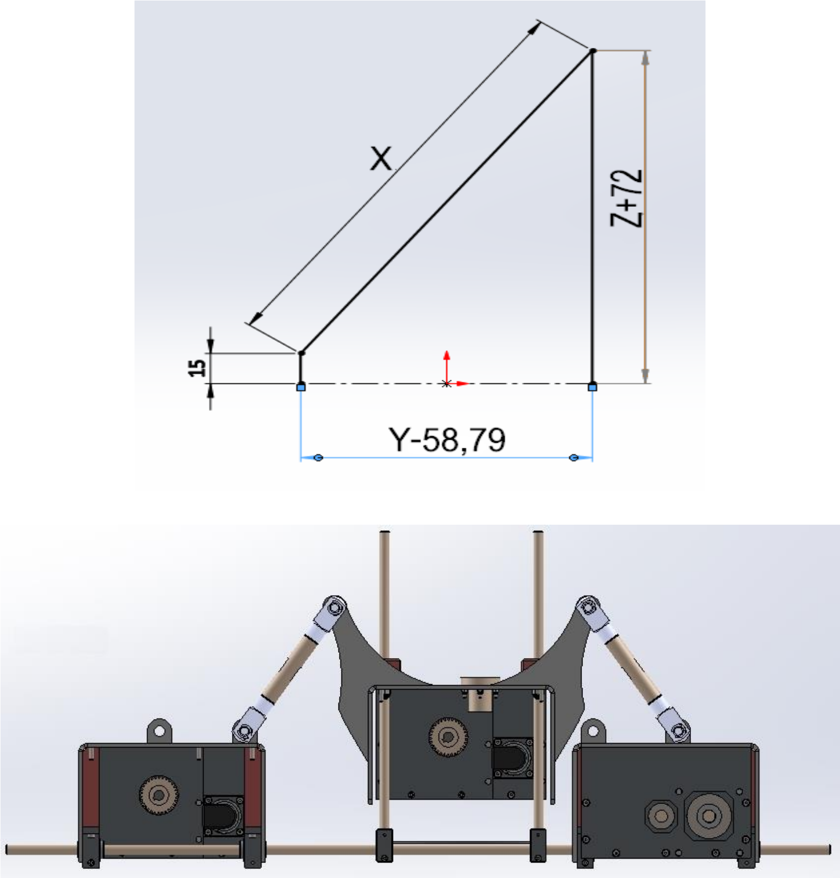

Figure 2.29: Arm Position in the Second Position

When the Pythagorean Theorem is applied to the triangles in the above pictures, following equations can be found as,

$$X^2 = Y^2 + (z - 15)^2 \tag{2.16}$$

$$X^2 = (Y - 58.79)^2 + (z + 72)^2 \tag{2.17}$$

Due to the design criteria, z length should be 95 mm. According to this, the length of y was calculated as 169.2 mm. When the equations 16 and 17 were used, the length of x was found as 187.16 mm. The front and back modules were designed by using the same analogy. Assembly of the mechanisms can be seen Figure 2.30 and 2.31.

