MECHANICAL DESIGN AND DEVELOPMENT OF A DIFFERENTIAL DRIVE MOBILE ROBOT

This report is submitted in accordance with requirement of the University Teknikal Malaysia Melaka (UTeM) for Bachelor Degree of Manufacturing Engineering (Hons.)

by

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This report is submitted to the Faculty of Industrial and Manufacturing Technology and Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment of the requirement for Degree of Manufacturing Engineering (Hons). The members of the supervisory committee are as follow:

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ABSTRAK

Kajian ini bertujuan untuk menangani cabaran reka bentuk mekanikal robot mudah alih pemacu pembezaan dalam sektor perindustrian terutama dalam industri ringan dan sederhana, di mana sistem tradisional menghadapi batasan yang ketara dalam kekompakan dan integrasi komponen. Objektif utama adalah untuk mereka bentuk dan membangunkan robot mudah alih pemacu pembezaan dengan sinergi sistem pemacu tali pinggang. Seterusnya, robot mudah alih pemacu pembezaan akan disimulasikan serta dianalisiskan dengan menggunakan perisian MSC Adams, dan menilai kecekapannya serta memberi tumpuan kepada ciri-ciri tork. Dengan menggunakan Fusion 360 dalam pemodelan 3D, reka bentuk mengutamakan proses pembuatan dan pemasangan melalui teknologi percetakan 3D. Simulasi dan pengesahan eksperimen dilakukan pada pelbagai rupa bumi, termasuk platform rata serta kecerunan pada 5%, 10% dan 15%, mendedahkan bahawa robot beroperasi dengan lancar di permukaan rata dengan variasi tork yang minimum. Walau bagaimanapun, peningkatan kecerunan cerun dengan ketara meningkatkan tork yang diperlukan oleh kedua-dua roda, menggambarkan kerja yang diperlukan untuk mengatasi rintangan graviti. Pada cerun 10% dan 15%, sistem kawalan bergelut untuk mengekalkan gerakan yang stabil, dibuktikan oleh ayunan tork yang kerap dan tidak teratur dan bias trajektori, terutamanya disebabkan oleh kehilangan daya tarikan yang dialami oleh roda pemacu semasa peralihan dari tanah rata ke cerun, akibat daripada reka bentuk robot. Kehilangan daya tarikan semasa peralihan ke cerun menunjukkan batasan reka bentuk roda dan kastor. Kajian ini memberikan pendekatan yang mantap untuk membangunkan robot mudah alih pemacu pembezaan yang padat dan cekap, menawarkan pandangan berharga untuk meningkatkan produktiviti dan fleksibiliti dalam automasi industri dalam persekitaran yang terhad dan dinamik yang mencabar. Integrasi alat simulasi canggih dan teknik pengesahan praktikal memastikan sistem robotik yang dibangunkan sesuai untuk memenuhi keperluan aplikasi perindustrian moden yang sedang berkembang.

ABSTRACT

This study addresses the mechanical design challenges of differential drive mobile robots in light and medium industrial environments, where traditional systems face significant limitations in compactness and component integration. The primary objectives are to design and develop a differential drive mobile robot with an integrated belt drive system, simulate and analyse its performance using MSC Adams software, and evaluate its efficiency, focusing on torque characteristics. Utilising Fusion 360 for 3D modelling, the design prioritises ease of fabrication and assembly through 3D printing technology. Simulations and experimental validations on various terrains, including flat platforms and slopes of 5%, 10%, and 15%, revealed that the robot operates smoothly on flat surfaces with minimal torque variations. However, increased slope gradients significantly raise the torque required by both wheels, reflecting the effort needed to overcome gravitational resistance. On 10% and 15% slopes, the control system struggled to maintain stable motion, evidenced by frequent and irregular torque oscillations and trajectory deviations, primarily due to loss of traction experienced by the drive wheels during transitions from flat ground to slopes, a consequence of the robot's design. The loss of traction during transitions onto slopes pointed to the limitations of the current wheel and caster design. This research presents a reliable approach to developing compact and efficient differential drive mobile robots, offering valuable insights for enhancing productivity and flexibility in industrial automation within spatially limited and dynamically challenging environments. Integrating advanced simulation tools and practical validation techniques ensures that the developed robotic systems are well-suited to meet the evolving needs of modern industrial applications.

