DUAL MOBILE ROBOT:
ADAPTABLE MOBILITY SYSTEM

by

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for the degree of Doctor of Philosophy
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This thesis presents an adaptive and reconfigurable mobile robot: the Dual Mobile Robot (DMR). It is driven by two adaptive track-wheel driving modules that combine wheels and tracks to allow real-time interchangeability according to terrain condition. The DMR can automatically convert from a wheel-based robot into a track-based robot by rotating the track-wheel driving modules by 90 degrees, either only tracks or wheels contact with the ground without any interference. It can be driven as a wheel-based robot when operating over a paved road to achieve higher speed and low energy consumption, and as a track-based robot over uneven terrain. In addition, unlike most state-of-the-art mobile robot designs that have an integrated architecture, this design provides a modular architecture which allows modifications and upgrades to be performed via simple replacements or local changes of modules.

To establish the modular architecture, this research utilized a unique design paradigm,
“Design for product adaptability”. A function-based design process for product adaptability has been conducted in the conceptual design stage. By following the design process, two types of design alternatives of the DMR have been created. After the best product configuration was chosen through evaluation and prioritization, the selected configuration has been implemented by detail design.

The DMR prototype was developed and tested to demonstrate its adaptability and advanced mobility functions in real-world environments. The experimental results successfully validated the hypothesis of the proposed robot with its track-wheel interchangeable ability, significantly exceeding the capability of other existing systems.
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To my wife Xia and my Family
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CHAPTER 1

INTRODUCTION

1.1 Motivation

Mobile robots have become increasingly present in human-related activities either to remove the hazards, or to carry large and critical payloads safely. In the past decade, both industry and academia have become more responsive to developing new designs for mobile robot platforms with better functionality, quality and features. At the present, there is a focus on designing robots with the capability of traveling over a variety of surfaces, carrying a range of payloads, changing into different configurations by modularity of structure and interface, and fast recovery from accidental rollover or getting stuck. Today, most of the current mobile robot platforms still cannot fulfill the said features due to a fixed structure (as opposed to modular and adaptive structure) of its locomotion system and chassis design.

Majority of the current mobile robot platforms (commercially available and made-for-research) are either wheel or track-based. Wheels are suitable for motion over smooth, plain terrain at high speed, whereas tracks are suitable for motion over unstructured terrain, stairs, and ditches at slow speed. Some mobile robots allow the user
to manually re-configure tracks over the wheels, but usually only one option of mobility
is available at a time. There is an inherent limitation in the use of either type of mobile
robot in that the terrain must be known beforehand. What is needed is an adaptable
mobile robot capable of maneuvering over unstructured or smooth terrain without the
need of manual re-configuration while optimizing speed and energy consumption. This
can be achieved with the use of an adaptive wheel and track mobility.

For locomotion, most existing mobile robots have a track-based or wheel-based drive
train, battery power source, radio frequency communication and control system.
Normally, electric motors, transmissions, battery and control systems are placed in a
compact layout within the chassis; however, functionality of existing mobile robots is
limited to the capability of their components and accessibility to change components with
ease is not provided. Adding or replacing components often causes incompatibility issues,
thus integration of additional components and upgrades are often difficult, and require
redesign of the entire robot. Also, the failure of one component in a traditional mobile
robot may render the entire unit useless.

Regardless of the application, mobile robots are expensive units, and their acquisition is a
serious decision. As such, mobile robots capable of multi-use and multitasking would be
advantageous. Furthermore, there is a need to navigate over various terrains, and the
assumption is that a mobile robot with modular, re-configurable and adaptive drives
would provide more flexible locomotion. Moreover, with the mobile robot being re-configurable in real-time, the state-of-the-art would provide the users a higher level of use of technology. Therefore, the focus of the reported research is to design a mobile robot that is suitable for different scenarios, such as traveling over various surfaces, carrying variable payloads, while being modular and structurally reconfigurable.

This research presents a new approach to mobile robot design for a wide range of applications and practical situations. This work is to develop an adaptive and reconfigurable mobile robot that is driven by two adaptive track-wheel driving modules for various outdoor and indoor terrains. It can be driven as a wheel-based robot when operating over a paved road to achieve higher speed and low energy consumption, and as a track-based robot over uneven terrain. In addition, the modular architecture of the proposed dual mobile robot allows modifications and upgrades to be performed via simple replacements or local changes of modules. This research does not attempt to design a novel mobile robot for any specific application, as it is aimed to present a generic modular mobile robot system that can be used in various applications on different terrains with proper modifications.

1.2 Objective

The objective of this research is to develop an adaptive and reconfigurable track-wheel mobile robot to overcome some drawbacks of current commercially or made-for-research
mobile platforms, such as the lack of adaptability to various terrains, difficulty in module reuse and component upgrade, and poor extendibility of functions. In addition, this research introduces a unique design paradigm of “Design for Product Adaptability” [1]. This is used to enhance the ability of mobile robot to be adapted for various uses in different environments.

The work presented covers conceptual system development, modeling and control system design, and design of a physical prototype of the proposed Dual Mobile Robot (DMR). The DMR was developed and tested to demonstrate its adaptability and advanced mobility functions in real-world environments. The experimental results successfully validated the hypothesis of the proposed robot with its track-wheel interchangeable ability, significantly exceeding the capability of other existing systems.

1.3 Overview of the Thesis

The thesis is organized as follows. Chapter 2 provides a background of current mobile robots and a literature review on Adaptable Design. Several mobile robots with various types of locomotion methods such as wheels, tracks, legs and hybrids are reviewed. Two types of track-wheel mobile robots: reconfigurable and adaptive, are classified and discussed. Existing issues and proposed solutions are summarized as well. Chapter 3 presents the concept of the proposed DMR and its key innovative features. Chapter 4 summaries the design process that is based on the adaptable design method, which was
introduced in the conceptual design stage. By following the design process, two DMR
design candidates are created; both are adaptable and fulfill the design requirements.
These design candidates are judged and the best design candidate is chosen by an
evaluation and prioritization process that is described in Chapter 5. Chapter 6 illustrates
the mechanical design architecture and presents the detailed design. Chapter 7 presents a
low cost and reliable control system design of the DMR. Two types of operator control
modes are described. The results and experiments using the full functional prototype are
discussed in Chapter 8. Various configurations of the DMR prototype have been set up to
show its product adaptability. A range of mobility modes and maneuvers that can be used
in different applications are demonstrated successfully to validate the original hypothesis.
Chapter 9 provides the conclusions and future work on this research.

1.4 Contributions

The contributions of this work fall into three categories: adaptive track-wheel driving
system, new mechanism designs, and modular architecture for mobile robot.

1. The main contribution of this work is the development of a novel adaptive track-wheel
driving system for mobile robot that allows real-time interchangeability according to user
commands based on the terrain condition in order to increase the efficiency of the robot
on different terrains. Currently, the wheels are mounted parallel to the tracks in most of
the existing adaptive track-wheel mobile robots [2] [3] [4] [5]. In addition, wheels and
tracks share the same drive system and drive synchronously all the time. Compared with the parallel layout of tracks and wheels, the track-wheel driving module which was developed in DMR has a different layout, as shown in Fig 1.1. Since the wheels are mounted perpendicular to the tracks, the DMR can automatically convert from a wheel-based robot into a track-based robot by rotating the track-wheel driving modules by 90 degrees. In this case, the DMR is an adaptive track-wheel hybrid mobile robot, either only tracks or wheels contact with the ground without any interference.

![Fig. 1.1: Comparison of parallel layout and perpendicular layout of tracks and wheels](image)

2. The innovative perpendicular layout of tracks and wheels has been achieved though the designs of several new mechanisms:

(1) The dual drive system has one traction motor on each side. It can provide wheel and track driving modes with different gear ratios. Unlike the parallel layout of tracks and wheels which requires to drive both wheel and track at the same time, the dual drive system in DMR drives either wheel or track at a time which eliminates the unnecessary
power consumption.

(2) The track-wheel driving module has a hubless rear wheel that solves the challenge of having drive axes of wheel and pulley at 90° to each other in a compact space.

(3) Swing arm mechanism (flipper, as the shorter name) is attached at the front of track-wheel driving module enhances locomotion. The swing arm can work as lift mechanism to help the robot overcome obstacles in track mode. It also can act as an independent steering system in the wheel mode.

3. Most of mobile robot designs have an integrated architecture, thus when adding or replacing components often incompatibility issues occur. This research proposes a modular architecture for mobile robot that is preventing changes of parts to interfere with the rest of the system. Bus and sectional interfaces among modules have been specially designed. Therefore modifications and upgrades are performed via replacement or local changes of modules. In addition, the locomotion system of DMR can be manually reconfigured and upgraded as track-based, wheel-based, or track-wheel interchangeable for different applications.
CHAPTER 2

BACKGROUND

Mobility is an essential characteristic of mobile robots which enables them to successfully complete tasks. The ability of mobile robotic platform to navigate over uneven terrain, such as asphalt in cities, a corridor in buildings, over carpets, or in water, mud, grass, snow, smoothly and efficiently is a challenge. There are numerous designs of mobile robots that are mainly based on wheel mechanisms, track mechanisms or hybrid mechanisms, such as High-impact Survivable Robot [6], Care-O-bot 3 [7], SPIDAR [8], ExoMars [9], CRAB [10], Shrimp [11], NUGV [12], Warrior 700 [13], TALON [14], HTV [15], VGT [16], Versatrax [17], HMR [18], HUR [19], CoMoRAT [20] and AZIMUT [21].

Wheeled robots have high velocity and can save energy than track-based robots. Although wheels are the most common form of locomotion and mechanically simple, they perform poorly on uneven terrain and stairs. Obstacles with height of more than the radius of the wheels will cause difficulty, unless the wheels are mounted on the pivoting legs [22]. For instance, some current planetary rover locomotion subsystems are based on bogie system to improve their ability to navigate uneven terrain. Though this passive suspension concept provides a lightweight design, it does have limitations. The rocker-bogie was originally
designed as a rigid mechanism for very small, slow rovers such as Rocky IV [23]. The rocker-bogie system does not step over obstacles as much as climb over them after impact [24]. This is not a problem when operating at low speed, but can result in large forces to the chassis and payloads when speed increases. When scaled up for a larger mobile robot, significant compliance had to be designed into the rocker arm so that it could absorb the larger driving loads [25]. As well, the need to climb over obstacles that are more than the wheel diameter is not apparent when used on a mobile robot with large wheels. Analysis has shown that the rocker-bogie is more limited than a standard four-wheel drive vehicle when it comes to slope climbing [26]. For larger mobile robot, the ability to climb over boulders does not justify the extra mass of the linkages, drive and steering motors, and the increased complexity of a six wheels design.

In unstructured environments, the locomotion system of mobile robot must be able to overcome both regularly shaped obstacles such as stairs and those of an unspecified shape such as rocks, downed trees and other miscellaneous objects. Tracked robots with high propulsion and tracks can easily negotiate larger obstacles and are less susceptible to environmental hazards. Additionally, tracked robots can quickly and smoothly climb stairs up to 45 degrees by using flipper mechanisms (Tracker [27], PackBot [28]). They can be used in both outdoor and indoor environments. However, tracked robots consume more energy than wheeled robots, and are unable to increase speed significantly when road
conditions are good.

Legged robot represents an alternative to traditional wheeled and tracked robot [29] [30]. Legged robots can provide sufficient adaptability for many real-world terrain conditions, but also require extremely complex control algorithms to manipulate multiple degrees of freedom for each leg. In addition, multiple legs bring high manufacturing costs and have higher peak power and torque requirements than wheeled and tracked robots. It is possible to obtain the advantages of both traditional wheeled and legged systems by combining these into a hybrid wheeled-leg robot, such as PAW [31], JPL “ATHLETE” [32], Roller-Walker [33]. However, the disadvantages of legged robot such as complex control algorithms and high power requirements will still affect the hybrid wheeled-leg robot [34].

2.1 Review of Track-Wheel Hybrid Mobile Robots

Since the legged locomotion has many disadvantages in high mechanical and control complexity, relatively low speed, low reliability and possibility of high maintenance requirements, legged locomotion is opted out. Several types of track-wheel hybrid mobile robots have been developed to navigate quickly on flat ground and have ability of climbing stairs and large obstacles. In this case, combining the tracked and wheeled locomotion together will increase the advantages of both locomotion mechanisms.

Track-wheel hybrid mobile robots are categorized into two classes: the manually
reconfigurable track-wheel robots and the adaptive track-wheel robots. The manually reconfigurable track-wheel robots are usually available in wheeled or tracked configurations. The wheel or track system can be changed by user, with quick snap on or bolt on tools. The adaptive track-wheel robots are comprised of wheels for driving on flat floor and tracks for it to effectively overcome obstacles in the same system.

**Manually Reconfigurable Track-Wheel Mobile Robots**

MMP-30 mobile platform from The Machine Lab provides a conversion system for manually converting a wheeled robot to a tracked robot [35]. It is available in pneumatic wheel or tracked configurations, as shown in Fig. 2.1. Track drive sprockets are designed with spiraled flexible spokes to absorb impacts before they translate into the drive train or electronic components. Wheels are rugged nylon split rims with pneumatic rubber all-terrain tires and inner tubes.

![MMP-30 mobile platform from The Machine Lab](image)

**Fig. 2.1:** MMP-30 mobile platform from The Machine Lab

Dragon Runner SUGV [36] [37], as shown in Fig. 2.2 has a reconfigurable robot chassis as
well. A wheel or sprocket is attachable to and removable from each drive shaft. When tracks instead of wheels are desired, wheel and wheel adapter in the each corner can be removed by removing four screws securing wheel adapter to chassis and replaced by sprocket and track hub adapter. Then track can be located and wrapped around sprockets. In addition, track extenders and longer track also can be installed for climbing stairs. However, the angle of track extender can only be adjusted manually.

![Fig. 2.2: Dragon Runner SUGV from QinetiQ North America](image)

Tracker, developed by Engineering Services Inc., is a step forward in reconfigurable track-wheel mobile robot [38]. Tracker can be manually converted into pneumatic wheel or variable track configurations, as shown in Fig. 2.3. In variable track configuration, Tracker allows user-controlled terrain adaptability to be performed with variable tracks configuration technology to suit real-time surface conditions. The variable tracks configuration is provided by simultaneously positioning a pair of planetary wheels whose location is controlled precisely by a proprietary track configuration-controlling
Adaptive Track-Wheel Mobile Robots

Remotec Andros F6A [2] is an adaptive track-wheel mobile robot with articulated tracks and quick release wheels shown in Fig. 2.4. The platform consists of a main chassis with two main tracks, two front auxiliary tracks, two rear auxiliary tracks and four wheels. The auxiliary tracks can be raised or lowered individually to allow the robot to climb over large obstacles and move up and down stairs. The articulating track system is used to traverse rough terrain. On the other hand, the pneumatic wheel is for navigating on benign environment. The diameter of pneumatic wheel is larger than the height of track to eliminate the track's contact length during wheeled navigation. When four pneumatic wheels install beside the articulated tracks, four wheels are contacted with the ground without considerable friction between tracks and the ground to reduce energy consumption.
However, due to the parallel layout of tracks and wheels, the traction motors have to drive six tracks and four wheels all the time. Track load added from the mass of six tracks is not eliminated during wheeled navigation. In addition, the larger wheel will interfere with the stair steps and cause unsmooth climbing and descending.

![Remotec Andros F6A from Northrup Grumman](image)

**Fig. 2.4:** Remotec Andros F6A from Northrup Grumman

Kim et al. proposed a new track-wheel hybrid robot platform with transformable track which is able to perform fast navigation in flatland and stairs. Track arms installed in the front, rear, and side of the robot are used for mode change of the transformable track between floor navigation and stair-climbing [3] [4]. Fig. 2.5(a) shows shapes for wheel driving where the tracks on the left and right side of the robot are folded and the four wheels are in contact with the flat surface. In this case, the robot can drive on the flat surface rapidly. Track drive mode for ascending stairs is represented in Fig. 2.5 (b). In this configuration, two tracks are unfolded and enclose the four wheels. Therefore, only two
tracks are in contact with the ground. In this case, the robot goes upstairs and downstairs stably using the two tracks. Kim's hybrid robot platform solved the wheel interference issue of Remotec Andros F6A by using transformable track. Nevertheless, the linkage mechanism of the transformable track limits the flexibility of the track itself. The front and rear end of tracks can only be raised up to 36 degrees and is incapable of providing a lift mechanism using the ends of the tracks. Furthermore, since Kim's hybrid robot platform is still based on parallel layout of tracks and wheels, the track load added from the mass of tracks is not eliminated during wheel mode navigation [3].

![Fig. 2.5: Track-wheel hybrid robot platform proposed by Kim et al.](image)

Amoeba-III is a robot with the self-adaptive mobile mechanism [39] [40]. It consists of a control system unit and two symmetric transformable track-wheel units. The robot can efficiently drive over the rough terrain by changing autonomously the mode of locomotion and transforming the track configuration without any sensors. As shown in Fig. 2.6 (a), during the wheel mode, when the robot moves on the flat surface, the mobile mechanism is
in contact with the ground by the wheels and tracks which is tangent to the ground. The track-wheel unit can make the front adjusting link rotated to change the mode of mobility between wheel mode and track mode, and to transform the track configuration to generate various attack angles to cope with diverse obstacles, as shown in Fig. 2.6 (b) and (c). Compared to Remotec Andros and Kim's hybrid robot platform, Amoeba-III has the same limitations on wheel interference while overcoming obstacles, and additional track load in wheel mode. Similar to the mechanism of Kim’s robot, Amoeba-III is incapable of performing a lift function to the ends of the tracks.