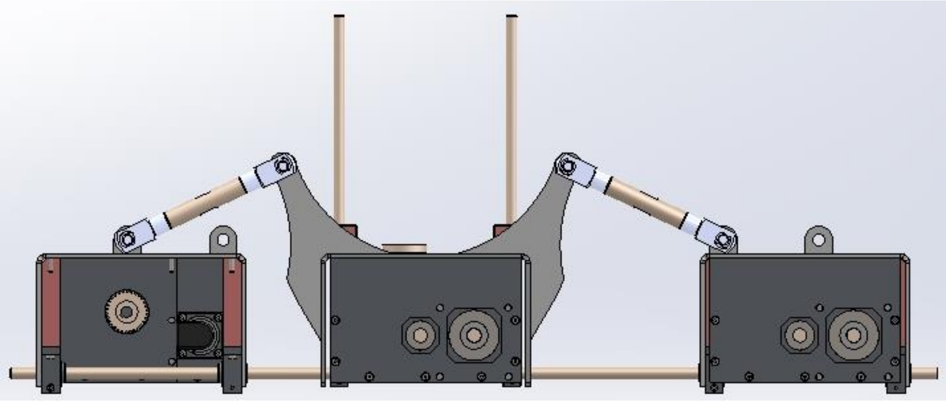

Figure 2.30: Arm Position in the First Position

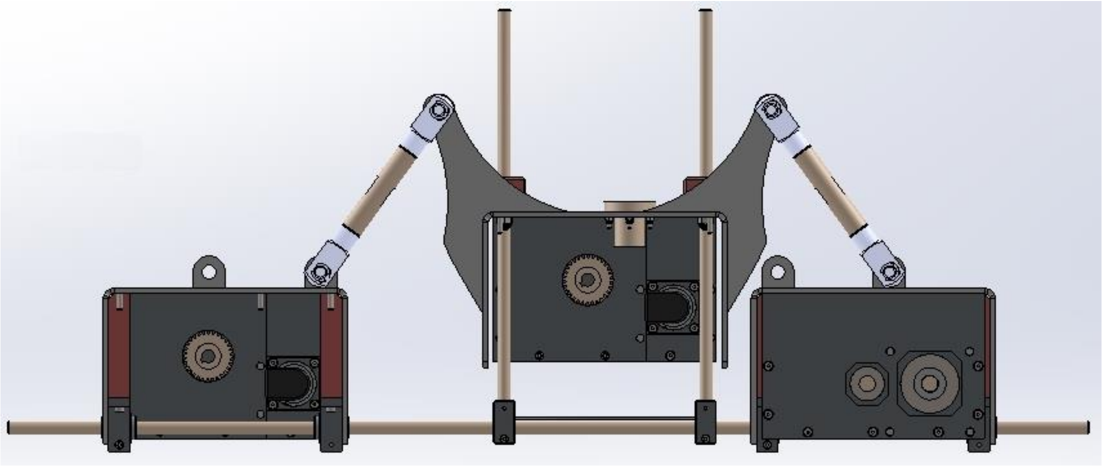

Figure 2.31: Arm Position in the Second Position

In order to provide prismatic motion a linear guide is selected to be used for movement of the front and rear motion modules. Accordingly, a mechanism for controlling the up and down movement of the middle module was also contemplated. All of the parts were assembled to the body of the system as shown in Figure 2.32.

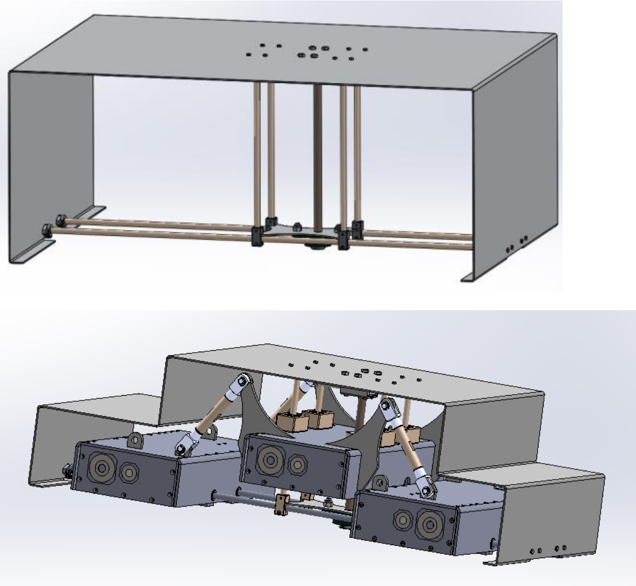

Figure 2.32: Body Group Assably

In order to save space, the front and rear modules cradle shafts were connected to the movement system of the middle cell. Trapezoidal screw was used to provide up and down movement in the middle due to their ability of autoblocking. Assembly of the whole mobile platform can be seen in Figure 2.33.