DEDICATION

To my supervisor

Dr. Shariman Bin Abdullah

Thank you for giving me moral support, cooperation, encouragement and also understanding

Thank You So Much I love You All Forever

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LIST OF ABBREVIATIONS

DDMR	-	Differential Drive Mobile Robot
WMR	-	Wheeled Mobile Robot
DDOF	-	Differential Degrees of Freedom
OMR	-	Omnidirectional Wheeled Mobile
AGV	-	Automated Guided Vehicle
ICC	-	Instantaneous Center of Curvature
CAD	-	Computer-Aided Design
PLA	-	Polylactic acid
SDGs	-	United Nations Sustainable Development Goals

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In the dynamic field of mobile robotics, selecting an appropriate drive system is pivotal. It influences a robot's maneuverability, controllability, and overall performance. Among the various drive systems available—such as Omnidirectional Drive, Synchro Drive, and Differential Drive—each has distinct characteristics that shape its performance.

Omnidirectional Drive systems excel in navigating crowded spaces and confined environments (Tagliavini et al. 2022). However, their specific wheel configuration and motor characteristics impose constraints on dynamics, making precise control challenging. Advanced control strategies are necessary to ensure accurate trajectory tracking, adding complexity to the system (Zijie et al. 2022).

Similarly, Synchro Drive systems, including three-wheel synchro-drive steering, offer high manoeuvrability but require sophisticated control algorithms for accurate trajectory tracking and motion control (Parween et al. 2021). The intricate designs of these drive systems and the need for advanced control highlight challenges in achieving both maneuverability and controllability.

This research project compares these advanced drive systems with the more conventional and simplistic differential drive system. The latter, characterized by its ease of control and inherent controllability advantages, emerges as a viable alternative. The aim is to elucidate the design intricacies and control challenges associated with each drive system, shedding light on comparative advantages and disadvantages to inform future developments in mobile robotics.

Furthermore, the field of robotics has witnessed unprecedented evolution, with applications spanning diverse sectors, from manufacturing to healthcare. Within this expansive landscape, the advent of mobile robots, particularly those employing a differential drive mechanism, has emerged as a critical domain requiring meticulous exploration and innovative contributions. The differential drive configuration, characterized by two independently driven wheels, offers a versatile and agile platform for autonomous systems. As industries increasingly integrate robotic solutions into their workflows, the demand for precise, efficient, and adaptable mobile robots becomes paramount.

The mechanical design and development of a differential drive mobile robot are at the forefront of current research endeavours in robotics and automation. This study is driven by recognizing the need for a systematic and scientific approach to enhance the understanding of the intricate design process and subsequent development of such robotic systems. The significance of this research is underscored by the escalating role played by mobile robots in addressing real-world challenges, such as autonomous navigation in dynamic environments, material handling, and surveillance.

Moreover, employing standard modelling software for the design phase reflects a commitment to industry best practices, ensuring that the resulting mobile robot adheres to rigorous standards of precision and reliability. The use of standard modelling software not only aligns with contemporary engineering methodologies but also facilitates seamless integration with existing design and manufacturing workflows.

The development process post-design signifies a phased and methodical progression, where each stage is meticulously planned to optimize efficiency and resource utilization. By providing essential components for the robot, this research acknowledges the collaborative nature of engineering projects, leveraging existing knowledge and resources to enhance the overall quality of the robotic system.

The fabrication process, primarily based on 3D printed parts, aligns strategically with additive manufacturing technologies. This choice is driven by the increasing accessibility and affordability of 3D printing and its inherent advantages, such as rapid prototyping, complex geometry capabilities, and material versatility. The reliance on 3D printing underscores the project's commitment to staying at the forefront of technological advancements, aligning with industry trends, and prioritizing agility and adaptability.

Furthermore, the fitting process, executed in a laboratory environment, serves as a practical bridge between the virtual design and the physical realization of the differential drive mobile robot. Integrating theoretical design with hands-on fabrication and assembly ensures a holistic and practical understanding of the development lifecycle.

The simulation and analysis of the mobile robot's performance, facilitated by implementing MSC Adams software, provide a dynamic simulation environment. Researchers can explore the mobile robot's response to diverse scenarios in a landscape where computational tools are indispensable for predicting real-world behaviour. The focus on torque characteristics and dynamic behaviour addresses the critical need to bridge the gap between theoretical design and practical application, ensuring that the robot performs optimally under varying conditions.

Evaluating performance efficiency represents the final dimension of this research, reflecting a commitment to producing not just functional but highly efficient robotic solutions. By focusing on torque characteristics and dynamic behaviour, this research aims to contribute nuanced insights to refine future robotic designs. This evaluation extends beyond theoretical simulations, incorporating practical considerations that align with real-world applications of differential drive mobile robots.

In summary, this study's background delves into the evolving landscape of robotics, emphasizing the pivotal role of differential drive mobile robots. By addressing the design and development phases using standard modelling software, 3D printing technology, and laboratory fitting processes, this research aims to contribute to the academic understanding of mobile robotics and the practical implementation and advancement of these technologies in real-world applications. As industries increasingly embrace automation, the insights gained from this study are poised to have far-reaching implications in shaping the future of robotic systems and their integration into diverse sectors of our technologically evolving society.