![Amoeba-III proposed by Li et al.](image)

**Fig. 2.6:** Amoeba-III proposed by Li et al.

### 2.2 Review of Research on Adaptable Design

Although many existing mobile robots claim as a modular design [8] [13] [15], most of them have an integrated architecture. Motors, transmissions, battery and control systems
are placed inside the chassis. However, functionality of existing mobile robots is limited to the capabilities of their components. Adding or replacing components often causes incompatibility issues. Thus, integration of additional components and upgrades are often difficult, and require redesign of the entire robot. Also, the failing of one component in a traditional mobile robot often renders the entire unit useless. Moreover, purchasing a new robot for different locomotion systems is not feasible both in terms of money and time. Unlike reconfigurable track-wheel mobile robots, many adaptive track-wheel mobile robots cannot reconfigure into either wheel mobile robot or track mobile robot due to their highly integrated architecture.

In recent years, a new approach of product design, namely Adaptable Design (AD), for efficient and effective product design considering functionality, manufacturing efforts, customization and environment friendliness was introduced [41] [42].

Adaptable design is a design paradigm for both economical and environmental benefits. The underlying philosophy of adaptable design is the ability of product to adapt to new requirements and the reuse of a product and design when requirements are changed. Adaptable design is conducted through replacement of multiple products by one adaptable product with a set of add-on accessories and/or attachments. Three key elements need to be addressed in adaptable design: independence of functions, evaluation of adaptability, and a process of adaptive design based upon functions of the product [41].
Adaptable design is different from modular design, although modularization is primarily used in adaptable design for increasing adaptability. Adaptable design can provide: (1) modular architecture of the product which can be reconfigured without breaking it into its constituent subsystems; (2) extra features and functionalities in a design for possible future needs; (3) compatibility among subsystems through standardization and generic forms of interfaces. Both adaptable design and modular design use modularization for upgrading and customization.

Hashemian and Gu established the framework of adaptable design [41]. They defined the term of adaptability in adaptable design and then categorized various types of adaptabilities from different views, such as design adaptability and product adaptability, specific adaptability and general adaptability, etc. They also discussed the benefits of adaptable design from perspectives of users, producers and environment. In this framework, a method has been developed for assessing the adaptability of a design based on the amount of “saving” which is achieved via adaptation. However this measurement could not measure the adaptability of a design based on its architectures. They also provided a brief methodology for adaptable design in which specific adaptability is designed based on forecast information and then general adaptability is achieved by a set of guidelines to increase the adaptability of the design to unforeseen changes.

Based on the previous framework in adaptable design, continuous efforts have been made
towards the development of adaptable design in depth. Xu et al. presented a framework of design method and realization for adaptable product design and manufacturing [43]. Li et al. developed the adaptable design method and Li further detailed the design process for product adaptability into six major steps [44]. Gu et al. and Hashemian developed a method to measure specific product adaptability by comparing the relative efforts of product adaptation and new product creation [41]. Li et al. extended this specific product adaptability evaluation method by considering three types of product adaptation tasks: extendibility of functions, upgradeability of modules, and customizability of components [45]. Fletcher et al. developed a method to quantify general product adaptability [46].

In addition, Shao et al. extended the adaptable design into product family-based adaptable design (PFBAD) [47]. Based on the market segment theory, a novel metric for the adaptability of PFBAD was proposed. This metric can be further used to optimize the product family and product platform. Several applications of adaptable design have been presented.

### 2.3 Issues and Proposed Solutions

This thesis proposes an adaptive and reconfigurable track-wheel mobile robot which is developed under the Adaptable Design methodology for arriving at product adaptability of mobile robots. By utilizing its track-wheel driving system and modular architecture, the DMR will overcome the drawbacks of traditional platforms, and provide advantages of adaptability as follow:
(1) Issue. Current design architectures of most mobile robots have an integrated architecture. Adding or replacing components often causes incompatibility issues and conflicts. Thus, the integration of additional components and upgrades are often difficult and require redesign of the entire robot, resulting in high cost and long development and implementation time. Also, the failure of one component in a traditional mobile robot may render the entire unit useless.

Approach to solution: The proposed dual mobile robot is based on a modular architecture which is able to prevent changes in some parts of the robot from interfering with the rest of it. The DMR is modularized and modifications are performed via replacements or local changes of modules.

For instance, the locomotion system of the DMR can be selected and upgraded among track-based, wheel-based and track-wheel interchangeable configurations for different applications and budgets. The user can modify the existing DMR from track-based configuration into track-wheel interchangeable configurations rather than buying a new robot, thus reducing the cost to achieve the required functions.

(2) Issue. When the circumstances change, new functionalities may be needed, or more efficient technologies of mobility must be utilized, and the current operational mode of the mobile robot may no longer be satisfactory. A new design or product needs to be developed due to integrated architecture.

Approach to solution: The design of the DMR, its associated process plans, manufacturing set-ups, and even existing parts and assemblies can be used to produce different robots, thereby reducing manufacturing cost and time. The supplier could gain a
marketing advantage due to user benefits from product adaptability.

(3) Issue. Many current mobile robots are either track-based robots or wheel-based robots, each with their own advantages and disadvantages. Some track-wheel hybrid mobile robots attempt to obtain the advantages of both locomotion systems, but there are still limitations. As discussed in Section 2.1, reconfigurable track-wheel hybrid mobile robots require manual conversion into wheel or track configurations. Most of the adaptive track-wheel mobile robots are based on parallel layout of tracks and wheels which has limitations on wheel interference while overcoming obstacles and additional track load during wheel mode.

Approach to solution: Track-wheel driving module with the unique perpendicular layout of tracks and wheels is developed in the DMR. The wheel and track are driven separately with the same motor and diverse gear ratios to eliminate the additional unnecessary power consumption during different modes. Furthermore, the DMR can automatically convert from a wheel-based robot into a track-based robot by rotating the track-wheel driving module 90 degrees thus eliminating any interference.

(4) Issue. The disadvantages of some wheel-based robots are their inadequate ability to overcome obstacles and properly steer the platform. Some track-based robots are incapable of providing a lift mechanism using the ends of the tracks.

Approach to solution: A swing arm which is driven by a motor is designed at the front of track-wheel driving module of the DMR. It has two functions in two modes. In wheel mode, the swing arm acts as a steering system of the platform. This type of steering system
will smooth the robot mobility in comparison to differential steering which is used in many current mobile robots. In track mode, the swing arm is working as a lifting mechanism. It can lift the robot’s nose up to climb stairs and overcome obstacles.
CHAPTER 3

DESIGN CONCEPT

3.1 Introduction

This thesis introduces a new design paradigm for mobile robots. The design approach is systematic and practical. The novel concept design process and design evaluation tools are presented in Chapters 4 and 5. The proposed design is a new modular mobile robot that overcomes some basic drawbacks of current commercially or made-for-research mobile robots, such as lack of adaptability to various terrains, difficulty in module reuse and component upgrades, poor extendibility of function.

Section 3.2 provides the concepts of the proposed mobile robot. Section 3.3 discusses how the concepts are implemented in the design, and presents the key innovative features. Product adaptability is defined in details in Section 3.4. The embodiment design of specific product adaptability and general product adaptability in the proposed mobile robot have been discussed in Section 3.5.

3.2 Description of DMR Design Concept

The proposed design of DMR is an adaptive and reconfigurable mobile robot with dual drive system that combines wheels and tracks to allow real-time interchangeability
according to terrain condition. The modular and dual drive concept of the DMR is unique and provides all-purpose mobility for the mobile robot platform. The concept is based on the realization that mobile platforms must remain operational on a variety of terrains, in particular when the terrain is not known a priori. In some cases, a mobile robot platform may render itself only partially useful, as it tends to be used when the terrain is known so that the user can select a wheeled or a tracked platform as necessary.

There are circumstances in many practical applications where it is beneficial if a wheel robot can be converted into tracked robot and vice versa. If the terrain is unknown or unstructured, or there is a security mission in an urban setting that involves flat terrain (street) and stairs, a wheeled robot may be unsuitable and a tracked robot may be too slow if the distance to travel is large. What is needed is a mobile robot that can be easily and quickly adapted in-flight to either, unstructured or smooth terrain, for low and high speed, respectively.

The special feature of DMR is the track-wheel driving module that provides real-time interchangeability to various outdoor and indoor terrains. It can be driven as a wheeled robot when operating over a paved road to achieve higher speed and low energy consumption, and as a tracked robot over uneven terrain and obstacles.

In addition, DMR is based on a modular architecture of self-contained and relatively independent driving modules that can be attached, detached, modified, relocated, and
replaced easily in relation to a platform. It allows attachment of parallel modules for higher drive power, and inclusion of add-on accessories (cameras, sensors) on the mobile platform.

The proposed DMR is suitable for various situations, such as traveling over various surfaces, carrying variable payloads, and is structurally reconfigurable. It can generate new configurations for a wide range of applications, such as the applications of explosive ordnance disposal, search-and-rescue, surveillance, bomb squad, SWAT teams, and other vital tasks. Furthermore, user and manufacturers can benefit from this concept through the reuse of modules, for higher utilization and reduction of manufacturing cost.

3.3 Concept Embodiment

To illustrate the concept, Fig. 3.1 shows an exploded view of the proposed DMR. Between wheeled and tracked locomotion, each type has its own separate advantages and disadvantages as discussed before. However, during operation, a robot will not stay in one type of terrain at all times. In this case, combining the tracked and wheeled locomotion together will increase the effectiveness of the robot. Hence, the proposed robot can be configured as wheeled, tracked or dual drive between wheeled and tracked with real-time interchangeability.

Unlike most other mobile robot designs that have an integrated architecture, this design
provides a modular architecture which encourages the development of self-contained and relatively independent (or loosely connected) modules that can be modified easily. Moreover, DMR provides its modules for reuse with a different platform when new requirements are presented.

The DMR consists of four major components as shown in Fig. 3.1: 1) track-wheel driving module; 2) track-based driving module; 3) center platform; and 4) add-on functional attachments.

Fig. 3.1: The design of the dual drive mobile robot consists of four major components

The track-wheel driving module combines wheel and track which can be driven separately with the same motor. It also can be modified as wheel driving or track driving only. The
center platform houses the rotation mechanism, batteries, and other electronic components. It also provides the payload interface for add-on attachments.

The add-on attachments are specific units for different functions, such as a manipulator for handling hazardous items or manipulating suspected packages, camera with adjustable arm for surveillance and reconnaissance. The components and attachments are designed for easy installation by using payload interfaces. In addition, the track-based driving module is an add-on all-in-one track system which can be driven by its own electric power individually. The mobile robot platform can be reconfigured by attaching a pair of additional track-based driving modules to provide higher power for special task requirements.

The special feature of this design is that the track-wheel driving module can convert from a tracked robot into a wheeled robot by user command in 25 seconds and has potential to convert automatically based on sensory information in the future. For instance, in track mode, the tracks are driven by motors and the wheels are idling. The robot can quickly convert from a tracked robot into a wheel robot by rotating the track-wheel driving module 90 degrees. Fig. 3.2 shows the configurations of track mode and wheel mode of DMR.
Other features are a swing arm mechanism that is attached at the front of track-wheel driving module, as shown in Fig. 3.3. It has two functions in two modes. In wheel mode, the swing arm mechanism is acting as a steering system similar to car steering. In high speed, this type of steering can make the robot steering smoother than differential steering which is used in many current mobile robots. In track mode, the swing arm mechanism can be used as a flipper to lift the robot’s nose up to climb stairs and overcome obstacles.
3.4 Embodiment of Product Adaptability

In adaptable design [41], Product adaptability refers to the ability of a product to be adapted to various usages or capabilities. The adaptation task is usually carried out by users when they want to modify the product to achieve various functions or to enhance its performance [42]. Generally, users adapt products that have already been created or purchased. Therefore the product adaptability can be considered as the main attribute of the adaptable product.

Product adaptability can be classified into specific product adaptability and general product adaptability depending on whether planned information for specific adaptations is available [41]. When particular adaptability and its use is foreseen, the product can be designed to accommodate the specific product adaptability. For achieving some unpredictable requirements and changes, the product can be designed to have some general product adaptability by its product architecture and interfaces.

To achieve such general product adaptability, a modular architecture is designed to prevent the changes in one place from propagating into the rest of the product [41]. This modular architecture is normally composed by the self-contained and relatively independent assemblies or modules that can be detached, modified, relocated and replaced easily.

The center platform of DMR is modeled by a set of common components and interfaces
that are shared by a set of configurations to achieve multiple functions. General product adaptability is initiated by adding, substituting, and/or removing one or more add-on functional modules from the center platform.

Add-on modules, such as track-based driving module, manipulator, surveillance camera etc, can be changed according to changes of requirements and duties. These changes would not result in significant impact on the other parts of the existing DMR, since add-on modules are independent and self-contained.

Add-on modules also can be used to achieve extendibility of functions by changing add-on modules with different functions to obtain multiple functions in current configuration of DMR. Furthermore, they can be used to achieve upgradeability by replacing older modules with new ones to enhance performance and improve service time. Variants of add-on modules are designed to achieve customizability. The customer’s requirements can be accommodated with variants of add-on modules.

The physical connections among modules are specially designed so that the functional interactions among the modules permit easy assembly and disassembly. The adaptable interface is a special interface between center platform and an add-on module or among variants of add-on modules. By utilizing interfaces between the center platform and various add-on modules, the DMR can be created to accommodate customization and upgrading, as well as to achieve new functions by designing new add-on modules without changing
the rest of the whole mobile robot.

In the design of DMR, the functions of flipper, wheel drive and interchangeable between track drive and wheel drive have been foreseen and designed as specific product adaptabilities. Fig. 3.4 shows the specific product adaptabilities have been achieved by the DMR. The DMR utilizes a modular architecture and provides various types of interface design for different add-on modules to achieve general product adaptability. Fig. 3.5 shows several possible additional functions which can be achieved by adding add-on modules via interfaces in DMR.

Fig. 3.4: The specific product adaptabilities can be achieved by the DMR
Fig. 3.5: The general product adaptabilities can be achieved by the DMR
CHAPTER 4

DESIGN FOR PRODUCT ADAPTABILITY

4.1 Introduction of Design for Product Adaptability

This research introduces a unique design paradigm, “Design for Product Adaptability” [1] [44], into mobile robot design. It is expected that the research will lead to effective manufacturing in terms of customization, cost, service and maintenance. The design aims to provide multi-functionality through modularity and re-configurability. The proposed mobile robot will provide adaptability to terrains and operations, and effective use of energy.

The proposed approach is based on the Axiomatic Design Theory [48] and Adaptable Design paradigm [42]. A function-based design process for product adaptability has been conducted in the conceptual design stage. The design process for product adaptability is composed of five phases: function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design, as shown in Fig. 4.1.

By following the design process, several design candidates have been created, which all are adaptable and fulfill the design requirements. Therefore, a new method to evaluate design candidates, the grey relational analysis approach [45], was introduced. In this
approach, design candidates are evaluated by different life-cycle evaluation measures including specific product adaptability, part and assembly time of manufacturing, operationability of customers, etc. The grey analysis approach [49] is used to integrate the different evaluation measures for prioritizing different design candidates.

**Fig. 4.1:** The schematic of design process for product adaptability

This research has been investigating two types of design alternatives of the DMR. After the best product configuration was chosen through evaluation and prioritization, the selected configuration has been modeled analytically and investigated by simulation. It has been
also implemented by detail design. A prototype was used in the final stage of this research to validate experimentally the original hypothesis.

4.2 Design Process for Product Adaptability in DMR Development

To illustrate the effectiveness of the design process for product adaptability, the design process of DMR is provided in this section.

Function Modeling

Function modeling is an important step in systematic design. Paul and Beitz [56] suggest the main requirements need to be singled out and abstracted into physical functions. These functions are systematically decomposed into a functional structure. Then, the elements of the function structure are incrementally replaced by solution principles (function carriers). The decomposition and replacement of functions continue until all functions have been replaced by solutions [61]. However, the systematic design approach is a practice-oriented procedure. The quality of function modeling highly depends on designer’s experience [62].

To help designers achieve good results of function modeling naturally, the "function decomposition method" of the axiomatic design approach [48] is employed in this research. A functional requirement (FR) is usually decomposed into sub-FRs to divide a system into smaller, coherent, self-contained functional elements. The decomposition is performed only after a solution for the FR is found.
The uncoupled design and decoupled design satisfy the Axiom 1 in axiomatic design [48], i.e., the independence of FRs is assured if design parameters (DPs) are arranged in a certain order. Since the components and modules in an adaptable product need to be changed, all these components and modules should be designed as independent as possible to minimize potential propagation of changes. By using the axiomatic design as a guide, the product can be designed to satisfy the Axiom 1. This method can enhance both specific and general product adaptabilities by the independent structure.

According to analysis of the current mobile robots and a list of customer requirements, the solutions are generated based on the requirements of design functions. For instance, the high level of functional requirement for mobile robot is to transport sensors, tools and/or manipulators to any accessible and desirable location to perform a desired task. An all-terrain mobile robot platform is definitely the best solution.

In adaptable design, the product with specific product adaptability is designed to extend for better and/or extra functions. To design the product which has different extra functions, the designers must determine fundamental functions and adaptable functions at the conceptual design stage, and then decompose the next level of functional requirements to create detailed solutions/design concepts.

In the conceptual design stage of DMR, the first level function of transporting in outdoor rough terrain situation has been selected as the fundamental function. The functions of
transporting in benign environments, obstacles overcoming/climbing stairs and maximizing efficiency were determined as the adaptable functions. The functional requirement decomposition process is repeated to create detailed solutions level by level to establish the trees of functional requirements (FRs) and design parameters (DPs). Fig. 4.2 shows the trees of FRs and DPs at the high level and the first level.

**Fig. 4.2:** The trees of FRs and DPs at the high level and the first level

The first level of FRs and DPs are decomposed to make a hierarchy and a "zigzag mapping process" is used during the decomposition. The first level FRs and DPs are as follows:

**FR1**= Transport in outdoor rough terrain situation
**FR2**= Overcome obstacles and climb stairs
**FR3**= Transport in benign environments (indoor, paved road)
**FR4**= Utilize suitable drive system according to the terrain condition.