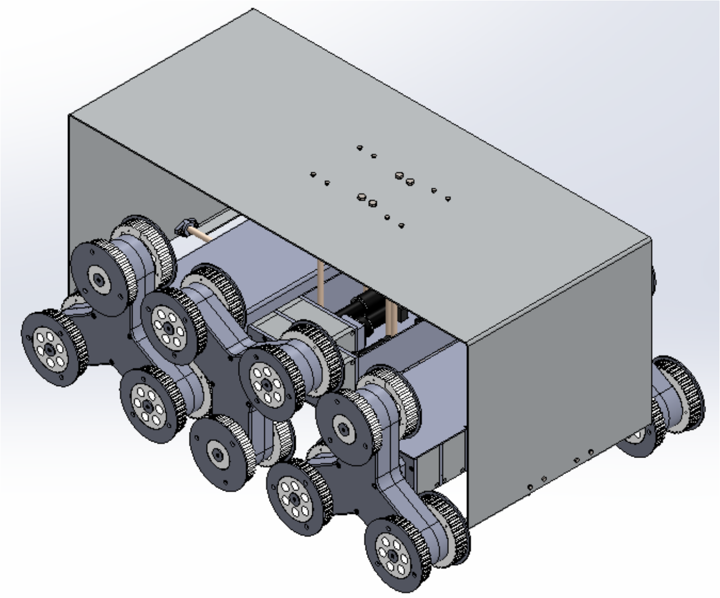

Figure 2.33: Full Assembly

3. MODIFICATIONS ON THE MOBILE PLATFORM DESIGN

The design and development of the mobile platform was mentioned in the previous sections. Every step of the design procedure has created new challenges about mobile platform design. Some problems were noted during the first analysis and simulation runs. This chapter will discuss the reasons behind the modifications that were applied to the proposed mobile platform and the differences between the new and previous design.

3.1 Reasons for Modifications

It should be noted that there should be no change in the constraints, working conditions and overall concept of the mobile platform. As described previously modified system should also has conformity to the terrain, obstacles, etc. At the beginning of the project there was an issue to be solved, one wheel being able to overcome obstacles (changes in section 2.2.1 can be seen). Although most of the constraints and objectives defined in Chapter 2 have been successfully achieved, at the end of the motion analyzes design improved. it was seen that the sould be

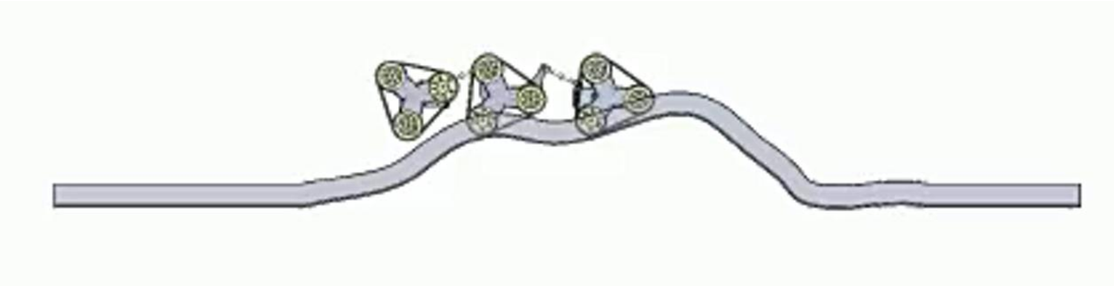

Figure 3.1: Motion Analysis View 1

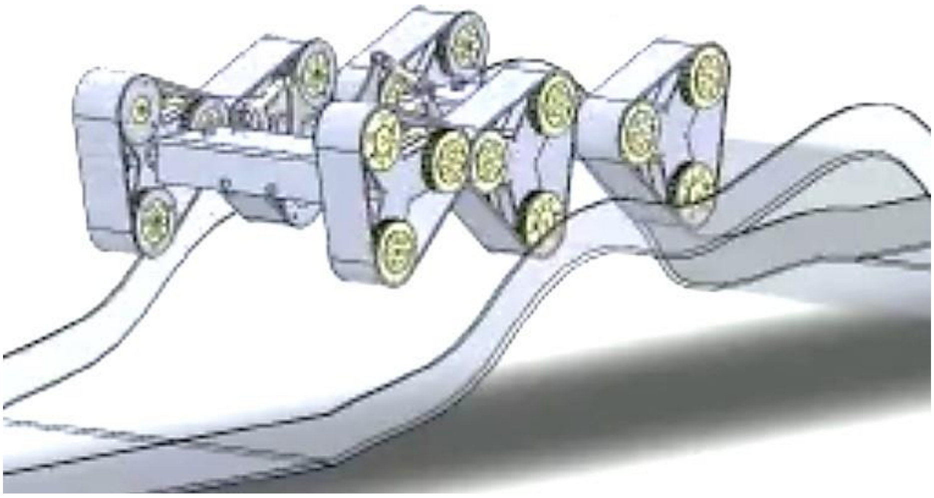

Figure 3.2: Motion Analysis View 2

As seen in the motion analysis results (Figure 3.1 and 3.2) the wheels during cruising of the mobile platform on rough terrain cannot retain terrain connection due to the lack of suspension motion. Therefore an additional suspension system must be added to the wheel mechanisms.