1.2 Problem Statement

The rapid advancement of robotics technology has spurred significant interest in developing autonomous mobile robots for various applications, including industrial automation, logistics, surveillance, and personal assistance. Differential drive robots are particularly popular among the various types of mobile robots due to their simplicity, maneuverability, and cost-effectiveness. However, the mechanical design and development of differential drive mobile robots present several challenges that need to be addressed to optimize their performance and reliability, particularly in relation to their size.

In regions such as Malaysia, cluster factories are commonly used for light and medium industrial purposes. These factories typically have limited dimensions, with production areas often constrained by machinery and apparatus placements. For example, the typical dimensions of these factory spaces are around 30 meters in length and 12 meters in width. These constraints highlight the limited space availability for mobile robots, necessitating a compact design to navigate and operate within these environments effectively.

Additionally, the size of door frames in many industrial settings poses another constraint. Standard door frames in these environments are usually about 1 meter in width and 2 meters in height. A mobile robot designed to operate in such settings must be compact enough to easily pass through these doorways, ensuring seamless movement between different factory or industrial site areas.

A smaller-sized robot is required to expand the usage of mobile robots in the industrial sector, particularly in confined production areas and through narrow doorways. One of the primary challenges in the mechanical design of differential drive mobile robots is achieving an optimal balance between size and functionality. The size of the robot significantly impacts its ability to navigate through different environments, especially in confined or cluttered spaces. A compact design can enhance the robot's manoeuvrability and flexibility, enabling it to operate efficiently in tight spaces such as warehouses, factories, or homes. However, reducing the size of the robot often complicates the integration of necessary components, such as motors, sensors, batteries, and control systems, without compromising on performance.

Traditional motor designs often attach directly to the wheels, resulting in larger robot dimensions. To overcome this issue, implementing a belt drive system can separate the motors from the wheels, addressing the space constraints. However, this solution introduces new challenges, such as ensuring proper tension in the belt to prevent slipping and efficiently transferring torque from the motor to the wheels.

Previous studies have highlighted the use of large motors in differential drive mobile robots without considering the robot's limited space. This has led to issues such as timing belt slippage due to insufficient space for a belt-tightening mechanism. These problems often arise from a lack of simulation and analysis tools to accurately predict and optimize the mechanical performance and torque requirements of the robot.

To address these challenges, implementing multibody dynamics simulation software, such as MSC Adams, in the design process can provide valuable insights into the robot's performance before proceeding to prototyping. By using simulation tools, designers can better understand the interactions between various components, optimize the placement and size of motors and other elements, and ensure the overall robustness and functionality of the mobile robot within the constraints of a compact design.

This research aims to systematically explore and develop innovative mechanical design solutions for differential drive mobile robots, focusing on optimizing size without compromising performance. By leveraging advanced simulation tools and techniques, the goal is to enhance their maneuverability, stability, and overall performance, enabling them to operate effectively in various environments. This will advance the field of autonomous robotics and expand their potential applications in the industrial sector, particularly in regions like Malaysia, where space constraints are significant.

1.3 Objective

1. To design and develop a differential drive mobile robot with an integrated belt drive system

2. To simulate and analyze the designed differential drive mobile robot's performance using MSC Adams software.

3. To evaluate the performance efficiency of the differential drive mobile robot, focusing on aspects of torque characteristics.

1.4 Project Scope

The project aims to design and develop a differential drive mobile robot with an integrated belt drive system tailored for efficient operation in light and medium industrial purposes, which poses unique spatial constraints with production areas often confined by machinery and apparatus placements. The robot's design will emphasize compact dimensions, essential for seamless navigation through narrow spaces and standard industrial door frames, typically measuring around 1 meter in width and 2 meters in height.

Using Fusion 360, the project will commence with comprehensive 3D modelling and design of the robot. This phase will optimize the layout and integration of the differential drive system alongside the belt drive mechanism to ensure functionality and compactness. The design process will prioritize ease of fabrication and assembly, leveraging 3D printing technology to produce components with precision and efficiency.

Simulation and performance analysis will constitute a critical project phase, employing MSC Adams software to simulate various operational scenarios. This simulation-driven approach aims to evaluate the robot's maneuverability, torque distribution efficiency, and overall stability across diverse terrain configurations. The simulations will provide insights into the robot's performance capabilities, guiding iterative design refinements to enhance operational effectiveness in real-world industrial environments.

Furthermore, experimental validation will complement the simulation results by conducting trials across different terrain configurations. These experiments will include flat platforms and inclined surfaces with 5%, 10%, and 15% road slopes. The objective is to validate the simulated performance metrics and assess the robot's ability to navigate and perform tasks under realistic operational conditions. This iterative simulation, analysis, and experimental validation process will ensure that the developed mobile robot meets the stringent requirements of industrial automation, particularly in environments characterized by limited spatial constraints and dynamic operational challenges.