**DP1**= Track-based mobile robot platform
**DP2**= Flipper mechanism
**DP3**= Wheel drive system
**DP4**= Online interchangeable system

The first level of FRs and DPs are decomposed to make a hierarchy and a "zigzag mapping process" is used during the decomposition. The first level FRs and DPs are as follows:

**FR1**= Transport in outdoor rough terrain situation
**FR2**= Overcome obstacles and climb stairs
**FR3**= Transport in benign environments (indoor, paved road)
**FR4**= Utilize suitable drive system according to the terrain condition.

**DP1**= Track-based mobile robot platform
**DP2**= Flipper mechanism
DP3= Wheel drive system
DP4= Real-time interchangeable system from track drive to wheel drive

The design equation for first level of FRs and DPs can be written in terms of the FR vector, the DP vector, and the design matrix as shown below.

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
FR_4
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 & 0 \\
X & X & 0 & 0 \\
X & X & X & 0 \\
X & X & X & X
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
DP_4
\end{bmatrix}
\]

Based on the coupling analysis of first level FRs and DPs, it is a decoupled design.

The second level FRs and DPs and the off-diagonal coefficients in the detailed design matrixes are shown as follows:

**The decomposing of FR_2,DP_2**

FR\(_{11}\)= Provide support structure for all components and add-on modules
FR\(_{12}\)= Control mobile robot
FR\(_{13}\)= Provide energy for long operation time
FR\(_{14}\)= Provide traction

DP\(_{11}\)= Center platform
DP\(_{12}\)= Electronic control system
DP\(_{13}\)= Power supply
DP\(_{14}\)= Independent track-based drive module

\[
\begin{bmatrix}
FR_{11} \\
FR_{12} \\
FR_{13} \\
FR_{14}
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 & 0 \\
X & X & 0 & 0 \\
X & 0 & X & 0 \\
0 & X & X & X
\end{bmatrix}
\begin{bmatrix}
DP_{11} \\
DP_{12} \\
DP_{13} \\
DP_{14}
\end{bmatrix}
\]
The decomposing of \( FR_2,DP_2 \)

FR\(_{21}\) = Provide support structure for flipper mechanism  
FR\(_{22}\) = Provide motion  
FR\(_{23}\) = Limit the rotation range of flipper  

DP\(_{21}\) = Detachable flipper frame  
DP\(_{22}\) = Drive system  
DP\(_{23}\) = Limit switch  

\[
\begin{bmatrix}
FR_{21} \\ FR_{22} \\ FR_{23}
\end{bmatrix} = \begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{21} \\ DP_{22} \\ DP_{23}
\end{bmatrix}
\]

The decomposing of \( FR_3,DP_3 \)

FR\(_{31}\) = Provide wheel drive  
FR\(_{32}\) = Provide car-like steering  

DP\(_{31}\) = Rear wheel drive  
DP\(_{32}\) = Front wheel on flipper  

\[
\begin{bmatrix}
FR_{31} \\ FR_{32}
\end{bmatrix} = \begin{bmatrix}
X & 0 \\
0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{31} \\ DP_{32}
\end{bmatrix}
\]

The decomposing of \( FR_4,DP_4 (Alternative 1) \)

FR\(_{41}\) = Provide rotary motion to transform from track drive to wheel drive  
FR\(_{42}\) = Reduce speed and increase torque  
FR\(_{43}\) = Transmit rotary motion to rotation axis  
FR\(_{44}\) = Provide rotation axis and support  

DP\(_{41}\) = DC motor  
DP\(_{42}\) = Warm gear reducer  
DP\(_{43}\) = Roller chain system  
DP\(_{44}\) = Hinges
The decomposing of FR,DP (Alternative 2)

FR₄₁ = Provide linear motion to transform from track drive to wheel drive
FR₄₂ = Transmit linear motion to rotation axis
FR₄₃ = Provide rotation axis and support

DP₄₁ = Linear actuator
DP₄₂ = Slider-canks mechanism
DP₄₃ = Hinges

\[
\begin{bmatrix}
FR_{41} \\
FR_{42} \\
FR_{43} \\
FR_{44}
\end{bmatrix} = 
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{41} \\
DP_{42} \\
DP_{43} \\
DP_{44}
\end{bmatrix}
\]

The third level FRs and DPs and the off-diagonal coefficients in the detailed design matrixes are shown as follows:

The decomposing of FR₁₂,DP₁₂

FR₁₂₁ = Process commands and control motors
FR₁₂₂ = Receive commands

DP₁₂₁ = Master controller
DP₁₂₂ = 900MHz radio transmitter

\[
\begin{bmatrix}
FR_{121} \\
FR_{122}
\end{bmatrix} = 
\begin{bmatrix}
X & 0 \\
0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{121} \\
DP_{122}
\end{bmatrix}
\]

The decomposing of FR₁₃,DP₁₃
FR$_{131}$ = Store energy
FR$_{132}$ = Provide adequate power output

DP$_{131}$ = lithium-ion battery (20Ah)
DP$_{132}$ = Drivers for DC motor

\[
\begin{align*}
\{ FR_{131} \} &= X \quad 0 \quad \{ DP_{131} \} \\
\{ FR_{132} \} &= 0 \quad X \quad \{ DP_{132} \}
\end{align*}
\]

The decomposing of FR$_{14}$, DP$_{14}$

FR$_{141}$ = Provide support structure for track-based drive module
FR$_{142}$ = Provide adequate tension to keep the track in contact with the pulley
FR$_{143}$ = Provide large contact surface
FR$_{144}$ = Provide traction to two outputs

DP$_{141}$ = Chassis of drive module
DP$_{142}$ = Belt tension system
DP$_{143}$ = Trimming belt type track
DP$_{144}$ = Dual drive system

\[
\begin{align*}
\{ FR_{141} \} &= X \quad 0 \quad 0 \quad 0 \quad \{ DP_{141} \} \\
\{ FR_{142} \} &= X \quad X \quad 0 \quad 0 \quad \{ DP_{142} \} \\
\{ FR_{143} \} &= X \quad X \quad X \quad 0 \quad \{ DP_{143} \} \\
\{ FR_{144} \} &= X \quad 0 \quad 0 \quad X \quad \{ DP_{144} \}
\end{align*}
\]

The decomposing of FR$_{22}$, DP$_{22}$ (Alternative 1)

FR$_{221}$ = Provide rotary motion
FR$_{222}$ = Reduce speed and increase torque
FR$_{223}$ = Transmit rotary motion to front shaft

DP$_{221}$ = DC motor
DP$_{222}$ = Planetary gearhead
DP$_{223}$ = Bevel gears
\[
\begin{bmatrix}
FR_{221} \\
FR_{222} \\
FR_{223}
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{221} \\
DP_{222} \\
DP_{223}
\end{bmatrix}
\]

The decomposing of \(FR_{22},DP_{22}\) (Alternative 2)

- \(FR_{221}\) = Provide rotary motion
- \(FR_{222}\) = Reduce speed and increase torque
- \(FR_{223}\) = Transmit rotary motion to front shaft

- \(DP_{221}\) = DC motor
- \(DP_{222}\) = Harmonic drive
- \(DP_{223}\) = Roller chain

\[
\begin{bmatrix}
FR_{221} \\
FR_{222} \\
FR_{223}
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{221} \\
DP_{222} \\
DP_{223}
\end{bmatrix}
\]

The forth level FRs and DPs and the off-diagonal coefficients in the detailed design matrixes are shown as follows:

The decomposing of \(FR_{144},DP_{144}\) (Alternative 1)

- \(FR_{1441}\) = Provide rotary motion
- \(FR_{1442}\) = Split power output into 2 directions
- \(FR_{1443}\) = Select power output direction

- \(DP_{1441}\) = DC motor
- \(DP_{1442}\) = Spur gear set
- \(DP_{1443}\) = Electromagnetic clutches in parallel layout

\[
\begin{bmatrix}
FR_{1441} \\
FR_{1442} \\
FR_{1443}
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{1441} \\
DP_{1442} \\
DP_{1443}
\end{bmatrix}
\]

42
The decomposing of FR$_{144}$, DP$_{144}$ (Alternative 2)

FR$_{1441}$ = Provide rotary motion
FR$_{1442}$ = Split power output into 2 directions
FR$_{1443}$ = Select power output direction

DP$_{1441}$ = DC motor
DP$_{1442}$ = Bevel gears
DP$_{1443}$ = Electromagnetic clutches in perpendicular layout

\[
\begin{bmatrix}
FR_{1441} \\
FR_{1442} \\
FR_{1443}
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{1441} \\
DP_{1442} \\
DP_{1443}
\end{bmatrix}
\]

The detailed results of the proposed design (Alternatives 1 and 2) are summarized in Table 4.1 and 4.2.

**Table 4.1:** The detailed levels of FRs and DPs trees for modeling DMR (Alternative 1)

<table>
<thead>
<tr>
<th>High level of FR:</th>
<th>FR1 Transport In rough terrain</th>
<th>FR14 Provide Traction</th>
<th>FR21 Provide support structure for flipper mechanism</th>
<th>FR22 Provide motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR11 Provide support structure</td>
<td>FR121 Control motors</td>
<td>FR122 Receive commands</td>
<td>FR21 Provide support structure</td>
<td>FR221 Provide rotary motion</td>
</tr>
<tr>
<td>FR12 Control</td>
<td></td>
<td></td>
<td></td>
<td>FR222 Reduce speed and increase torque</td>
</tr>
<tr>
<td>FR13 Provide Energy</td>
<td>FR131 Store energy</td>
<td>FR141 Provide support structure</td>
<td>FR223 Transmit rotary motion to front shaft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR132 Provide power output</td>
<td>FR142 Provide adequate tension</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FR143 Provide large contact surface</td>
<td>FR23 Limit the rotation range of flipper</td>
<td></td>
</tr>
<tr>
<td>FR14 Provide Traction</td>
<td></td>
<td></td>
<td></td>
<td>FR23 Limit the rotation range of flipper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FR23 Limit the rotation range of flipper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FR23 Limit the rotation range of flipper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FR3 Limit the rotation range of flipper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FR3 Limit the rotation range of flipper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FR3 Limit the rotation range of flipper</td>
</tr>
<tr>
<td>Transport in benign environment</td>
<td>FR32 Provide car-like steering</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>--------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR4 Utilize suitable drive system</td>
<td>FR41 Provide rotary motion to transform between modes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR42 Reduce speed and increase torque</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR43 Transmit rotary motion to rotation axis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR44 Provide rotation axis and support</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High level of DP: All-terrain mobile robot platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP1 Track-based mobile robot platform</td>
</tr>
<tr>
<td>DP 11 Center platform</td>
</tr>
<tr>
<td>DP 12 Electronic control system</td>
</tr>
<tr>
<td>DP 121 Master controller</td>
</tr>
<tr>
<td>DP 122 900MHz radio transmitter</td>
</tr>
<tr>
<td>DP 13 Power supply</td>
</tr>
<tr>
<td>DP 131 lithium-ion battery (20Ah)</td>
</tr>
<tr>
<td>DP 132 Drivers for DC motor</td>
</tr>
<tr>
<td>DP 14 Track-based drive module</td>
</tr>
<tr>
<td>DP 141 Chassis of drive module</td>
</tr>
<tr>
<td>DP 142 Belt tension system</td>
</tr>
<tr>
<td>DP 143 Trimming belt type track</td>
</tr>
<tr>
<td>DP 144 Dual drive system</td>
</tr>
<tr>
<td>DP 1411 DC motor</td>
</tr>
<tr>
<td>DP 1412 Spur gear set</td>
</tr>
<tr>
<td>DP 1413 Electromagnetic clutches in parallel layout</td>
</tr>
<tr>
<td>DP 21 Detachable flipper frame</td>
</tr>
<tr>
<td>DP 22 Drive system</td>
</tr>
<tr>
<td>DP 221 DC motor</td>
</tr>
<tr>
<td>DP 222 Planetary gear head</td>
</tr>
<tr>
<td>DP 223 Bevel gears</td>
</tr>
<tr>
<td>DP 23 Limit switch</td>
</tr>
<tr>
<td>DP 31 Rear wheel drive</td>
</tr>
<tr>
<td>DP 32 Front wheel on flipper</td>
</tr>
<tr>
<td>DP 41 DC motor</td>
</tr>
<tr>
<td>DP 42 Warm gear reducer</td>
</tr>
<tr>
<td>DP 43 Roller chain system</td>
</tr>
<tr>
<td>DP 44 Hinges</td>
</tr>
</tbody>
</table>
Table 4.2: The detailed levels of FRs and DPs trees for modeling DMR (*Alternative 2*)

<table>
<thead>
<tr>
<th>High level of FR:</th>
<th>FR1 Transport In rough terrain</th>
<th>FR2 Overcome obstacles</th>
<th>FR3 Transport in benign environ.</th>
<th>FR4 Utilize suitable drive system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FR11 Provide support structure</td>
<td>FR21 Provide support structure for flipper mechanism</td>
<td>FR31 Provide wheel drive</td>
<td>FR41 Provide linear motion to transform between modes</td>
</tr>
<tr>
<td></td>
<td>FR12 Control</td>
<td>FR22 Provide motion</td>
<td>FR32 Provide car-like steering</td>
<td>FR42 Transmit rotary motion to rotation axis</td>
</tr>
<tr>
<td></td>
<td>FR121 Control motors</td>
<td>FR221 Provide rotary motion</td>
<td></td>
<td>FR43 Provide rotation axis and support</td>
</tr>
<tr>
<td></td>
<td>FR122 Receive commands</td>
<td>FR222 Reduce speed and increase torque</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR13 Provide Energy</td>
<td>FR144 Provide traction to two outputs</td>
<td>FR223 Transmit rotary motion to front shaft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR131 Store energy</td>
<td>FR141 Provide support structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR132 Provide power output</td>
<td>FR142 Provide adequate tension</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR14 Provide Traction</td>
<td>FR143 Provide large contact surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR141 Provide support structure</td>
<td>FR1411 Provide rotary motion</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR142 Provide adequate tension</td>
<td>FR1412 Split power output into 2 directions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR143 Provide large contact surface</td>
<td>FR1413 Select power output direction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High level of DP:</th>
<th>DP 11 Center platform</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DP 12 Electronic control system</td>
</tr>
<tr>
<td></td>
<td>DP 121 Master controller</td>
</tr>
<tr>
<td></td>
<td>DP 122 900MHz radio transmitter</td>
</tr>
<tr>
<td>DP1 Track-based mobile robot platform</td>
<td>DP 13 Power supply</td>
</tr>
<tr>
<td>DP 131 lithium-ion battery (20Ah)</td>
<td></td>
</tr>
<tr>
<td>DP 132 Drivers for DC motor</td>
<td></td>
</tr>
<tr>
<td>DP 14 Track-based drive</td>
<td></td>
</tr>
<tr>
<td>DP 141 Chassis of drive module</td>
<td></td>
</tr>
<tr>
<td>DP 142 Belt tension system</td>
<td></td>
</tr>
<tr>
<td>DP 143 Trimming belt type track</td>
<td></td>
</tr>
</tbody>
</table>
Adaptable Platform/Modular Design

Based on the information of DPs created from the previous step, the product architecture and interactions among modules can be generated by considering the modularity of the product using the four-step process method [50]. The first step is to create a schematic of the product by laying out the functional elements to represent the designer’s understanding about the product. For example, Fig. 4.3 and 4.4 show the functional elements of the proposed DMR from Alternatives 1 and 2.

And then, the elements of the products are grouped into modules. These modules form the assemblies of the product. And the dependency relations among these modules are initially
described by solid and dashed lines to represent different types of relationships. Fig. 4.5 and 4.6 show the clustered functional elements of the proposed DMR from *Alternatives 1 and 2*. 

![Functional Elements Diagram]

**Fig. 4.3:** The functional elements of the proposed DMR from *Alternative 1*
**Fig. 4.4:** The functional elements of the proposed DMR from *Alternative 2*
Fig. 4.5: The clustered functional elements of the proposed DMR from *Alternative 1*
Fig. 4.6: The clustered functional elements of the proposed DMR from *Alternative 2*
After the clustered functional structure has been developed, sketches were created for modeling alternative layouts of the product modules. Iterations are required during this step. Fig. 4.7 and 4.8 illustrate two types of rough geometric layouts of the proposed DMR. Track and wheel drive configurations are created by combining alternative modules. These layouts were created through a number of iterations.

When the rough geometric layout has been created, interactions between modules in the layout can be finally defined. The information of interactions will be used in the phase of adaptable interface design.

**Fig. 4.7:** The rough geometric layouts of the proposed DMR (*Alternative 1*)
Fig. 4.8: The rough geometric layouts of the proposed DMR (Alternative 2)

At the last, the conceptual result of product candidates can be modeled by an AND-OR tree based on the structures of product. The AND-OR tree structure is used to model the relationships among sub-structures with AND and OR relations. The customizable modules and upgradeable modules in the AND-OR tree are described by the symbols of C and U, respectively. The AND-OR tree structure presents a clear layout of all the modules and relationships. That information will be used in the design evaluation stage for calculating measures of different product configurations.
For example, Fig. 4.9 shows the AND-OR relationships among sub-structures in the designs of the proposed DMR with C and U indicating the customizable modules and upgradeable modules, respectively.

**Fig. 4.9:** The AND-OR relationships among sub-structures in the proposed DMR
Adaptable Interface Design

The interface design is carried out by designing the locking, release, and safety mechanisms to satisfy the key features such as convenience, high reliability, low cost, maximum generality, and self-alignment. Several types of interfaces are designed in DMR under several guidelines for accommodating different types of modularity architectures. The details of interface mechanical design will be presented in Section 6.4.4 Interface Design.

Concept Design Evaluation

By following the design process, two types of design alternatives, which are both adaptable and fulfill the design requirements were generated. However, different design alternatives have different architectures. Due to the different architectures, the physical modules that provide distinct functions and the interfaces among the different modules are usually different. Therefore, evaluation of the different design alternatives with different architectures is required for selecting the best design alternative.