3.2 Modified Design

The most important issue for the suspension implementation is the fact that dual telescopic shafts should be arranged in the suspension system to transmit two degrees of freedom motion from the actuators to the wheels. Although in regular normal systems with regular single degrees of freedom wheels cardan joints are usually utilized, problem of implementation of the actuation shafts to the proposed mobile platform is more complex. Thus both the wheel connections and the gearbox connections have been redesigned to transfer rotation to different axis and a new design was proposed to achieve two independent consantric rotations. Since the motion transmitting shafts should be telescopic, a complete special design that can be seen in Figure 3.3 was proposed.

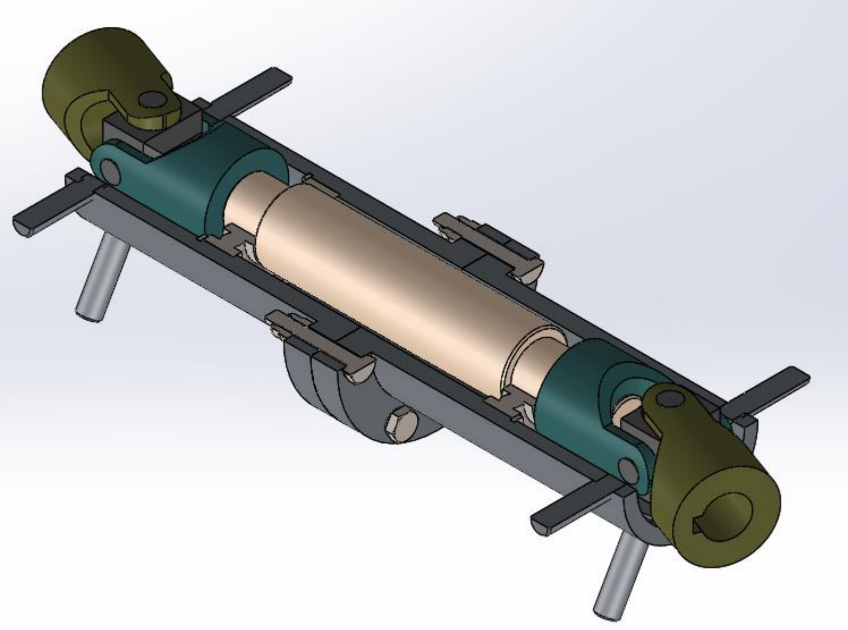

Figure 3.3: Motion-Transmitting Safts Design (Inside)

As seen in the figure cardan joints at the inner shaft ends can transfer both the vertical suspension movement and the rotational actuation movement to the gears in the wheel. The outside pipe consists of two parts at the top and creates housing for the bearings of the inner shaft. In order to transmit the actuation of the triangular wheel rotation at the same time with suspension compensation, outer shaft also creates a type of cardan connection by utilizing a smart structural design Figure 3.4. Thus outer pipe also serves as the shaft that rotates the wheel from the center. At this point it should be noted that in order to compensate synchronized suspension motion, centers of the inner and outer cardan joints should be designed to be coincident.

Figure 3.4: Motion-Transmitting Safts Design (Outside)

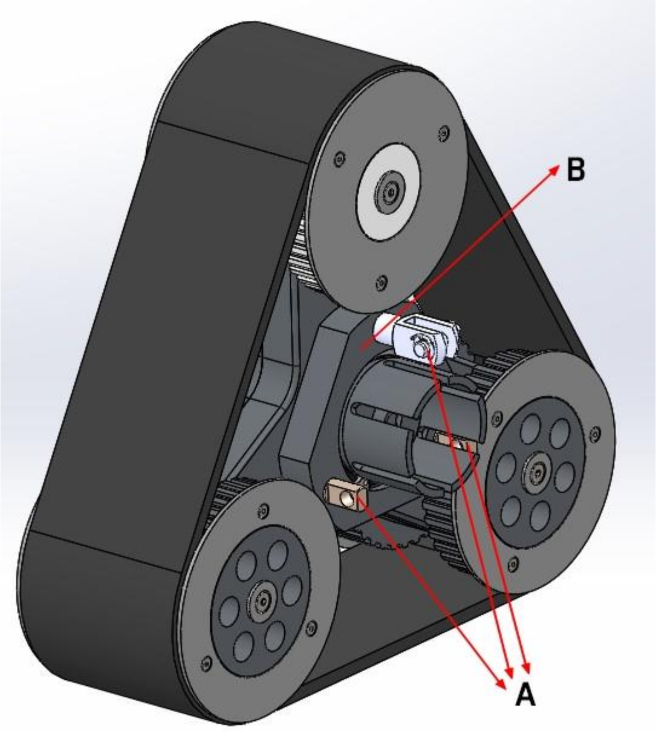

Figure 3.5: Modified Wheel Connection

As seen in figures a special bearing connection flange is designed for the wheel connections to be fixed while the wheel is rotating from the center (Figure 3.5

Connection Point B). Connection flange will remain stable while the wheel is rotating thanks to the structural design (Figure 3.5 Connection Point A). Internal structure of the special bearing connection flange can be seen in Figure 3.6.