A new method to evaluate design alternatives in adaptable design is introduced in this work using the grey relational analysis approach. The different design alternatives created in adaptable design are evaluated by different life-cycle evaluation measures including specific product adaptability, part cost, assembly time, and operationability of customers.
The grey analysis approach is used in this work for prioritizing different design alternatives considering different evaluation measures. The details of evaluation process and results will be presented in the Chapter 5.

**Detail Design**

Following the product architecture design and design evaluation, the result of the detail design of the selected design alternative is the complete design model with components and assemblies ready for manufacturing. This phase of design process includes mechanical design, kinematics and dynamic analysis, control system design.

Solidworks and Solidworks COSMOSMotion software are used for the detail mechanical design. The CAD model of the final design of DMR consists of 270 parts, 36 sub-assemblies and 98 2D drawings. The detailed structure presents in Chapter 6. Fig. 4.10 shows the modules and assembly of the DMR. Fig. 4.11 presents the other possible configurations of DMR.
Fig. 4.10: The modules and assembly of the DMR

Fig. 4.11: The other possible configurations of DMR (Left: Track Mobile Robot; Right: Wheel Mobile Robot)
CHAPTER 5

DESIGN EVALUATION AND PRIORITIZATION OF CONFIGURATIONS

5.1 Introduction

In adaptable design, most suitable design alternative has to be selected for subsequent production. Since a product with better adaptability usually requires more efforts in design and manufacture due to its variety and complexity [51], a priori evaluation and prioritization of the product configurations considering all relevant life-cycle aspects is required.

Selection of design alternatives and prioritization of product configurations through formal evaluations by considering different evaluation measures are typical multiple criteria decision-making problems. The key issue in solving this problem is to convert the different evaluation measures with different values into comparable evaluation indices.

Since decision of the design alternative and prioritization of the product configuration are taken at early conceptual design stage, the available information is usually limited, incomplete and uncertain. The relationships among various evaluation measures are also unclear. In this case, the analysis using classical statistical procedures for multiple criteria decision-making problems may not be acceptable or reliable without large data sets that satisfy certain statistical criteria.
The Grey Relational Analysis (GRA) from the grey theory [52] compares evaluation measures quantitatively whether or not the measures are quantitative or qualitative. Since grey relational analysis makes use of relatively small data sets and does not demand strict compliance to certain statistical laws, it can be applied when sample size is small and sample distribution is unknown. The grey relational analysis has been demonstrated as a simple and effective approach for analyzing relationships among different decision related parameters (e.g., performance and costs) in multiple criteria decision-making problems [53]-[55].

Based upon the concepts of grey relational analysis, this research employs the grey relational analysis approach to integrate the different evaluation measures for evaluating different design alternatives and prioritizing product configurations with different fundamental and adaptable functions.

5.2 Evaluation Measures

Since different evaluation measures of different product life-cycle aspects – including manufacturing costs, ease of operation. – influence the competitiveness of the product, evaluation of the adaptable designs considering all relevant life-cycle aspects has to be carried out.

In the evaluation of design for product adaptability, four evaluation measures – specific product adaptability, total part cost, assembly time, and operationability of customers – were selected for evaluating design alternatives and configurations [45].
**Specific Product Adaptability**

Specific product adaptability is an evaluation measure from the design perspective that considers functions, upgrade of functions and customizations. The fundamental functions and adaptable functions of a product are identified by the forecast information of particular adaptabilities and possibilities at the product planning stage, and then the product is designed to accommodate the product adaptabilities. Such product adaptability is called “specific product adaptability”. The measures for evaluating specific product adaptability are formulated in Section 5.2.

**Total Part Cost and Assembly Time**

Total part cost for each product configuration is the sum of the costs of all parts. Assembly time is the lead time for all assembly activities. Different product architectures usually require different assembly times. Since the product architecture and interfaces for each product configuration are established in previous design phases, the cost of parts and assembly time can be estimated and represented quantitatively.

**Operationability**

The operationability of a product is evaluated based on convenience of interface, degree of difficulty to adapt to different functions, and the reactions of customers. Because the operationability is evaluated in terms of good, fair, and poor, this evaluation measure is qualitative in nature. Operationabilities are rated on scales between 0 and 5, representing totally unsatisfactory and totally satisfactory, respectively. These four evaluation measures are summarized in Table 5.1.
Table 5.1: Life-cycle evaluation measures

<table>
<thead>
<tr>
<th>Evaluation Measure</th>
<th>Adaptability</th>
<th>Part Cost</th>
<th>Assembly Time</th>
<th>Operationability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life-cycle Aspect</td>
<td>Design</td>
<td>Manufacturing</td>
<td>Manufacturing</td>
<td>Operation</td>
</tr>
<tr>
<td>Type of Measure</td>
<td>Quantitative</td>
<td>Quantitative</td>
<td>Quantitative</td>
<td>Qualitative</td>
</tr>
<tr>
<td>Calculation</td>
<td>Eq. (5.10)</td>
<td>Sum of Costs of All Parts</td>
<td>Sum of time for All Assembly Activities</td>
<td>Rating on Scale of 0-5</td>
</tr>
</tbody>
</table>

5.2 Measures for Evaluating Specific Product Adaptability

This section discusses the measures to evaluate specific product adaptability. These measures are developed based on comparing the effort of an adaptation task with the effort of producing a new product. Therefore these measures can be evaluated when the adaptation task is known. Since the general product adaptability is based on the unanticipated adaptation, the measures are only used for evaluating specific product adaptability.

Three evaluation measures, extendibility of functions, upgradeability of modules, and customizability of components, are introduced for evaluating specific product adaptability.

5.2.1 Extendibility, Upgradeability, and Customizability

Extendibility of Functions

Extendibility of functions is obtained by a product which is designed with multiple functions. Functions of an adaptable design are classified into two categories: fundamental functions and adaptable (extendable) functions. For example, a computer system with several expansion slots for adding functionality in the future is a typical adaptable design.
When a computer is sold without the TV tuner card, the functions of the computer are the fundamental functions, while the function of receiving television signals to computer which is provided by the TV tuner card is the adaptable function. When a computer with a TV tuner card is sold, the function of receiving television signals is also a fundamental function.

Suppose the probability to adapt the current product with an adaptable function $T_{pi}$ (i.e., the i-th target adaptation) in the future is defined as $Pr(T_{pi})$, the effort to adapt the current product to the adaptable function $T_{pi}$ is described by $\text{Inf}(S_1 \rightarrow AS_2)$, and, the effort to create a completely new product with the same function is described by $\text{Inf}(\text{ZERO} \rightarrow IS_2)$. The extendibility factor, $EF(T_{pi})$, is then defined by:

$$EF(T_{pi}) = 1 - \frac{\text{Inf}(S_1 \rightarrow AS_2)}{\text{Inf}(\text{ZERO} \rightarrow IS_2)}, \quad 0 \leq EF(T_{pi}) \leq 1$$

When all $n$ possible adaptable functions are considered, the extendibility of the existing product is defined by:

$$E(P) = \sum_{i=1}^{n} [Pr(T_{pi})EF(T_{pi})]$$

In this method, the costs are usually selected to describe the efforts for adapting an existing product or for creating a new product. In Eq. (5.1), the efforts to adapt an existing product or to create a new product are defined by:

- $S_1$: the current state of the existing product,
- $AS_2$: the modified state with the additional adaptable function,
- $\text{ZERO}$: the state to design a new product from scratch, and
IS2: the state with only the required adaptable function.

From Eq. (5.1), when the effort for adapting an existing product is greater than the effort for creating a new product, the extendibility factor is calculated as 0. In this case, no adaptation is required. When the effort for adapting an existing product is smaller than the effort for creating a new product, the extendibility factor is calculated as a value between 0 and 1. In this case, adaptation of the existing product should be considered. When no extra effort is required to achieve the adaptable function from the existing product, the extendibility factor of this product is 1.

Continue with the computer example, S1 is the state that the computer is sold without the TV tuner card. AS2 is the state of a computer with the TV tuner card. IS2 is the device with only the receiving TV signals function, such as Apple TV (a digital media receiver made and sold by Apple Inc.). The $Inf_{(S1 \rightarrow AS2)}$ is then the cost to change the existing computer to provide the function of receiving TV signals. The $Inf_{(ZERO \rightarrow IS2)}$ is the cost of the new digital media receiver.

Assume the cost to build a digital media receiver, such as Apple TV is $80, and the cost to add a TV tuner card to S1 is $22. The extendibility factor $EF(Tp_1)$ can be calculated by:

$$EF(Tp_1) = 1 - \frac{Inf_{(S1 \rightarrow AS2)}}{Inf_{(ZERO \rightarrow IS2)}} = 1 - \frac{22}{80} = 0.725$$

From the result, the extendibility factor is calculated as a value between 0 and 1. In this case, adaptation of the existing product should be considered, since it is cheaper to add a TV tuner than to build a new product of digital media receiver.
Upgradeability of Modules

When technologies and user requirements are changed, the adaptable product should accommodate these changes through an upgrading process. Upgradeability is another evaluation measure of product adaptability in which the existing products are adapted based on the new requirements.

Suppose the probability to upgrade the current part with an upgraded part $Up_i$ (i.e., the i-th target upgrading) in the future is defined as $Pr(Up_i)$, the effort to provide the upgrading function in the current part is described by $Inf(p_{i\rightarrow Up})$, and, the effort to create current part without upgrading capability is described by $Inf(p_i)$. The upgradeability factor, $UF(Up_i)$, is then defined by:

$$UF(Up_i) = 1 - \frac{Inf(p_{i\rightarrow Up})}{Inf(p_i)}, \quad 0 \leq UF(Up_i) \leq 1$$

When all $n$ possible upgrading parts are considered, the upgradeability of the existing product is defined by:

$$U(P) = \sum_{i=1}^{n} [Pr(Up_i)UF(Up_i)]$$

In this method, the costs are usually selected to describe the efforts for providing the upgrading function and for creating the part without upgrading function. Generally, the cost for providing upgrading function is calculated by the cost of the interface which allows for the upgrading of the new part. In Eq. (5.3), the effort for providing upgrading function is defined by:
$P_1$: the physical state of the part without upgrading function
$UP_1$: the physical state of the part with upgrading function

From Eq. (5.3), when the effort for making available to upgrade an existing part is greater than the effort for creating this part, the upgradeability factor is calculated as 0. In this case, no upgrade is advised. When the effort for a making available to upgrade an existing part is smaller than the effort for creating this part, the upgradeability factor is calculated as a value between 0 and 1. In this case, upgrade of the existing part should be considered. When no extra effort is required to achieve the upgrade from the existing part, the upgradeability factor of this part is 1. The selected upgradable modules are indicated in AND-OR tree for further development.

**Customizability of Components**

Customization is the adaptation of a product based on requirements and preferences of customers. The product with ability of customization can be easily developed into many models which provide various combinations of features in response to various customer requirements. In this work, the customization mainly focuses on part customization.

Same as the upgradeability, suppose the probability to customize the current part with another part with same function $C_{pi}$ (i.e., the i-th target customization) in the future is defined as $Pr(C_{pi})$, the effort to make available to customize the current part to the another part $C_{pi}$ is described by $Inf_{(P_1 \rightarrow C_{pi})}$, and, the effort to create current part without the
customizability is described by $\text{Inf}_{(P_1)}$. The customizability factor, $\text{CF}(C_{p_i})$, is then defined by:

$$\text{CF}(C_{p_i}) = 1 - \frac{\text{Inf}_{(P_1 \rightarrow C_{p_i})}}{\text{Inf}_{(P_1)}}, \quad 0 \leq \text{CF}(C_{p_i}) \leq 1$$

(5.5)

When all $n$ possible customization parts are considered, the customizability of the existing product is defined by:

$$C(P) = \sum_{i=1}^{n} [\text{Pr}(C_{p_i}) \text{CF}(C_{p_i})]$$

(5.6)

When the selected customization part is also an upgradeable part and they can share the same interface, there is no extra effort required to achieve the customization from the existing part. Same as the selected upgradeable modules, the selected customization modules are also indicated in the AND-OR tree.

5.2.2 Specific Product Adaptability Index

The specific product adaptability index is based on previous three main measures: (1) extendibility of functions, (2) upgradeability of modules, and (3) customizability of components [1]. Each of these measures results in a percentage of specific product adaptability, which can then be combined to determine an overall measurement of specific product adaptability for a design alternative of the product by using appropriate weights for each item.
To use above three different evaluation measures, these measures should be converted into dimensionless evaluation measures in advance. The normalized measure for extendibility of functions is calculated by

$$NE(P)_i = \frac{E(P)_i}{E(P)_{\text{max}}}$$  \hspace{1cm} (5.7)

where:

- $E(P)_i$ = extendibility of functions of the $i^{th}$ design candidate
- $E(P)_{\text{max}}$ = the maximum value of extendibility of functions considering all the compared design candidates

Similarly, the upgradeability of modules and customizability of components can be calculated in the same manner:

$$NU(P)_i = \frac{U(P)_i}{U(P)_{\text{max}}}$$  \hspace{1cm} (5.8)

$$NC(P)_i = \frac{C(P)_i}{C(P)_{\text{max}}}$$  \hspace{1cm} (5.9)

These three values can then be combined into an overall specific product adaptability index in several different manners. The most useful one is the weighted-sum formulation. The specific product adaptability index of the $i$-th product configuration is calculated by:

$$A(P)_i = I_E \times NE(P)_i + I_U \times NU(P)_i + I_C \times NC(P)_i$$  \hspace{1cm} (5.10)

where:
In this case, the weighting factor of each evaluation measure is defined equally as 33.3%, because extendibility of functions, upgradeability of modules, and customizability of components are at the same important level of specific product adaptability.

The result of specific product adaptability index \( A(P) \) of each design alternative ranges from 0 to 1. When \( A(P)=0 \), there is no specific product adaptability; When \( A(P)=1 \), the product configuration has complete specific product adaptability.

### 5.3 Evaluation Method by Using GRA Approach

Evaluation of adaptable designs by using the grey relational analysis approach is conducted in the following six steps.

1. Establish comparative series and standard series.

The comparative series is an information series with \( m \) adaptable product configurations and \( n \) evaluation measures described by:

\[
A_i = (x_{i1}, x_{i2}, \cdots, x_{ij}, \cdots, x_{in}), \quad i = 1, 2, 3, \ldots, m
\]

(5.11)

where \( x_{in} \) denotes the \( n^{th} \) evaluation measures of \( x_i \).

The \( m \) adaptable designs and the \( n \) evaluation measures of these adaptable designs form an \( m \) by \( n \) decision matrix, \( D \).

The standard series is a target series modeled by:
The standard series is composed of the best values for each of all the evaluation measures.

2. Generate the normalized decision matrix $K$ (dimensionless).

To compare the different evaluation measures, these measures should be converted into dimensionless evaluation measures through the following 3 steps.

(a) If the evaluation measure is of the larger-the-better type (e.g., the adaptability), the normalized measure is calculated by:

$$x_{ij}^* = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}$$

(b) If the evaluation measure is of the smaller-the-better type (e.g., the cost), the normalized measure is calculated by:

$$x_{ij}^* = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}$$

(c) If the evaluation measure is of the nominal-the-best type, and the target value is selected as $x_{obj}$, the normalized measure is calculated by:

$$x_{ij}^* = \frac{|x_{ij} - x_{obj}|}{\max_i x_{ij} - x_{obj}}$$

The standard series should be converted into

$$A_0^* = (x_{01}^*, x_{02}^*, \ldots, x_{0j}^*, \ldots, x_{0n}^*)$$

in the same manner.
3. Obtain the differences between the comparative series and the standard series.

To discover the degree of the grey relationship, the differences, $\Delta_0$, between the normalized decision matrix $K$ and the normalized standard series $A_0^*$ are achieved by:

$$\Delta_{0ij} = \left| x_{0ij}^* - x_{y}^* \right|$$

(5.16)

4. Calculate the grey relational coefficients.

The grey relational coefficients, $\gamma_0$, indicate the contiguous grades between the comparative and standard series. A relational coefficient with higher value represents a closer relationship with the best evaluation measure considering all product configurations.

The grey relational coefficient is calculated by:

$$\gamma_{0ij} = \frac{\Delta_{\text{min}} + \zeta \Delta_{\text{max}}}{\Delta_{0ij} + \zeta \Delta_{\text{max}}}$$

(5.17)

Where $\Delta_{\text{max}}$ and $\Delta_{\text{min}}$ are obtained by:

$$\Delta_{\text{max}} = \max_i \max_j \Delta_{0ij}$$

(5.18)

$$\Delta_{\text{min}} = \min_i \min_j \Delta_{0ij}$$

(5.19)

$\zeta$ is called a distinguished coefficient, only affecting the relative value without changing the priority. Generally, $\zeta$ is selected as 0.5 [53].

5. Determine the degree of relation with the standard series.
To achieve the degree of relation with the standard series (i.e., the ideal one), the weighting factors of the evaluation measures must first be decided. These weighting factors can be determined by expert experience or marketing strategies in the firm. The degree of relation with the standard series for a product configuration is calculated by:

$$\Gamma_{0i} = \sum_{j=1}^{n} [w_j \times \gamma_{0ij}]$$

(5.20)

where $w_j$ is the weighting factor for the $j$-th evaluation measure satisfying:

$$\sum_{j=1}^{n} w_j = 1$$

(5.21)

6. Prioritize the product configurations.

From the degrees of relation between the comparative and standard series, the product configurations can be prioritized. The product configuration with a larger $\Gamma_{0i}$ can better satisfy the requirements considering different product life-cycle aspects.

This grey relational analysis approach treats each product configuration as a comparative series. The degree of relation between the comparative and standard series for each product configuration is then calculated. At the end, the best product configuration can be selected based on the rankings of all the product configurations.
5.4 Design Evaluation and Prioritization for the Concept of DMR

Through the design process of adaptable design, two design alternatives, shown in Fig. 5.1(a) and (b), were identified to fulfill the requirements of a tracked mobile robot with the potential to be adapted to other types of mobile robot, such as wheeled mobile robot, tracked mobile robot with flippers, etc. Both design alternatives can provide the functions of a tracked mobile robot together with the functions of wheel drive, flipper and interchangeable dual drive.

(a) Design Alternative 1
(b) Design Alternative 2

Fig. 5.1: Two design alternatives have been created to fulfill function requirements

For the first design alternative, when only the function of the tracked mobile robot is selected as the fundamental function of the product, and the functions of wheel drive, flipper and interchangeable dual drive are selected as adaptable (optional) functions of the product, the part and assembly costs of this product configuration are usually low, compared with a product configuration with all four functions selected as the fundamental functions. The specific product adaptability of the product configuration with all the four
functions is high, since no extra efforts are required to achieve any of the required functions in the future adaption.

In this case study, four product configurations with different fundamental and adaptable functions were selected considering each of these two design alternatives. These eight product configurations are summarized in Table 5.2. Fig. 5.2 illustrates two types of product configurations in Design Alternative 1.

**Table 5.2:** Product configurations with different fundamental and adaptable functions

<table>
<thead>
<tr>
<th>Design Alternative</th>
<th>Configuration</th>
<th>Track</th>
<th>w/Flipper</th>
<th>Wheel</th>
<th>Dual Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Alternative 1</td>
<td>Configuration 1</td>
<td>✓</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Configuration 2</td>
<td>✓</td>
<td>✓</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Configuration 3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Configuration 4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Design Alternative 2</td>
<td>Configuration 5</td>
<td>✓</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Configuration 6</td>
<td>✓</td>
<td>✓</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Configuration 7</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Configuration 8</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Note: ✓ indicates the function is a fundamental function in the configuration. ○ indicates the function is an adaptable function in the configuration.
3.4.1 Four Measures for Evaluating the Adaptable Designs

As discussed in section 5.1, specific product adaptability, total part cost, total assembly time, and operationability are selected as the evaluation measures considering design, manufacturing and operation life-cycle aspects of the products.

Specific Product Adaptability

Table 5.3 shows the costs of parts for design alternative 1. When the function of the tracked mobile robot is selected as the fundamental function of the product (i.e., product configuration 1 in Table 5.3), the total part cost for this product is then calculated as $21,900. Based on the tracked mobile robot in design alternative 1, the costs for achieving the adaptable functions of flipper, wheel drive and dual drive are identified as $6,500, $13,420 and $16,820, respectively. Table 5.4 gives the costs of parts for design alternative 2.
In this case study, since track, wheel drive and flipper mechanism are very useful for mobile robot to adapt various terrains, the probabilities of using different fundamental and adaptable functions are identified as:

\[ Pr(\text{Tracked Mobile Robot}) = 100\%; \quad Pr(\text{Tracked Mobile Robot with Flipper}) = 100\% \]

\[ Pr(\text{Wheeled Mobile Robot}) = 100\%; \quad Pr(\text{Dual Drive Mobile Robot}) = 100\% \]

When the costs for creating new products of tracked mobile robot with flipper, wheel mobile robot and dual drive mobile robot are selected as $25,000, $26,500 and $40,000, the extendibility of functions for product configuration 1 is then calculated using Equation (5.2).

\[
E(P_1) = 100\% \cdot (1 - 0) + 100\% \cdot (1 - \frac{6500}{25000}) + 100\% \cdot (1 - \frac{13420}{26500}) + 100\% \cdot (1 - \frac{16820}{40000}) = 2.81
\]

The extendibilities of all other configurations for design alternatives 1 and 2 can be calculated in the same manner.
Table 5.3: The individual part list for Design Alternative 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Part</th>
<th>Unit Cost ($)</th>
<th>ConFig. 1</th>
<th>ConFig. 2</th>
<th>ConFig. 3</th>
<th>ConFig. 4</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rear Pulley</td>
<td>2000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Front Pulley</td>
<td>2800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Traction Unit</td>
<td>3000(200)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>4</td>
<td>Flipper Power</td>
<td>4000(150)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>5</td>
<td>Clutch Frame</td>
<td>1800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Left Clutch</td>
<td>2500</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Right Clutch</td>
<td>3000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Flipper</td>
<td>1700</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>Belt Suspension</td>
<td>2000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Slide Wheel</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Front Wheel</td>
<td>120</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Rear Wheel</td>
<td>4300</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Chassis</td>
<td>3000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Center Platform</td>
<td>1800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C</td>
</tr>
<tr>
<td>15</td>
<td>Control System</td>
<td>700</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>16</td>
<td>Battery</td>
<td>1000(50)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>17</td>
<td>Drivers for Traction Motors</td>
<td>800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Drivers for Flipper Motors</td>
<td>800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Interchangeable System</td>
<td>2600(100)</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td></td>
<td>Sub-total ($)</td>
<td></td>
<td>21900</td>
<td>28400</td>
<td>35320</td>
<td>38720</td>
<td></td>
</tr>
</tbody>
</table>

Note: C indicates this part is selected as customization part
U indicates this part is selected as upgradeable part
( ) indicates the cost to provide the upgrading or customization function
### Table 5.4: The individual part list for Design Alternative 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Part</th>
<th>Unit Cost ($)</th>
<th>Config. 5</th>
<th>Config. 6</th>
<th>Config. 7</th>
<th>Config. 8</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rear Pulley</td>
<td>1800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Front Pulley</td>
<td>2500</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Traction Unit</td>
<td>3000(200)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>4</td>
<td>Flipper Power</td>
<td>5000(150)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>5</td>
<td>Clutch Frame</td>
<td>2200</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Top Clutch</td>
<td>2200</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Side Clutch</td>
<td>2800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Flipper</td>
<td>1700</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>Belt Suspension</td>
<td>2000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Slide Wheel</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Front Wheel</td>
<td>120</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Rear Wheel</td>
<td>3400</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Chassis</td>
<td>3000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Center Platform</td>
<td>1800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C</td>
</tr>
<tr>
<td>15</td>
<td>Control System</td>
<td>700</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>16</td>
<td>Battery</td>
<td>1000(50)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>17</td>
<td>Drivers for Traction Motors</td>
<td>800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>18</td>
<td>Drivers for Flipper Motors</td>
<td>800</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Interchangeable System</td>
<td>3400(200)</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>C,U</td>
</tr>
</tbody>
</table>

Sub-total ($)  

21600 29100 34820 39020

Note: C indicates this part is selected as customization part  
U indicates this part is selected as upgradeable part  
( ) indicates the cost to provide the upgrading or customization function

From And-OR tree as shown in Fig. 4.10 and Table 5.3/5.4, some parts are selected as upgradeable parts and customizable parts. The cost to upgrade or customize the current part
to another part is given in a bracket and modeled using the unit cost. In this case study, all of the selected parts are considered to be upgraded or customized in the future. The upgradeability of product configuration 1 considering traction motor, master controller and battery parts is then calculated using Equation (5.4).

\[ U(P_1) = 100\% \cdot (1 - \frac{200}{3000 - 200}) + 100\% \cdot (1 - \frac{0}{700 - 0}) + 100\% \cdot (1 - \frac{50}{1000 - 50}) = 2.88 \]

The upgradeabilities of all other configurations for design alternatives 1 and 2 can be calculated in the same manner.

Since some parts are selected as both the upgradeable parts and the customizable parts, they can use the same interfaces to be upgraded or to be customized. If the interface cost has been calculated considering the upgradeability, the cost for customization of the same part will be selected as 0, because both measures are achieved using the same interface.

In this case study, traction motor, master controller and battery are also selected as customizable parts in product configuration 1. All the center platform of DMR share the same interface, therefore there is no additional cost for this customization task. The customizability of product configuration 1 can be calculated using Equation (5.6).

\[ C(P_1) = 100\% \cdot (1 - \frac{0}{3000 - 200}) + 100\% \cdot (1 - \frac{0}{1800 - 0}) + 100\% \cdot (1 - \frac{0}{700 - 0}) + 100\% \cdot (1 - \frac{0}{1000 - 50}) = 4 \]

The customizabilities of all other configurations for design alternatives 1 and 2 can be calculated in the same manner.
The results of extendibility, upgradeability and customizability of all the eight product candidates are summarized in Table 5.5.

Table 5.5: Design evaluation summary

<table>
<thead>
<tr>
<th>Product Configuration</th>
<th>Design Alternative 1</th>
<th>Design Alternative 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Adaptability evaluation</td>
<td>Extendibility</td>
<td>2.81</td>
</tr>
<tr>
<td></td>
<td>Upgradeability</td>
<td>2.88</td>
</tr>
<tr>
<td></td>
<td>Customizability</td>
<td>4</td>
</tr>
<tr>
<td>Product life-cycle evaluation</td>
<td>Adapatability (0–1)</td>
<td>0.625</td>
</tr>
<tr>
<td></td>
<td>Total part cost ($)</td>
<td>21900</td>
</tr>
<tr>
<td></td>
<td>Assembly time (h)</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>Operationability(0-5)</td>
<td>2</td>
</tr>
<tr>
<td>Evaluation result</td>
<td>Degree of relation (Γ)</td>
<td>0.582</td>
</tr>
<tr>
<td>Ranking</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

To use these three different measures to evaluate the eight product configurations, these three measures should be first converted into dimensionless evaluation measures. The normalized measures for extendibility of functions, upgradeability of modules and customizability of components are calculated using Equations (5.7)–(5.9), respectively.

These three normalized values can then be used to calculate the specific product adaptability index. The specific product adaptability index of the i-th product configuration

---

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is calculated by Equation (5.10). In this case study, the weighting factor of each adaptability evaluation measure is defined equally as 33.3%, because extendibility of functions, upgradeability of modules, and customizability of components are considered the same important. The adaptabilities of all the eight product configurations are summarized in Table 5.5.

**Total Part Cost**

Total part cost for each product configuration is calculated by adding the costs of all its composing parts. For example, the total part cost of configuration 1 is calculated as $21,900 based on the parts list in Table 5.3. The total part costs of other product configurations are calculated in the same way, as shown in Table 5.5.

**Assembly Time**

Assembly time is the measure for assembly activities. Different product architectures usually require different assembly time. As more parts are used in a product, the assembly time usually increases. From Table 5.5, design alternative 1 requires a higher assembly time compared with the design alternative 2, due to its complex architecture.

In addition, the dual drive configuration in both design alternatives needs more assembly time than track mobile robot configuration, because the dual drive configuration requires more addition modules to fulfill its functions. In this case study, the assembly times of the
eight selected product configurations are given in Table 5.5.

*Operationability*

The operationability of product is based on convenience of interface, degree of difficulty to adapt to different functions, and the feelings of customers. Operationabilities are rated on scales between 0 and 5, from totally unsatisfactory to totally satisfactory. The operationabilities of the eight product configurations are also given in Table 5.5.

*Selection of Weighting Factors for Different Evaluation Measures*

The weighting factors of the four different evaluation measures are determined from expert experience and marketing strategies. Since this research focuses on adaptable design, a high weighting factor is selected for the adaptability evaluation measure. These weighting factors are identified as follows.

\[
\begin{align*}
    w_{\text{adaptability}} &= 45\%; \\
    w_{\text{part-cost}} &= 20\%; \\
    w_{\text{assembly-time}} &= 20\%; \\
    w_{\text{operationability}} &= 15\%
\end{align*}
\]

**3.5.2 Prioritization of Product Configurations**

Prioritization of the product configurations using the grey relational analysis approach is conducted as follows:
1. Establish the decision matrix \( D \)

\[
D = \begin{bmatrix}
  0.625 & 21900 & 11.1 & 2 \\
  0.842 & 28400 & 13.4 & 2 \\
  0.879 & 35320 & 16.1 & 3 \\
  1.000 & 38720 & 19.5 & 4 \\
  0.621 & 21600 & 10.8 & 3 \\
  0.847 & 29100 & 12.7 & 3 \\
  0.877 & 34820 & 14.9 & 4 \\
  0.999 & 39020 & 17.3 & 5
\end{bmatrix}
\]

2. Obtain the standard series

\[
A_0 = \begin{bmatrix} 1 & 21900 & 10.8 & 5 \end{bmatrix}
\]

3. Generate the normalized decision matrix \( K \) and standard series \( A_0^* \)

\[
K = \begin{bmatrix}
  0.011 & 0.983 & 0.966 & 0.000 \\
  0.583 & 0.610 & 0.701 & 0.000 \\
  0.681 & 0.212 & 0.391 & 0.333 \\
  1.000 & 0.017 & 0.000 & 0.667 \\
  0.000 & 1.000 & 1.000 & 0.333 \\
  0.596 & 0.569 & 0.782 & 0.333 \\
  0.675 & 0.241 & 0.529 & 0.667 \\
  0.997 & 0.000 & 0.253 & 1.000
\end{bmatrix}
\]

\[
A_0^* = \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}
\]

4. Calculate the differences between the comparative and standard series
\[
\Delta_0 = 
\begin{bmatrix}
0.989 & 0.017 & 0.034 & 1.000 \\
0.417 & 0.390 & 0.299 & 1.000 \\
0.319 & 0.788 & 0.609 & 0.667 \\
0.000 & 0.983 & 1.000 & 0.333 \\
1.000 & 0.000 & 0.000 & 0.667 \\
0.404 & 0.431 & 0.218 & 0.667 \\
0.325 & 0.759 & 0.471 & 0.333 \\
0.003 & 1.000 & 0.747 & 0.000
\end{bmatrix}
\]

\[
\Delta_{\text{max}} = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}
\]

\[
\Delta_{\text{min}} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}
\]

5. Determine the grey relational coefficients

\[
\gamma_0 = 
\begin{bmatrix}
0.336 & 0.967 & 0.935 & 0.333 \\
0.545 & 0.562 & 0.626 & 0.333 \\
0.610 & 0.388 & 0.451 & 0.429 \\
1.000 & 0.337 & 0.333 & 0.600 \\
0.333 & 1.000 & 1.000 & 0.429 \\
0.553 & 0.537 & 0.696 & 0.429 \\
0.606 & 0.397 & 0.515 & 0.600 \\
0.995 & 0.333 & 0.401 & 1.000
\end{bmatrix}
\]

6. Determine the degrees of relations with the standard series

Using the weighting factors and Eq. (5.10), the degrees of relations for all the 7 product configurations are obtained as follow.

\[
\Gamma_{01} = 0.582; \quad \Gamma_{02} = 0.533; \quad \Gamma_{03} = 0.507; \quad \Gamma_{04} = 0.674;
\]

\[
\Gamma_{05} = 0.614; \quad \Gamma_{06} = 0.560; \quad \Gamma_{07} = 0.545; \quad \Gamma_{08} = 0.744
\]

Fig. 5.3 shows the degrees of relations for 8 product configurations.
Fig. 5.3: The degrees of relations for eight product configurations

7. Prioritize the 8 product configurations

From the ranking of the product configurations, configuration 8 is selected as the best one, considering all the relevant life-cycle evaluation measures. Compared with configuration 4, configuration 8 can provide the same level of specific product adaptability with minor additional cost. Since the design alternative 2 has less complexity in the design of real-time interchangeable system and dual drive system than design alternative 1, the former requires less assembly time and can provide easier operation for expanding functions. Compared with configuration 5, configuration 8 provides three more often-used functions, which can increase the mobile robot’s terrain adaptability significantly, with reasonable additional cost. As a result, the product configuration 8 from the design alternative 2 has been chosen after the evaluation and prioritization. The selected best design alternative and its product configuration can then proceed to detail design.
CHAPTER 6

MECHANICAL DESIGN PARADIGM

6.1. Introduction

This chapter presents the mechanical design of the proposed concept as a case study. In this case study, the mechanical design architecture is derived from the novel concept design process, “Design Process for Product Adaptability”, which is summarized in Chapter 4. The mechanical design is based on the design alternative 2 and product configuration 8 which were selected from a range of alternatives and configurations in Chapter 5. This chapter provides the detailed mechanical design architecture.

Section 6.2 presents the general mechanical design architecture of the proposed mobile robot. Sections 6.3 and 6.4 discuss the detail designs of two major components: track-wheel driving module and center platform as well as the design parameters. The required force capacity of the linear actuator was derived from dynamic simulations in Solidworks COSMOSMotion, which are described in Section 6.4.3. The unique mechanical structure of DMR not only provides product adaptability, but also improves its functionality. Several mobility modes and maneuvers which can be used in various applications were introduced in details in Section 6.5.
6.2. Mechanical Design Architecture

Considering the concept of product adaptability, the DMR is developed with the expectations that traction system can be easily adapted to suit a wide range of terrains, and additional hardware can be attached to the platform with minimal effort.

Fig. 6.1 gives the mechanical structure of the DMR. The DMR consists of two major components: track-wheel driving module and center platform. Center platform and track-wheel driving module include several side plates which are made from 6061-T6 aluminum to achieve sufficient strength and lower weight. These side plates are coupled by cross members and shafts to form rigid structures.

Fig. 6.1: The mechanical structure of the DMR platform
The mechanical design of DMR embodies the concepts described in Chapter 3, and includes the following design requirements:

(1) Various locomotion methods could be selected and changed to increase the efficiency and adaptability of the robot to different terrains.

(2) Different hardware devices are required for a wide range of applications. The center platform of robot should have interfaces and space to attach new hardware with minimal cost and effort.

(3) When technologies and user requirements change, the robot should accommodate these changes through an upgrading process. All the upgradable modules should be designed to be compatible with other components.

(4) Customization is the adaptation of a product based on requirements and preferences of customers. The robot should have the ability of customization, and be converted into models that provide various combinations of features in response to a range of customer requirements.

(5) The robot should provide several mobility modes in a range of operations in order to increase the locomotion ability on and off road.
6.3. Design of Track-wheel Driving Module

The track-wheel driving module combines wheels and tracks that are driven separately with the same motor. It can be also easily modified as wheel driving only or track driving only. The track-wheel driving module is shown in Fig. 6.2. It integrates one dual drive system including track and wheel, and one swing arm mechanism. The innovative design provides three major functions, driving in two modes, steering, and climbing, in one module. This makes it possible to build a modular mobile robot with the flexibility and adaptability.