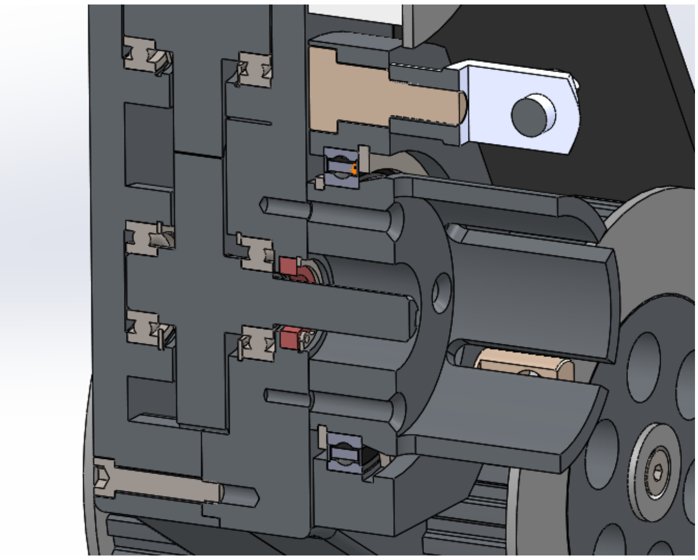

Figure 3.6: Special Wheel Connection

In order to provide fix orientation for the wheels, a linkage system was designed to connect the wheel and gearbox to each other. Figure 3.7 shows the connection of the linkage mechanism. The upper link was shaped differently from the other links, so that it does not hit the shaft when the system moves.

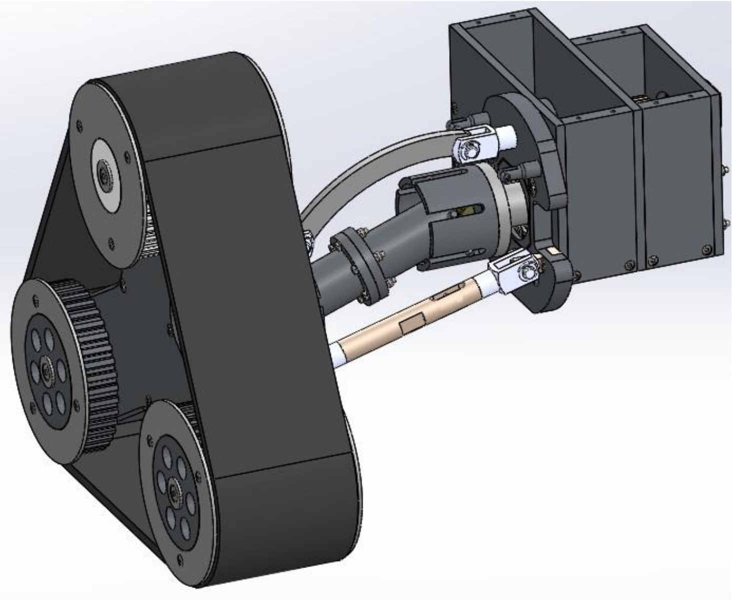

Figure 3.7: Gearbox And Wheel Connection with Balance Arms

4. SUSPENSION SYSTEM

In this section, required spring constant k of the spring that will be utilized in the suspension system will be found with respect to the given constraints. Since the platform can overcome obstacles up to a maximum height of 130 mm, the lower part of the body must be higher than 130 mm above the ground. Thus the height was decided to be 140 mm between the bottom and the ground.