Fig. 6.2: The mechanical structure of the track-wheel driving module

6.3.1. Dual Drive System

The DMR’s locomotion system is powered by two separate motors. Each track-wheel
driving module has one dual drive system with an identical drive motor. In this version of DMR, the drive motor is a 363 watt brushless DC motor (M8WQ90-03E4-008HZ, from Zexen Technology) and is geared down through a 1:20 ratio planetary servo gearhead (AccuDrive E60, from Cone Drive Operations Inc.).

To achieve the unique dual drive function, three bevel gears are used to transfer the motion to two output shafts at a 90-degree angle to the input shaft. As shown in Fig. 6.3, a 1:1.5 ratio bevel gear set transfers the motion to the output shaft in –Z direction and amplifies the torque capacity required for propelling the pulley that drive the track. Further, the motion is transmitted through a 1:1 ratio bevel gear set to another output shaft in Y direction for driving the sprocket that drives the wheel.

Fig. 6.3: The mechanical structure of the dual drive system
In addition, two electromagnetic clutches (Series 0008-10-05, from Ortlinghaus AG) switch between the two output shafts to provide wheel and track driving mode separately. Electromagnetic clutches operate electrically, but transmit torque mechanically. It is suitable for remote operation since no linkages are required to control their engagement. Clutches also prevent overloading of the drivetrain if the torque exceeds the maximum torque that can be provided by each drive motor, such as the case of stuck wheel or pulley.

In the conceptual design stage, the dual drive system was defined to be customizable and upgradeable. The design and layout of the dual drive system has been considered to be compatible with other models of drivetrain and reconfigurable to other states. Alternative versions of the dual drive system can use other types of drive motors and gearheads, such as 482 watt brushless DC motor (BN34-35EU-02, from Moog Components Group) and a 1:10 ratio planetary servo gearhead (AccuDrive E40/E60, from Cone Drive Operations Inc.). Also, the dual drive system can be configured easily into a single drive system, either wheel drive or track drive, by simply removing the clutch assemblies, as shown in Fig. 6.4.
Fig. 6.4: The configurations of single drive system: track drive and wheel drive

6.3.2. Track System

In the track mode, DMR moves around on a pair of parallel tracks. They are 75mm wide and are joined with reinforced alligator lacings. To remove the tracks, they can be easily disconnected by removing the hinge pins which are inserted in the alligator lacings. For maximizing the tractions, the tracks have soft rubber cleats spaced along their length. Each track is driven by a toothed rear drive pulley. Teeth in each drive pulley mate with grooves on the inside surface of the track. An idler pulley supports each track at the front of the robot. To save cost and reduce weight, bronze sleeve bearings are used to support the rear drive pulley. Although sleeve bearings have greater friction than ball bearings, they have advantages in cost, weight, and maintenance.
A pair of track tensioning mechanisms is located between rear and front pulley. Each supporting roller is mounted on a transverse bar which is supported by a pair of struts and compression springs. The strut can slide vertically inside the linear bearing. It is used to adjust the position of the supporting roller by tightening or loosening the nut in the bottom. The track tensioning mechanism provides a predetermined tension in the track and allows quick replacement of the tracks. Under the track tensioning mechanisms, an aluminum board with Teflon low-friction surface is attached by screws to the main frame of track-wheel driving module to support the bottom of the track.

6.3.3. Hubless Rear Wheel

It is a design challenge to have the drive axes of wheel and pulley at 90° to each other in a compact space. Since traditional wheels have a hub in the center and spin around a central axis, the wheel and central axis will interfere with the pulley. To provide adequate space for the pulley and track, the rear wheel has been innovatively designed as a hubless wheel. Hubless wheel is a type of wheel with no center hub. It is open in the middle -- no spokes, no hubcaps. Hubless wheels work by fixing the rotating parts onto the outer side of a non-rotating inner ring that attaches to the fixed frames.

The outer frame with the tire on its outside of the hubless rear wheel is supported by the outer rings of two thin section ball bearings (INA CSCU080-2RS, from Schaeffler Group). The selected CSCU080-2RS bearing is a deep groove ball bearing and sealed on
both sides. Therefore, the selected bearing can support axial loads in two directions and dynamic radial load up to 9900 N. The inner rings of the thin section ball bearings attach to the track-wheel driving module’s frame. A sprocket is fixed on the outer frame of hubless rear wheel and a chain drive system is used to convey power to the rear wheel in the DMR’s wheel mode. The overview of hubless rear wheel and rear pulley is shown in Fig. 6.5.

![Fig. 6.5: The overview of hubless rear wheel and rear pulley](image)

6.3.4. Swing Arm Mechanism

Another invention in the track-wheel driving module is the swing arm mechanism (flipper, as the shorter name). It includes an arm, a removable front wheel and front roller, as shown in Fig. 6.6. The proximal end of the arm is pivotally and rigidly contacted to the main frame of the track-wheel driving module about a transverse axis that is
perpendicular to the sides of the main frame.

**Fig. 6.6:** The overview of swing arm mechanism at the front

The swing arms are coupled to the main frame of the track-wheel driving module such that they can rotate in front of the tracks (limited degrees in the range -50 to +75), as shown in Fig. 6.7. The two swing arms can be rotated individually or synchronously by two identical flipper drive motors. A flipper drive motor is used to drive and control the angle between arm and main frame of the track-wheel driving module. In this version of DMR, the flipper drive motor is a 363 watt brushless DC motor (M8WQ90-03E4-008HZ, from Zexen Technology). The motion is transmitted through a 1:160 ratio harmonic drive (CSF-20-160-2UH, from Harmonic Drive Systems Inc.) and a 1:2 ratio drive chain as an additional transmission stage in order to achieve greater torque output and transfer to the
transverse axle. Each flipper drive motor is also equipped with a spring applied break (FSBR007, from Inertia Dynamics). Two limit switches with hinge roller lever are utilized to limit the rotation range and prevent the collision between swing arm and main frame.

**Fig. 6.7:** The swing arm mechanism can rotate in the range -50 to +75 degrees

Since the flipper drive unit is also defined as a customizable and upgradeable module in the concept stage, the motor adapter has been designed to be compatible with other DC motors. In this case, a 482 watt brushless DC motor (BN34-35EU-02, from Moog Components Group) can be customized or upgraded on the flipper drive unit without any further modification. Meanwhile, another customizable module, the swing arm, can be selected between wedge shape and rounded rectangle shape for different applications, as shown in Fig. 6.8.
6.4. Design of Center Platform

The center platform, including the electronics, payload volume and rotation mechanism, is housed in a thin aluminum shell as shown in Fig. 6.9. The center platform provides a ground clearance of 240 mm in wheel mode and 57 mm in track mode (Fig. 6.10 (a)-(b)).
6.4.1. Platform Layout

To achieve the low and forward positioned center of gravity, the volume of the center platform has been divided into three sections. All the light-weighted electronic components, such as controller, drivers and power distribution board, are located in the rear section. The rotation mechanism including linear actuators is placed in the middle section. The front section is reserved for battery and a small payload volume for sensors.

Since the payload volume inside the center platform is limited, larger payloads, such as manipulator and surveillance camera can be placed on the top of center platform, preferably over the center of mass. In this case, the DMR can still perform functions such as stair climbing and obstacles crossing.

6.4.2. Rotation Mechanism

The rotation mechanism is used to convert the DMR from the wheel mode into the track mode, vice versa. This mechanism consists of two linear actuators and slider-crank
mechanisms, as shown in Fig. 6.11. To simplify the mechanical design, linear actuators are selected as the driving system. Since the selected linear actuator model has self-locking feature, the track-wheel driving modules can be fixed in position all the time. The slider-crank mechanism is used to convert the linear motion of the linear actuator to rotational motion of the track-wheel driving module. The built-in electrical end stop sensor of linear actuator and limit switches which are located under the center platform are used to limit the rotational motion in the 0-90 degree range.

![Fig. 6.11: The side view of rotation mechanism](image)

In this version of DMR, the linear actuator is driven by a 12V DC motor and can provide 2500 N force with 100 mm stroke (LA23, from LINAK Group). It is a compact and strong push or pull actuator with built-in electrical end stop sensor. The required force capacity of the linear actuators is derived from the analysis results of the dynamics simulations as described in Section 6.4.3.
6.4.3 Dynamic Simulation of the Rotation Mechanism

The DMR can automatically convert between a wheel-based robot and a track-based robot by rotating the track-wheel driving modules by 90 degrees. During the transition, the linear actuators of the rotation mechanism must provide adequate force. To assess and predict the force capability of linear actuators, several dynamic simulations have been performed in Solidworks COSMOSMotion. The simulations are based on DMR's CAD model and account for weights, contact and friction forces between the robot and ground.

The weights of the different parts of DMR and payload are summarized in Table 6.1. These weights are estimated from 3D CAD models and used while performing the simulations. Ref. [57] [58] [59] discusses in detail the dynamics of the track-ground interaction. Experiments were conducted to find the frictional properties for the interaction between the track system and ground. The static friction coefficient between the rubber track and hard (concrete) ground was found to have a value of 0.60.

Table 6.1: Part weights of DMR (estimated from 3D CAD model)

<table>
<thead>
<tr>
<th></th>
<th>Center Platform</th>
<th>Driving Module (Left)</th>
<th>Driving Module (Right)</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>15</td>
<td>25</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Chassis Weight (kg)</td>
<td></td>
<td></td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Total Weight (kg)</td>
<td></td>
<td></td>
<td>115</td>
<td></td>
</tr>
</tbody>
</table>
To demonstrate the force requirement of linear actuators, force plots for several scenarios are shown. Based on the force plots, the maximum force and its occurrence can be identified.

Case 1: Transition from track mode to wheel mode (platform only)

The force plot depicted in Figure 6.12 shows the force requirement of one side of linear actuator during the transition from track mode to wheel mode. The robot platform can convert from a tracked robot into a wheel robot within 28 seconds. At the beginning, a large amount of pushing force is required when the tracks are rubbing against the ground. A maximum force of 901 N is required when the wheels are in contact with the ground. The instantaneous jump in the force plot at 19.6 sec indicates the touching point with the ground.

![Force Plot](image)

**Fig. 6.12:** Linear actuator force requirement - from track mode to wheel mode
Case 2: Transition from wheel mode to track mode (platform only)

Figure. 6.13 shows the force requirement of one side of linear actuator during the transition from wheel mode to track mode. At the beginning, the wheels rub against the ground. Beyond that point, when the tracks touch the ground, a larger force value is required. According to the force plot, the peak value of 593 N for this case occurs at the middle of the motion (10.2 sec) when the tracks are in contact with the ground.

![Fig. 6.13: Linear actuator force requirement - from wheel mode to track mode](image)

Case 3: Transition from wheel mode to track mode (with 50 kg payload)

The simulation results of case 1 and case 2 indicated the minimum force requirement of linear actuator to complete the transitions based on DMR platform. According to the
results, the transition from track mode to wheel mode requires higher force and uses more
time to complete. Additional weight of payloads will require the linear actuators to
provide higher level of force during the transition.

To determine the maximum force requirement of linear actuator, the force plot depicted in
Figure. 6.14 shows the force requirement of one side of linear actuator during the
transition from track mode to wheel mode based on the DMR platform with 50 kg
payload. A maximum force of 2346 N is required when the wheels are in contact with the
ground. The instantaneous jump in the force plot at 24.36 sec indicates the touching point
with the ground.

![Fig. 6.14: Linear actuator force requirement - from wheel mode to track mode (with 50 kg payload)](image-url)
6.4.4. Interface Design

In the conceptual design stage, both specific product adaptability and general product adaptability are initiated by adding, substituting, and/or removing one or more add-on functional modules from the center platform. To modularize mechanical components, the physical interfaces among modules have been specially designed so that the functional interactions among modules and operations of assembly and disassembly can be easily achieved.

According to the modular architectures developed by Ulrich [50], the interfaces can be classified into three categories: (I) slots, (II) buses and (III) sectionals. Usually one product may exhibit many types of interfaces. In this version of DMR, buses interface and sectionals interface have been developed, so that functions can be transferred between the center platform and the modules, and among modules. Those interfaces satisfy the following requirements: transfer of functions, convenience to use, high reliability, low cost, maximum generality, and self-alignment. For instance, the interface between center platform and add-on attachments has been designed as a bus interface, as shown in Fig. 6.15. A bus is a standard interface that accepts any different modules with the same type of interface. In the bus architecture, the add-on attachments have a standard interface that attaches to the bus interface of the center platform. Various add-on attachments, such as small manipulator or camera, can share with the same slide rails to
relocate on the top of center platform, as shown in Fig. 6.16.

**Fig. 6.15:** The bus interface between center platform and add-on attachments

**Fig. 6.16:** Small manipulator and camera can share with the same slide rails to relocate on the top of center platform

### 6.5. Mobility Modes and Maneuvers

The unique mechanical structure of DMR provides several mobility modes including extended/stowed, terrain crossing, push-up, free wheel and parking modes in operation. In addition, the DMR can perform several maneuvers, such as stair climbing, tube mobility and two types of steering.
6.5.1 Mobility Modes

*Extended/Stowed Mode*

The longest possible length (1100 mm) can be achieved by the extended mode as shown in Fig. 6.17. This mode is useful in a stair-climbing and ditch-crossing maneuver. The fully extended length can provide better stability.

In the other hand, to minimize the volume during transportation, the DMR can be set to its stowed mode, and the payload such as manipulator can be folded as well. The stowed dimensions of the DMR are a width of 0.89 meters, a height of 0.47 meter and a length of 0.86 meters. Therefore, the overall stowage volume of the DMR with payloads is 0.36 m³ as depicted in Fig. 6.18.
**Terrain Mode**

In order to efficiently traverse rough terrain, the DMR uses tracks and swing arms with a controlled angle of approach. In this mode, the DMR can cross up to 10 cm obstacles without slowing down. Experiments have been contacted to demonstrate the effectiveness of terrain mode in Section 8.3.3.

**Push-up Mode**

The DMR can deploy the swing arms to raise the forward end of main body in a push-up mode. This posture can directly increase the height of sensors and camera on the platform. Moreover, this mode is also important for enhancing the DMR’s terrain adaptability. Since the ground clearance is 57 mm which is a relatively small clearance under the center platform. The DMR may lose traction when it traverses some large obstacles. As shown in Fig. 6.19, the push-up mode can significantly increase ground clearance to recovery from the stuck situation. The push-up mode also can be used to support the DMR when it is off the large obstacle, as shown in Fig. 6.20.

![Fig. 6.19: Push-up mode of the DMR for increasing ground clearance](image)
In addition, with the help of rollers in the swing arms, the DMR can travel on four points of contact to reduce energy consumption by minimizing the contact length of tracks with the ground in push-up mode.

**Free-wheel Mode**

The DMR allows all wheels thereof to freewheel. Upon command or power off, the clutches are not engaged. The wheel drive system can be passively limped to all for assisted locomotion without damaging the mechanism. This mode can be used in the event of towing the DMR to its desired location to start the mission or after a failure in the drive mechanism.

**Parking Mode**

Upon command, the DMR can put itself in a parked mode in which locomotion is inhibited and maintain rigid vehicle stability. To perform this mode, the swing arms in the
front will rotate into opposite positions, and the rear wheel will be locked in position through clutches and brakes, as shown in Fig. 6.21.

![Fig. 6.21: Park mode of wheel configuration](image)

### 6.5.2 Maneuvers

**Stair Climbing**

The DMR can climb stairs by using its tracked chassis and swing arms. At first, both sides of the swing arms pivot synchronously to raise the arm higher than the rise of the first stair. Then the robot drives the tracks forward until the arms and tracks contact the first stair one after another. When the tracks contact the first stair, the swing arms can pivot to the position of extended mode. The robot can continue to ascend the stairs.

In this version, the dimensions of DMR are specifically designed to climb common stairs, with step dimensions of up to 17.8 cm (7’’) rise and 17.8 cm (7’’) tread, as depicted in Fig.
6.22. For stable and smooth travel on stairs, the extended mode provides the extended wheel base as 950 mm to cross at least three steps (509 mm for 17.8 cm (7'') by 17.8 cm (7'') stairs).

![Climbing a staircase with an incline of 45 degrees](image)

**Fig. 6.22:** Climbing a staircase with an incline of 45 degrees

The robot can climb different heights of obstacle or stairs for different values of the robot orientation angle $\alpha$. The center of gravity (COG) location is an important design parameter for a robot to enhance the maneuvers like stair and obstacle climbing. Therefore, the location of the COG has been analyzed and arranged in the mechanical design stage. The first step rise/obstacle height $H$ that the DMR can climb can be calculated using Eq. (6.1).

$$H \leq G_x \cdot \sin \alpha + R \cdot (1 - \sin \alpha \cdot \tan \alpha - \cos \alpha) \quad (6.1)$$

The optimum value of angle $\alpha$ results in the maximum first step rise that the robot can
climb. The relations between the orientation angle $\alpha$ and the first step rise are shown in Fig. 6.23.

![Diagram](image)

**Fig. 6.23:** Geometry of the DMR climbing the first step rise of stairs

The optimum angle $\alpha$ required to climb the maximum first step in tracked configuration and hybrid configuration are found to be 53 degrees and 52 degrees. The maximum first step rise is 235 mm for the tracked configuration and 214 mm for the hybrid configuration, as shown in Fig. 6.24. Since the extra rear wheels in hybrid configuration shift the COG backwards, the optimum angle $\alpha$ and maximum first step rise are lower than the tracked configuration. However, the optimum angle $\alpha$ and maximum first step rise in both configurations are higher than the requirements as 45 degrees and 178 mm respectively.
**Steering**

In the track mode, the DMR is controlled using left and right drive motors. The steering in this mode is accomplished using differential speed of the tracks on either side of the robot. In addition, tracks which are separated sufficiently for efficient skid steering can give higher maneuverability. The robot can turn in place with no forward or backward movement by driving the tracks in opposite directions. In this version of DMR, it can skid around its center of gravity allowing complete turning in a 100 cm diameter circle, as shown in Fig. 6.25. This makes it easier to maneuver in cramped quarters. But skid steering will fail to achieve the most aggressive steering possible which can be achieved with explicit steering because the maximum forward thrust is not maintained during a turn [60].
Fig. 6.25: Skid steering of track mode (turn in place)

Independent steering is used in the wheel mode. It coordinates the angle of the two front wheels to the desired heading by controlling the swing arms individually, as shown in Fig. 6.26. As a result, the DMR can move in a car-like fashion in high speed. Independent steering allows efficient maneuvering and reduces the affect of internal losses, comparing with skid steering. However, in order to maintain all wheels in a pure rolling condition during a turn the wheels need to follow curved paths with different radii originating from a common center, it requires the complex and accurate coordination control.

Fig. 6.26: Independent steering of wheel mode
**Pipe Mobility**

DMR can be configured for round pipe operation. The rotation mechanism is adjustable for a range of pipe diameters. The DMR is designed for operation in pipe with a minimum internal diameter of 860 mm and outside of pipe with a minimum external diameter of 420 mm.

For the operations within the pipes, such as internal pipe inspection, the robot can drive by wheels inside the narrow pipe, as shown in Fig. 6.27 (a). Both drive motors are providing the traction to the rear wheels, which are actuated by the dual drive systems. If the internal diameter of pipe is larger than 2 m, the DMR also can drive by tracks for better traction performance, as shown in Fig. 6.27 (b).

![Fig. 6.27: Configurations of DMR for operations within the pipes](image)

For the operations on the surface of pipes, the angles between track-wheel driving modules can be adjusted to fit the round surface of pipes, as shown in Fig. 6.28. In this
case, the robot is clamped outside the pipe by using the track-wheel driving modules. Both modules are providing the traction to the tracks.

**Fig. 6.28:** Configurations of DMR for operations on the surface of pipes
CHAPTER 7

CONTROL SYSTEM DESIGN

7.1 Introduction

This chapter presents the control system of the DMR. The platform of DMR involves five work statuses in which the controller has to control four brushless DC motors, two linear actuators, and four clutches. There are challenges in the control system design, such as simultaneous motions, switching between modes, function stability, and reliability.

To address the problems, for hardware design, Logosol Distributed Control Network modules were selected; for software design, "status machine" is adopted to analyze the working statuses, and μC/OS-II Real-Time Operating system selected to develop the embedded software. The experiments verified the rationality of the control system design.

Section 7.2 presents the electronic hardware architecture of DMR. Three major sub-systems are described in details. Section 7.3 discusses the detail design of embedded software. Three levels of tasks are performed to control the robot. DMR can be controlled by cable or wirelessly. Two types of operator control methods are described in Section 7.4. For the wireless control, the operator control unit (OCU) is not considered due to the limited budget. Gamepad and laptop provide a simple and low cost solution to substitute
the OCU. User interface software is developed by using Labview2009 to link the gamepad and laptop with the other subsystems on the DMR. The user interface software is presented in Section 7.5.

7.2 Electronic Hardware Design

The electronic hardware architecture includes three sub-systems: communication, onboard control/drive, and power supply. As shown in Fig. 7.1, master controller processes the data from wireless module or joystick, and then sends commands to drives respectively to control four brushless DC motors, two linear actuators and four clutches. In addition, six limit switches (LM) are used to perform the homing function, and two 37V batteries together with two DC/DC converters supply power to the system. The following sections will describe each sub-system in details.

7.2.1 Communication Subsystem

The DMR can be controlled in two remote control modes, as shown in Fig. 7.2: (a) Cable control with commands from joystick; and (b) Wireless control with commands from gamepad-computer-wireless modules. The remote control modes allow an operator to directly control the motors and actuators on the DMR from a distance via cable or wireless RF signals.
The cable control mode was developed for indoor testing as an early development stage. Since the master controller on DMR can directly process the signals from joystick, the cable control mode allows testing the robot without the complexity and expense of a wireless system. In this version of DMR, Logosol Joystick Node LS-731 is selected to send commands to master controller with the axes and buttons, and display the systemic status via the LEDs. As shown in Fig. 7.3, LS-731 is a multifunctional joystick controller. It has 3 axes, 3 pushbuttons and 2 stick pushbuttons. Standard RJ-45 connectors and commercially available cables are used to connect modules into a network.
Fig. 7.2: Two remote control modes of DMR: (a) cable control and (b) wireless control (Photos taken at ESI premises)

Fig. 7.3: Multifunctional joystick controller: Logosol Joystick Node LS-731

To obtain a greater operational range, the communication system of DMR was updated to wireless control at the prototype testing stage. XBee-PRO XSC RF modules are selected because of their compact design and low cost. Referring to Fig. 7.4, the data transmitted by the RF modem from laptop via USB port is received by XBee-PRO XSC RF module
which is installed on the top of DMR’s center platform. The RF module communicates with the master controller via RS-232 port.

Fig. 7.4: XBee-PRO XSC RF modules for wireless control mode

7.2.2 Control and Drive Subsystem

For reduction of overall system development time and cost, all the Distributed Control Network Modules, master controller and drivers considered in this design, are off-the-shelf components. As shown in Fig. 7.5 (a), a Rabbit 2000™ microprocessor based controller, Logosol Network Master Controller LS-981, is used to process the data from wireless module (via one RS-232 serial port) or from joystick (via one Logosol Distributed Control Network (LDCN) port), and then sends commands to drives via the other LDCN port and four optoisolated digital outputs (PE0, PE2, PE4 and PE6) respectively. The programming is accomplished via a standard RS-232 port by using Z-World’s Dynamic C development environment. There are three types of drives: servo drive for DC brush motor, clutch drive and linear actuator drive.
The servo drive, Logosol Intelligent Hall-Servo Drive LS-173U, is utilized to control brushless DC motors based on the commands from master controller LS-981 via a LDCN, as shown in Fig. 7.5 (b). LS-173U is a single-axis motion controller with integrated servo amplifier designed for applications using Hall-Servo mode for controlling of brushless motors. Trapezoidal brushless motor commutation is performed automatically if Hall sensors are connected to the unit.

![Logosol Network Master Controller LS-981 and Logosol Drive LS-173U](image)

**Fig. 7.5:** (a) Logosol Network Master Controller LS-981; (b) Logosol Drive LS-173U

In this version of DMR, four intelligent servo drives are controlled over a multi-drop full duplex RS-485 network in a distributed motion control environment, as shown in Fig. 7.6. Standard RJ-45 connectors and cables are used for daisy chaining of the modules.

The clutch drive is integrated on Power Board, so the master controller LS-981 can control two relays (HLS-4078-M-DC12V) to drive four clutches via its two opto-isolated digital outputs (PE4 and PE6). The linear actuator drive, NMI-D-Rex, is utilized to
control two linear actuators based on two opto-isolated digital outputs (PE0 and PE2) of master controller LS-981 and the information of two limit switches. The NMI-D-Rex is an inexpensive, easy-to-use, 0-to-150 KHz PWM control input, 7 Amp, 0-to-15 Volt, and true dual H-Bridge.

Fig. 7.6: The multi-drop full duplex RS-485 network

7.2.3 Power Supply Subsystem

Two packs of 10-cell high power polymer Li-Ion battery (PL-9759156-10S-MTM-G) are carried in the center platform of DMR. Each polymer Li-Ion battery cell provides 37V at 10Ah. The Li-Ion battery packs are connected in parallel for achieving higher current output and ampere-hour capacity. The battery system provides 37V and 20Ah capacity within a mass of 4.4 Kg, as shown in Fig. 7.7.
A protection circuit module (PCM) with balance function is installed in each battery pack. This PCM is specially designed for 37 V Li-Ion/polymer Li-Ion Battery pack with 30A discharging rate. PCM will detect each cell's voltage and trim higher voltage down until other cells reach the same voltage level. Therefore, it will increase Li-Ion cells service life, and provides protections for over charge or over discharge battery.

In the DMR prototype, the parallel connection polymer Li-Ion batteries provide peak voltage of 41V, nominal voltage of 37V, and peak current discharge under 60A. The rechargeable battery system covers up to 8 hours of platform operations (without any payload).
To supply the power for master controller, clutch and linear actuator, etc., an in-house designed Print Circuit Board (PCB) power board is used in the DMR, as shown in Fig. 7.8. The Power Board mainly includes two DC/DC converters: CHB150W_48S12 and CHB150W_48S24. The former generates 12V power to supply the master controller, servo drives and linear actuator drive. The latter generates 24V power to supply clutch drives and brakes.

Fig. 7.8: In-house designed Power Board for DMR
7.3 Embedded Software Design

μC/OS-II Real-Time Operating System is a simple, clean, efficient, easy-to-use real-time operating system that runs on the Rabbit microprocessor and is fully supported by the Dynamic C development environment.

It is capable of intertask communication and synchronization via the use of semaphores, mailboxes, and queues. User-definable system hooks are supplied for added system and configuration control during task creation, task deletion, context switches, and time ticks. In addition, with Dynamic C, there is no fee to pay for the “Object Code Distribution License” that is usually required for embedding μC/OS-II in a product. Whereas there are many advantages, the embedded software is developed based on μC/OS-II Real-Time Operating system, and the following functions have been performed:

• Stop the mobile robot if valid commands have not been received for 1 second.

• Send the status of mobile robot to display device (joystick or laptop) every 125 ms.

• The mobile robot can run into track, wheel, switch, flipper and stop mode according to the commands received from joystick or gamepad.
7.3.1 Task Assignment and μC/OS-II Configuration

According to the above required functions, three tasks are assigned.

- Task 0: Emergency Stop, the priority is 0 (high)
- Task 1: Status Sending, the priority is 1 (middle)
- Task 2: Mode Switching, the priority is 2 (low)

The following Table 7.1 summarized the main systemic parameter configurations of μC/OS-II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Annotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS_TICKS_PER_SEC</td>
<td>8</td>
<td>8 ticks in one second, i.e. one tick is 125ms.</td>
</tr>
<tr>
<td>OS_MAX_TASKS</td>
<td>3</td>
<td>The max number of tasks (less stat and idle tasks) is 3.</td>
</tr>
<tr>
<td>OS_MAX_MEM_PART</td>
<td>3</td>
<td>The max number of memory partitions is 3.</td>
</tr>
</tbody>
</table>

Task 0: Emergency Stop

Referring to Fig. 7.9, Task 0 with the high priority checks if the master controller receives valid commands from joystick or gamepad every one second, if not, it will stop the mobile robot peremptorily for safety reason.
**Task 1: Status Sending**

Task 1 with the middle priority reads and sends the status of DMR every 125ms, as shown in Fig. 7.10.

**Fig. 7.9:** Task 0 flow chart  **Fig. 7.10:** Task 1 flow chart

**Task 2: Mode Switching**

Task 2 with the low priority receives the commands (button and axis values) from joystick or gamepad and controls the robot to run in the following five statuses:

- **Track** - the two tracks of robot are driven to run
- **Wheel** - the two wheels of robot are driven to run
- **Switch** - switch the robot running mode between track and wheel mode
- **Flipper** - adjust the angle positions of two swing arms
- **Stop** - stop robot
In order to switch the status from one to another successfully and ensure the systemic stability, the finite-state-machine (FSM) is implemented to control the mode switching.

The state diagram for cable control method is showed in Fig. 7.11.

![Mode switch state diagram (cable control)](image)

**Fig. 7.11:** Mode switch state diagram (cable control)

Note: Button1, Button2 and Button3 are the button values; Js_x, Js_y and Js_z are the axis values.

### 7.4 Operator Control Methods

There are two operator control methods: (a) Cable control with commands from joystick (Fig. 7.12 (a)); and (b) Wireless control with commands from gamepad (Fig. 7.12 (b)).
Both controllers include several axis and control buttons that perform the following functions.

1. Perform forward, backward, right turn and left turn motions in Track and Wheel modes.
2. Switch the robot running mode between Track and Wheel modes.
3. Perform emergency stop.
4. Adjust the angle positions of two swing arms in Track and Wheel modes.

Two operation methods are illuminated by the following two tables (Table.7.2 and 7.3) in detail.

![Joystick Image]

**(a): Joystick**

*Fig. 7.12 (a): joystick*
(b): Gamepad
Front View

(b): Gamepad
Top View

Fig. 7.12 (b): gamepad
<table>
<thead>
<tr>
<th>Mode</th>
<th>LED</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
<td>x turn left (x-) or right(x+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
<td>y forward (y-) or back(y+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>z adjusting the angle of two flippers simultaneously</td>
</tr>
<tr>
<td>Wheel</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
<td>x turn left (x-) or right (x+) by controlling the angle of two flippers simultaneously</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
<td>y forward (y-) or back(y+)</td>
</tr>
<tr>
<td>Flipper</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
<td>B3 keep pressing Button3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
<td>x adjust the angle of left flipper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>y adjust the angle of right flipper</td>
</tr>
<tr>
<td>Switch</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
<td>B1 keep pressing Button1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>z control two linear motors: clockwise, switch to track mode; counterclockwise, switch to wheel mode.</td>
</tr>
<tr>
<td>Stop</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
<td>B2 keep pressing Button2</td>
</tr>
</tbody>
</table>
Table 7.3: Gamepad operation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Gamepad Command</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>LB</td>
</tr>
<tr>
<td>Track</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flipper</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stop</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: All statuses are shown on the User Interface that is developed by Labview.
7.5 User Interface Design

For the wireless control mode, the User Interface software interfaces the gamepad and laptop with the other subsystems on the DMR. It was developed in the Labview2009 development environment, and performed the following functions:

- Receive the input data of gamepad and convert them to corresponding commands
- Send the commands via wireless RF module every 100ms
- Receive and display the status of DMR via wireless RF module every 100ms

According to the above functions, multithreading is implemented, and two threads are configured: One thread receives the input data of gamepad and converts them to corresponding commands, and then sends the commands to the serial transmitting buffer; the other one reads the serial receiving buffer, unpacks the data, and then displays the status of DMR.

There are two levels of interface in the user interface software: main panel and data viewer. The main panel allows using graphical representations of the status of the robot. The second interface, data viewer is implemented for view and analysis the saved feedback data, such as motor speed, current, etc. Fig. 7.13 shows the main panel of user interface software.
**Fig. 7.13:** Overview of the main panel in user interface software

The main panel is a framework for real-time data visualization, logging, and analysis. It consists of real-time plotters, status indicators, pull down menu and control buttons. On the left side, four real-time plotters are used to display the speed and current of four motors. Real-time plotter can automatically update graphs of feedback data while it is being receiving by RF modules. In the middle of four real-time plotters, there is a mode status indicator which indicates the current mode of DMR to operator. On the right side, several tables and indicators show the information of gamepad. At the bottom of right corner, the pull down menu has commands for logging, reading and viewing the feedback data. As shown in Fig. 7.14 and 7.15, the file viewer interface can display the saved feedback data numerically and graphically.
Fig. 7.14: The data viewer of user interface software (data table page)

Fig. 7.15: The data viewer of user interface software (graph page)
CHAPTER 8

EXPERIMENTS AND RESULTS

8.1 Introduction

For demonstrating the novel design based on the adaptable design paradigm, a full functional prototype of DMR has been built as part of this research. Four different robot configurations of DMR can be created from the same design and can be modified from one type to another for different applications requiring various configurations of the robot. The adaptation of these configurations based on requirements of customers could also be performed with minimum effort by replacing parts.

The DMR has been designed for flat, rough and uneven terrain applications. A series of experiments have been conducted to demonstrate the effectiveness of DMR’s novel locomotion system. Mobility modes including extended/stowed, terrain crossing, push-up, free-wheel and parking modes have been verified with the prototype. In addition, several superior maneuvers, such as stair climbing, real-time interchanging, skid and independent steering have been performed with the physical prototype in real-world environments.

Section 8.2 presents various configurations of the DMR prototype to show its product adaptability. The traction system can be easily configured by users to use wheels, tracks
or the hybrid system. Various attachments, such as a manipulator can be installed and removed conveniently through adaptable interfaces. Section 8.3 and 8.4 demonstrate the validations of mobility modes and maneuvers which are presented in Section 6.5. A summary of the dual mobile robot derived specifications are outlined in appendix A.

8.2 Robot Configurations

Considering the concept of product adaptability, the DMR is developed with the expectations that traction system can be easily adapted to suit a wide range of terrains, and additional hardware can be attached to the platform with minimal effort.

Different applications require the robot to move on various types of terrain (indoor, structure and unstructured terrain). To increase the adaptability of the robot on different terrain types, the DMR can be configured to drive on four configurations as follows. Furthermore, users can easily modify or upgrade the DMR that has already been created to achieve these configurations.

8.2.1 Tracked Mobile Robot Configuration

Tracked mobile robot configuration is the simplest configuration of DMR. The platform consists of two driving modules and one center platform, as shown in Fig. 8.1. Referring to Fig. 8.2, the driving module is simplified from track-wheel driving module by removing several wheel components, such as hubless rear wheel, swing arm mechanism.
The center platform does not include the rotation mechanism. From Table 5.4, tracked mobile robot configuration has the least components and the lowest cost. It provides a basic locomotion function which is similar to most of conventional tracked mobile robots.