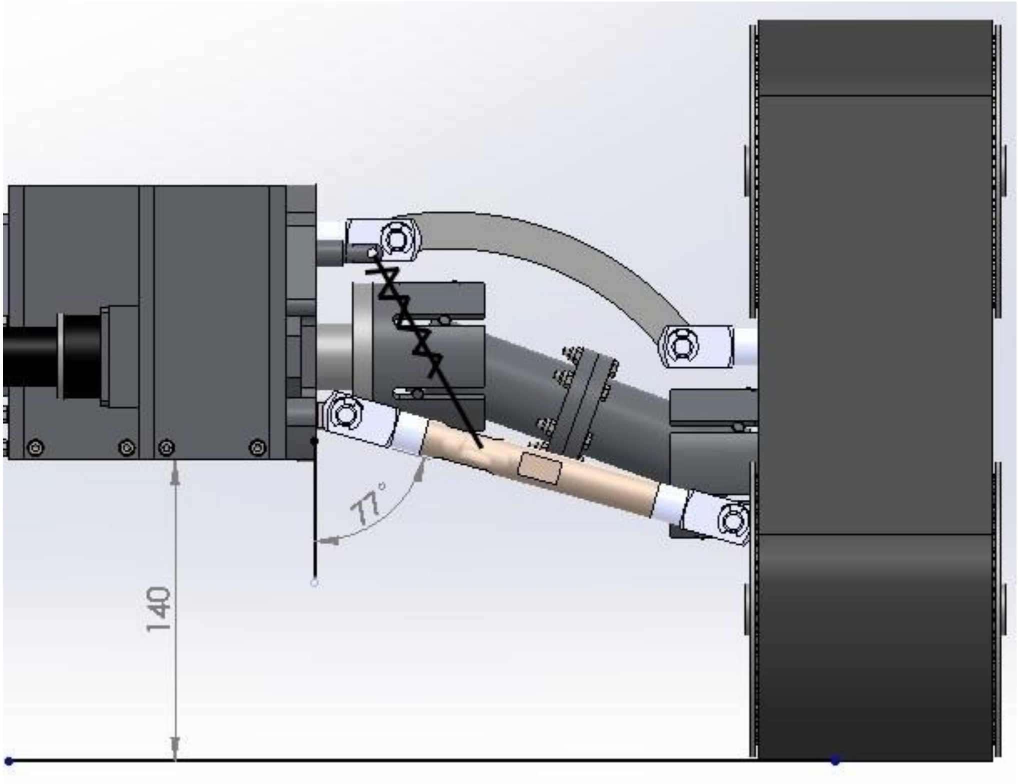

Figure 4.1: Platform Height From Ground

As the maximum possible total weight of the platform is 400 kg with the equipment on it, when at least three wheels are on contact with the ground, maximum weight carried by a single wheel will be 133,33 kg. As there will be dual suspension arms on single wheel, reaction forces from the ground will be divided and become 654 N at each wheel arm connection. Free body diagram of the system can be seen in Figure

4.2 where F_j is reaction force at joint, F_s is spring force and F_w is reaction force at wheel

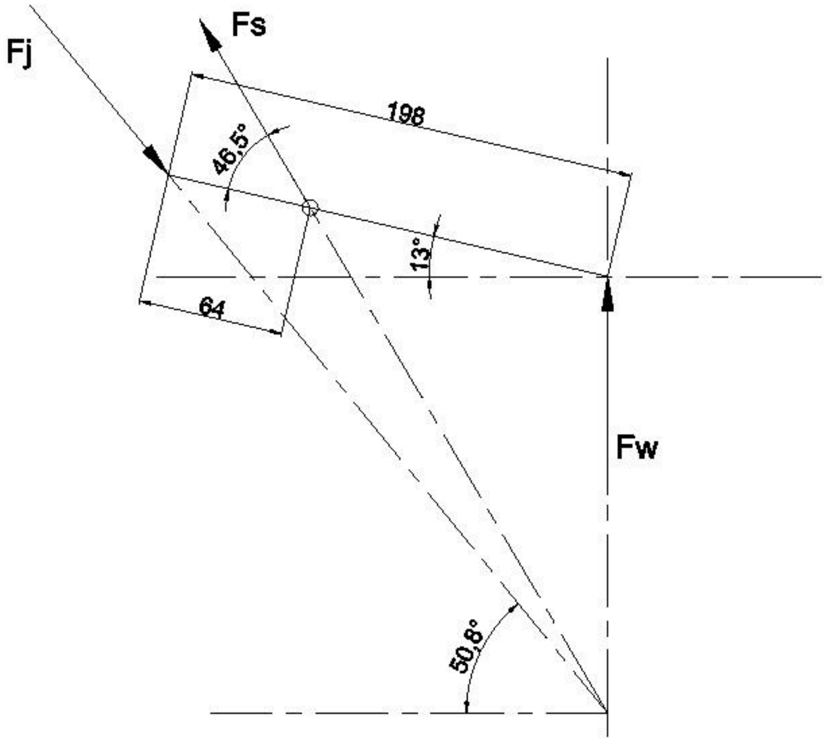

Figure 4.2: Free Body Diagram with Dimensions on Loaded Condition

$$\sum F_x = 0 \quad (4.1)$$

$$\sum F_y = 0 \quad (4.2)$$

$$\sum M_A = 0 \quad (4.3)$$

Using classical equilibrium equations on a three force member suspension arm and letting F_w=654 N, following equations can be written.