**Fig. 8.1:** Tracked mobile robot configuration of DMR

**Fig. 8.2:** Driving module for tracked mobile robot configuration of DMR

### 8.2.2 Tracked Mobile Robot with Swing Arm Configuration

Tracked mobile robot with swing arm configuration is based on the tracked mobile robot configuration of Section 8.2.1, as shown in Fig. 8.3. Referring to Fig. 8.4, two swing arm mechanisms and their driving systems have been added on the driving modules. Since the swing arm mechanism can be used as a flipper to lift the robot’s nose up to climb stairs and overcome obstacles, this configuration of DMR enhanced its ability of obstacle surmounting.
8.2.3 Wheeled Mobile Robot Configuration

Wheeled mobile robot configuration is different than the tracked mobile robot configuration. Referring to Fig. 8.5 and Fig. 8.6, the platform consists of two driving modules and one center platform. The driving module in this configuration is another version which is modified from track-wheel driving module by removing several track components, such as track, track tensioning mechanism. The swing arm mechanism is acting as a steering system similar to car steering.
8.2.4 Track-wheel Hybrid Mobile Robot Configuration

The rotation mechanism in the center platform and two track-wheel driving modules provide this unique track-wheel hybrid configuration of DMR. As shown in Fig. 8.7 and Fig. 8.8, the DMR can quickly convert from a tracked robot into a wheel robot by rotating the track-wheel driving module 90 degrees. Track-wheel hybrid mobile robot configuration is the most complex configuration of DMR. It requires more components and has higher cost. However, this configuration maximized the advantages of tracked and wheeled mobile robot.

![Fig. 8.7: Track mode in track-wheel hybrid mobile robot configuration](image)

![Fig. 8.8: Wheel mode in track-wheel hybrid mobile robot configuration](image)

8.3 Modes of Mobility Validation

The DMR prototype provides the opportunity to show the usability and capability of the platform. Several experiments and tests have been conducted to demonstrate the modes of mobility that the DMR can provide as claimed in Section 6.5.1. All the experiments and tests are based on the track-wheel hybrid mobile robot configuration of the DMR with a
10kg manipulator as payload.

8.3.1 Track and Wheel Mode

The DMR prototype with its track and wheel mode has been tested for velocity and energy consumption analysis. Two modes of the DMR have been tested on the same terrain condition and travelled distance separately. The indoor test is on a carpet surface and the surface of outdoor test is concrete. While the DMR prototype is travelling the testing path, the average velocity is obtained. The experimental results shown in Table 8.1 indicate that the velocity of wheel mode is more than 1.5 times faster than track mode.

<table>
<thead>
<tr>
<th></th>
<th>Track Mode (m/s)</th>
<th>Wheel Mode (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor (carpet)</td>
<td>0.76</td>
<td>1.21</td>
</tr>
<tr>
<td>Outdoor (concrete)</td>
<td>0.74</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Table 8.1: Velocity (m/s) of track mode and wheel mode

For the energy consumption, a set of tests have been conducted to measure the current drawn for a 10 m long straight path on the same terrain condition. During the tests, the voltage of the driving motors are set to 36V. The calculated results are listed in Table 8.2. The results show that wheel mode of the DMR consumes significant less energy and has a higher speed as expected.
Table 8.2: Energy consumption of track mode and wheel mode

<table>
<thead>
<tr>
<th></th>
<th>Track Mode</th>
<th>Wheel Mode</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor (carpet)</td>
<td>1.145wh</td>
<td>0.528wh</td>
<td>46.11%</td>
</tr>
<tr>
<td>Outdoor (concrete)</td>
<td>1.662wh</td>
<td>0.715wh</td>
<td>43.02%</td>
</tr>
</tbody>
</table>

8.3.2 Interchange Mode

A series of pictures in Fig. 8.9 show that the rotation mechanism is used to convert the DMR prototype from the track to the wheel mode. On each side, the linear actuator inside the center platform pushes forward. The slider-crank mechanism converts the linear motion of the linear actuator to rotational motion of the track-wheel driving module. Both sides move simultaneously.

In the transition from track mode to wheel mode, when the limit switches which are located under the center platform have been pressed, it means the transition has completed. The linear actuators will stop and remain in the self-locked status. On the other hand, the transition from wheel mode to track mode completes when the built-in electrical end stop sensors stop the linear actuators.

Extensive tests have been performed in outdoor and indoor environments in order to verify the interchange mode’s capability and durability. The DMR prototype can change from track mode to wheel mode, and vice versa, successfully on various surfaces, such as marble, carpet, concrete, gravel, and natural terrain.
Transitions between track and wheel of DMR prototype have been tested in indoor environments to measure the current drawn from interchanging modes. The indoor test area is a smooth flat surface. Fig. 8.10 shows the current drawn (a) and calculated force (b) of one side of linear actuator during the first test which has no payload on top of the platform. Fig. 8.11 shows the results of second test which has a 10 kg manipulator attached to the platform. During both tests the voltage of linear actuators are set to 12V. According to the results, the transition from wheel mode to track mode draws much lower current and uses less time to complete. Additional weight of payloads will require the linear actuators to provide higher level of force during the transition.
8.3.3 Other Mobility Modes Validation

This section shows a series of other mobility modes that can be achieved by the innovative design of DMR. Those modes can be used conveniently for overcoming obstacles, recovering, and transporting.

As shown in Fig. 8.12, extended mode can provide the longest possible length (1100mm) for better stability in a stair-climbing and ditch-crossing maneuver. Fig. 8.13 shows the stowed mode of DMR prototype to minimize its own volume during transportation.
For the terrain mode, the DMR’s swing arms can be set in a fixed angle of approach in order to efficiently traverse rough terrain, as shown in Fig. 8.14 (a) and (b).

Fig. 8.12: Extended mode of the DMR prototype in 45 degree stairs

Fig. 8.13: Stowed mode of the DMR prototype

Fig. 8.14 (a) and (b): Terrain mode helps DMR to traverse rough terrain efficiently

The push up mode in Fig. 8.15 (a)-(d) demonstrates very important postures for enhancing the DMR's terrain adaptability. Fig. 8.16 (a) shows the current drawn of one side motor when DMR deploys the swing arms to raise the forward end of main body in a push-up mode. Fig. 8.16 (b) indicates the current drawn of one side motor when DMR counterclockwise rotates the swing arms from push up posture into stowed posture.
(a) Increasing ground clearance to recovery from the stuck situation

(b) Minimizing the contact length of tracks to reduce energy consumption

(c) Supporting the robot when it is descending the stairs

(d) Supporting the robot when it is off the large obstacle

**Fig. 8.15:** Push-up mode of the DMR prototype

(a) Current drawn of left flipper motor (0 to -50 degree)

(b) Current drawn of left flipper motor (-50 to +75 degree)

**Fig. 8.16:** Experiments results of push-up mode
Fig. 8.17 (a) and (b) show two transportation methods by using free wheel mode. This mode can be used in the event of having to push or tow the DMR to a desired location to start the mission or after a failure of the drive mechanism.

(a) Pushing method in free wheel mode  
(b) Towing method in free wheel mode

Fig. 8.17: Two transportation methods by using free wheel mode

Fig. 8.18 (a) and (b) show how DMR puts itself into a parked mode in which locomotion is inhibited and rigidly vehicle stability is maintained.

(a) Parked mode in wheel configuration  
(b) Parked mode in track configuration

Fig. 8.18: Two types of parked mode in different configurations
8.4 Maneuvering Validation

8.4.1 Stair Climbing

The DMR prototype with 10kg payload has been tested for climbing various types of stairs. Fig. 8.19 shows the DMR prototype climbing a staircase with an incline of 28 degrees by using its tracked chassis and pivoting swing arms. The process is as follows:

(a) Both sides of the swing arms synchronously raise the arm higher than the rise of the first stair; (b) then the robot drives the tracks forward until the arms and tracks contact the first stair step one after the other; (c) when the tracks contact the first stair step, the swing arms pivot to the position of extended mode. (d) The robot can then continue to ascend the stairs; (e)-(f) at the end of staircase, the swing arms pivot to the position of the push-up mode to support the robot; (g)-(h) when the robot is on the platform, the swing arms rotate to lower the robot until the tracks are in full contact with the ground.

Fig. 8.20 shows a series of motions of the DMR prototype climbing a staircase with an incline of 45 degrees. Since the dimensions of the DMR are specifically designed to climb common stairs, the procedures to climb the 45 degree incline are the same as the 28 degree incline (a)-(d). For stable and smooth travel on stairs, the extended mode provides the DMR to extend the wheel base up to 950mm and to come in contact with at least three steps, as shown in (e)-(f).
Fig. 8.19: Climbing a staircase with an incline of 28 degrees
The current drawn from each traction motor and velocity of climbing a 45 degree incline staircase have been recorded by user interface software and plotted in Fig. 8.21.
8.4.2 Stair Descending

The DMR can descend stairs in forward and backward motion. This feature is particularly useful when the stair landing area is too narrow for turning. In both cases, the swing arms are used to perform the descending stage. The left column photos in Fig. 8.22 show the process of descending stairs forward. Both sides of the swing arms pivot to the push-up mode for supporting the DMR when it is off the first step. The series of motions in order to descend stairs backward is shown in the right column. The chassis is tilted by the swing arms at the beginning for performing smooth stair descend.

Fig. 8.21: Experiments results of climbing 45 degree stairs
Fig. 8.22: Forward and backward stair descending
8.4.3 Surmounting a Step Obstacle

The DMR prototype with a 10kg payload has been tested for surmounting step obstacles. Fig. 8.23 shows the DMR overcomes a 20cm tall obstacle with its track mode and pivoting swing arms. The steps are as follows: (a)-(b) before approaching the step obstacle, the swing arms are set to be higher than the height of obstacle; (c) when the arms contact the step obstacle, they rotate to lift the robot up; (d) then the robot drives the tracks forward; (e)-(f) when the tracks contact the edge of step obstacle, the swing arms can pivot to the position of push-up mode for supporting; (g)-(h) for descending the step obstacles smoothly, the swing arms rotates to lower the robot until the front of tracks are in contact with the ground.

8.4.4 Steering

Steering can be used in two ways with the DMR prototype. In the track mode, the skid steering is accomplished using differential speeds of the tracks on either side of the robot. The robot can skid around its center of gravity allowing complete turning in a 100cm diameter circle with no forward or backward movement, as shown in Fig. 8.24 (a).

On the other hand, Fig. 8.24 (b) shows independent steering, a car-like steering utilized in the wheel mode. The turning radius is 148cm. It requires more space to turn around than skid steering in track mode. However, independent steering handles better and more accuracy than skid steering in high speed.
Fig. 8.23: Surmounting step obstacle
Fig. 8.24: Steering validations of DMR prototype
CHAPTER 9

CONCLUSIONS

9.1 Thesis Summary

This research has made major contributions to the mobile robot and its platform design. The results shows that the DMR with the dual drive system enhances locomotion and functionality for various applications, such as explosive ordnance disposal, search-and-rescue, surveillance, SWAT teams, and other vital tasks.

This research illustrates a unique design paradigm, “Design for product adaptability”, and uses it in mobile robot design. Product adaptability is identified as the ability of the physical product to be adapted for various functions. It is shown that this research lead to effective design and manufacturing in terms of customization capability, cost, service and maintenance. Users will benefit from the product adaptability of the mobile robot obtained through the offered modularity and re-configurability.

The proposed DMR can provide modularity, adaptability to terrain and operations, and effective use of energy. This design is based on a modular architecture of self-contained and relatively independent driving modules that can be attached, detached, modified, relocated, and replaced easily in relation to a platform. In addition, it allows attachments
of add-on accessories (manipulator, cameras, sensors) on the mobile platform.

The DMR is made up of robotic modules that can generate a set of configurations for a wide range of applications in indoor and outdoor environments. Furthermore, user and manufacturers can benefit from this design through the reuse of modules, for higher utilization and reduction of manufacturing cost.

A function-based design process for product adaptability has been conducted in the conceptual design stage. The design process for product adaptability is composed of five phases: function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design. By following the design process, two design candidates were created, both adaptable and fulfilling the design requirements. To select the most appropriate design candidate at a conceptual design stage, implementation of a design evaluation method by using the grey relational analysis approach was employed in this research to integrate different evaluation measures for prioritizing different design candidates. These design candidates are judged by different life-cycle evaluation measures including specific product adaptability, part and assembly costs of manufacturing, and operationability of customers.

After the best design candidate was chosen through the evaluation and prioritization process, the selected product configuration had been implemented through detailed design for manufacturing a prototype. This thesis presented the mechanical and control
system design in Chapters 6 and 7, respectively.

As presented in Chapter 8, the full functional prototype has been used in the final stage of this research to validate the original hypothesis experimentally. Fig. 8.1-8.8 present various configurations of the DMR prototype to show its product adaptability. The locomotion system can easily be configured by users to use wheels, tracks or interchangeable configuration if needed. The interchangeable mode between track drive and wheel drive has been tested in indoor and outdoor environments as shown in Fig. 8.9. Other modes of mobility including extended/stowed, terrain crossing, push-up, free wheel and parking modes in operation are shown in Fig. 8.12-8.18. These modes of mobility which are provided by DMR’s unique structure can be utilized in many practical tasks. In addition, the DMR is able to perform several challenging tasks successfully, such as the ascend/descend of stairs and surmounting step obstacles as shown in Fig. 8.19-8.24.

The research presented an innovative paradigm of mobile robot design that overcomes drawbacks of traditional mobile platforms by providing adaptation to various outdoor and indoor terrains. Unlike most other mobile robot designs that have an integrated architecture, this design provides a modular architecture which encourages the development of self-contained and relatively independent modules. In addition, the DMR provides the use of its modules in different configurations when new requirements are presented. The DMR is unique and patentable, and is a step forward in relation to the
state-of-the-art commercial and made-for-research mobile robots through the following major contributions:

- The DMR is based on a modular architecture which is able to prevent changes in some parts of the robot from interfering with the rest of the system. Modifications and upgrades are performed via replacements of modules.

- New track-wheel driving module that combines wheels and tracks allows real-time interchangeability according to user commands, based on terrain conditions in order to increase the efficiency of the robot on various terrains.

- Unique swing arm that is attached at the front of track-wheel driving module enhances locomotion on and off-road. In the track mode, the swing arm can work as a flipper mechanism to lift the robot’s nose up to climb stairs and overcome obstacles. In the wheel mode, the swing arm is acting as an independent steering system similar to car steering.

- A control hardware and software architecture that includes three sub-systems: communication, onboard control/drive, and power supply. Gamepad and laptop provide a simple and low cost solution to substitute the expensive OCU for remote control function. User interface software was developed using Labview2009 to link the gamepad and laptop with the other subsystems of the DMR.
9.2 Future Works

Although the extensive tests and experiments performed to demonstrate that the DMR meets the research goals, some improvements need to be further addressed in future developments. These future work is summarized as follows:

- Improve the mechanical design of DMR to enhance performance:

  **Size reduction:** The width of the current DMR in track mode is 890 mm, which is wider than the normal door size. It limits the mobility of DMR’s track mode in the indoor environments. The target width for the redesigned DMR is 750 mm which can be implemented through changing the orientation and location of certain components.

  **Weight reduction:** The weight of current DMR platform is 65 kg. Although the free wheel mode allows the DMR to be towed to its desired location when the power is off, or after a failure of the drive mechanism, it still requires two persons to lift up. The target weight for the redesigned DMR platform is less than 50 kg. It can be achieved by size reduction and design optimization of current parts.

- Develop more add-on attachments and interfaces for expanding DMR’s functions and applications:

  The flat top of center platform is free for various add-on attachments. In the
current DMR prototype, a small manipulator has been mechanically attached to
demonstrate an add-on attachment. More add-on attachments, including cameras,
sonar sensors, and infrared detectors can be considered in the future.

Electronic interfaces and related control system need to be expanded and improved
for using of add-on attachments.

• Develop an autonomous control system which can be switched on and off by remote
  control to assist the user’s operations.

  The autonomous control can select between track mode and wheel mode
  automatically based on the terrain condition to increase efficiency.

  The autonomous control can also perform various tasks to reduce the user’s
  workload including mapping, obstacle avoidance, and climbing stairs.
REFERENCE


[39] Li, Z., Ma, S. Li, B., Wang, M., and Wang, Y., "Design and basic experiments of a


## APPENDIX A

### DUAL MOBILE ROBOT SPECIFICATIONS

<table>
<thead>
<tr>
<th>Platform</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>340mm (Wheel mode); 210mm (Track mode)</td>
</tr>
<tr>
<td>Width</td>
<td>625mm (Wheel mode); 890mm (Track mode)</td>
</tr>
<tr>
<td>Length</td>
<td>860mm (Flipper stowed); 1100mm (Flipper horizontal)</td>
</tr>
<tr>
<td>Weight</td>
<td>65kg</td>
</tr>
<tr>
<td>Speed</td>
<td>1.21m/s (Wheel mode); 0.76m/s (Track mode)</td>
</tr>
<tr>
<td>Switch Time</td>
<td>27 second (Track mode to wheel mode); 25 second (Wheel mode to track mode)</td>
</tr>
<tr>
<td>Environment</td>
<td>All-weather, All-terrain; Stair climbing 45 deg; Obstacles 20 cm; Maneuvers over marble, carpet, gravel, concrete, mud, sand, natural terrain</td>
</tr>
<tr>
<td>Payload</td>
<td>50kg</td>
</tr>
<tr>
<td>Number of Tracks</td>
<td>Two tracks (width 75mm each)</td>
</tr>
<tr>
<td>Number of Wheels</td>
<td>Four wheels</td>
</tr>
<tr>
<td>Number of Motors</td>
<td>6 – 2 for tractions; 2 for flippers; 2 for rotation mechanisms</td>
</tr>
<tr>
<td>Electronics</td>
<td>Micro-processor based controller (Logosol LS-981)</td>
</tr>
<tr>
<td>Operation</td>
<td>4 – 8 hours</td>
</tr>
<tr>
<td>Communication</td>
<td>Cable control (RJ45); Wireless control (XBee-PRO XSC RF)</td>
</tr>
<tr>
<td>Transportation</td>
<td>Portable by two people</td>
</tr>
<tr>
<td>Control Panel</td>
<td>Hardware</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------</td>
</tr>
<tr>
<td></td>
<td>Software</td>
</tr>
<tr>
<td></td>
<td>Controller</td>
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<td></td>
<td>Operation</td>
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