$$\sum F_x = -F_s \cos(46.5 + 13) + Fj \cos(50.8) \quad (4.4)$$

$$F_s = k.s_1 \quad (4.5)$$

$$F_j = \frac{k\, s_1\ \cos\,(59.5)}{\cos\,(50.8)} \quad (4.6)$$

$$\sum F_y = F_w - F_s \sin(46.5 + 13) + F_j \sin\,(50.8) \quad (4.7)$$

$$\sum F_y = 654 - k\, s_1 \sin(46.5 + 13) + \frac{k\, s_1 \cos(46.5{+}13) \sin(50.8)}{\cos(50.8)} \quad (4.8)$$

$$0 = 654 - k\, s_1\, 0.861 + k\, s_1\, 0.620 \quad (4.9)$$

$$k\, s_1 = 2713.69\, N \tag{4.10}$$

where s_1 is the displacement of the spring on loaded condition.

Due to the structural constraints, distance between the suspension connection points can be maximum 130 mm due to the designed cardan joint. Thus, the free length of the selected spring should be less than 130 mm. When the body of the platform stays at 140 mm on its fully loaded condition from the ground, distance between the suspension connection points becomes 103,5 mm.

In order to continue for the calculations, unloaded ground clearance of the platform was also decided to be 180 mm where the distance between the suspension connection points becomes 113,5 mm. Figure 4.3 shows the position of the unloaded platform.

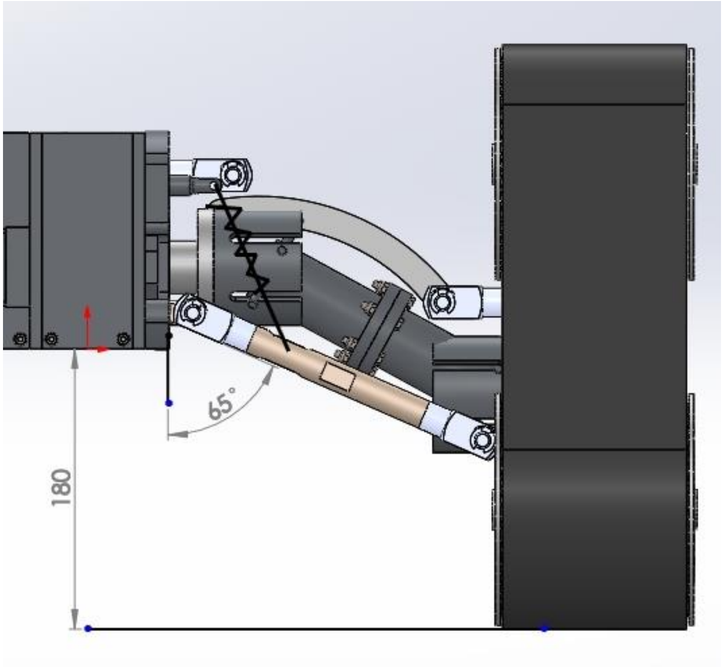

Figure 4.3: Platform Height From Ground Without Equipments On It

As the total weight of the platform is 200 kg without any equipment on it, when at least three wheels are on contact with the ground, the maximum weight carried by a single wheel will be 66,66 kg. As there will be dual suspension arms on single wheel, reaction forces from the ground will be divided and become 327 N at each wheel arm connection. Free body diagram of the system can be seen in Figure 4.4.

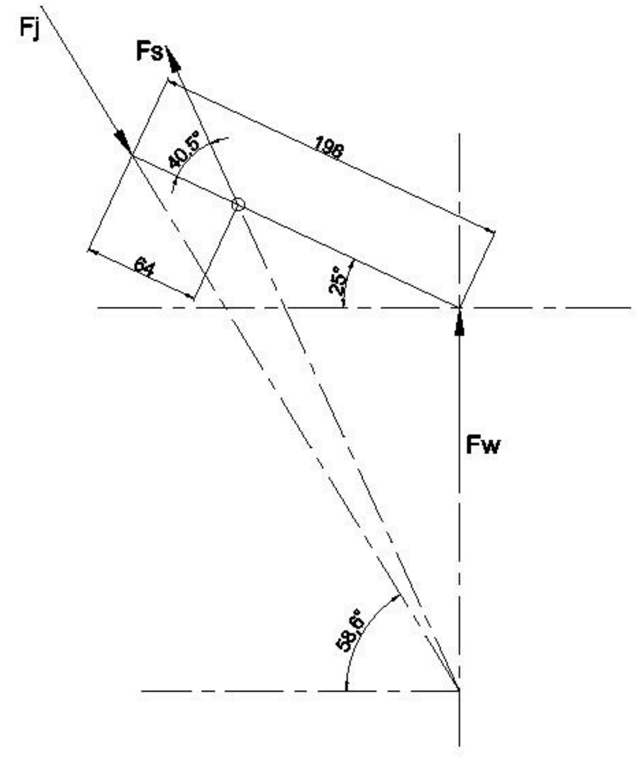

Figure 4.4: Free Body Diagram With Dimensions

Using similar calculations spring force in this configuration can be calculated as,

$$k\ s_2 = 1409{,}48\ N \tag{4.11}$$

As there exists 10 mm difference between the suspension connection points for two distinct situations, Equation 4.11 can be rewritten in following form

$$Fs_2=k\ (s_1-10)) \tag{4.12}$$

Using Equations 4.10 and 4.12, spring constant k can be found as k = 130.42 N/mm.

5. CONCLUSION

In this thesis, a reconfigurable mobile platform that can be utilized for various terrains was proposed. Througout the thesis structural design of the mobile platform that can adapt different terrain conditions and avoid obstacles within its path by changing its structural configuration was carried out. Reconfigurability of the system was provided by the idea of motion modules that can be reconfigured with respect to various needs during cruising. Design constraints of the proposed mobile platform, such as maximum speed, payload, operation conditions and etc. were determined by considering the properties of the existing commercial mobile platform designs in the literature including their advantages and disadvantages for different terrains. During the study necessary details for the related structural and dimensional design of transmission systems were given along with the concepts of mechanisms that were required for adaptability. Also informations about actuator selection and suspension systems were provided.

In the first proposed mobile platform design, gearboxes and wheels were connected directly to each other. On the other hand, this configuration failed during the locomotion simulation runs on rough terrains. Thus during the study the first design was modified so that it could be improved by replacing the rigid connection with the suspension system due to the excessive swing of the platform on rough terrain.

At the end of the study considering the selected materials, components and actuators desired design constraints were compared by the reached ones that can be seen in Table 5.1.

Table 5.1: Comparison of Design Constraints

	Design Constraints	Final Design
System Weight	200 Kg	186 Kg
Maximum Passable Obstacle Height	130 mm	130 mm
Maximum Speed	5-10 km/h	7.5 km/h
Maximum Payload Capacity	200 Kg	260 Kg

In order to verify the constructability of the proposed locomotion system, a small prototype of the half motion module was manufactured by using rapid prototyping.

Figure 5.1: Gearbox in Wheel Bearing Assembly and Gear Assembly

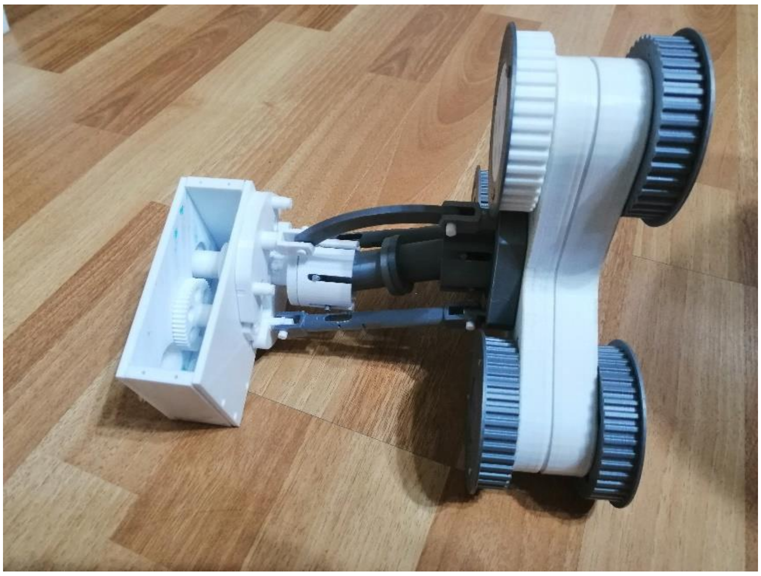

Figure 5.2: Half Motion Module

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