Ultimately, the project's scope encompasses a holistic approach to advancing autonomous robotics technology, specifically tailored for industrial applications in Malaysia's cluster factory settings. By integrating advanced design methodologies with practical simulation and experimental validation, the project aims to contribute to the evolution of compact and efficient mobile robots capable of enhancing productivity and flexibility in industrial automation scenarios.

1.5 Summary

In summary, this study focuses on the mechanical design and development of differential drive mobile robots, highlighting the importance of selecting an appropriate drive system for optimal maneuverability, controllability, and performance. The differential drive system, known for its simplicity and control advantages, is emphasized as a viable choice for various applications, including industrial automation, logistics, surveillance, and personal assistance.

The research addresses the challenges associated with designing compact differential drive robots that can navigate confined spaces and narrow doorways, particularly in regions like Malaysia, where cluster factories have limited dimensions. Standard modeling software and 3D printing technology are employed to ensure precision, reliability, and ease of fabrication and assembly.

The study involves a phased development process, including comprehensive 3D modeling using Fusion 360 and performance simulation using MSC Adams software. The simulations aim to evaluate the robot's maneuverability, torque distribution efficiency, and overall stability across diverse terrain configurations. Experimental validation complements the simulation results, ensuring the robot meets the stringent requirements of industrial automation.

Ultimately, this research aims to advance autonomous robotics technology by developing compact and efficient differential drive mobile robots. By integrating advanced design methodologies with practical simulation and experimental validation, the project seeks to enhance productivity and flexibility in industrial automation scenarios, particularly in environments characterized by limited spatial constraints and dynamic operational challenges.

CHAPTER 2
LITERATURE REVIEW

This chapter explores the fascinating world of mobile robot locomotion. It provides an in-depth exploration of the fundamentals of locomotion, essential characteristics of robot locomotion systems, and a detailed look at legged mobile robots, wheel-based locomotion, and wheel types and configurations in mobile robotics. This chapter also emphasizes the importance of understanding the mechanical intricacies of mobile robots for tailoring mobile platforms to specific tasks and developing precise control software.

2.1 Mobile Robot Locomotion: An In-Depth Exploration

In the past three decades, mobile robots have garnered substantial attention, propelled by their applications in exploring complex environments, navigating space, conducting rescue operations, and executing tasks without human intervention (Biswal & Mohanty. 2021). The cornerstone of a mobile robot's design lies in its locomotion system, a pivotal component intricately linked to the robot's intended function.

2.1.1 Fundamentals of Locomotion

While seemingly distinct, locomotion and manipulation share a fundamental scientific basis. Manipulation involves a stationary robot arm moving objects within its workspace by applying force, whereas locomotion sees the environment as fixed, with the robot propelling itself by exerting force on its surroundings. Common denominators in both locomotion and manipulation studies include actuators generating interaction forces and mechanisms implementing desired kinematic and dynamic properties.

Core issues binding locomotion and manipulation include stability, contact characteristics, and the type of environment:

1. Stability
    - Number and geometry of contact points.
    - Center of gravity.
    - Static/dynamic stability.
    - Terrain inclination.

2. Characteristics of Contact
    - Contact point/path size and shape.
    - Angle of contact.
    - Friction.

3. Type of Environment:
    - Structure.
    - Medium (e.g., water, air, soft or hard ground).

2.1.2 Essential Characteristics of Robot Locomotion Systems

The locomotion system of a robot is pivotal in mobile robot design, dictated not only by the working space but also by technical considerations such as maneuverability, controllability, terrain conditions, efficiency, and stability (Biswal & Mohanty. 2021). Given the myriad ways robots can move, the selection of a locomotion approach becomes a critical aspect of mobile robot design.

Research robots exhibit an impressive array of locomotion capabilities in laboratory settings, including walking, jumping, running, sliding, skating, swimming, flying, and rolling. Based on their locomotion systems, mobile robots can be broadly classified into two major categories:

1. Legged Robots:
   Legged robots emulate the walking or running motions observed in biological systems. Quadrupedal and hexapod configurations offer adaptability in traversing challenging terrains, making them suitable for search and rescue missions and exploration applications.

2. Wheeled Robots:
   Wheeled robots, equipped with various wheel configurations like differential drive and omnidirectional wheels, provide simplicity, stability, and ease of control. These systems excel in environments with flat and structured surfaces, where precise navigation is essential.

Understanding the intricacies of locomotion systems is fundamental to designing mobile robots that can effectively operate in various scenarios. As technology advances, the integration of advanced control algorithms, AI-driven decision-making, and innovative materials will continue to shape the landscape of mobile robot locomotion, unlocking new possibilities for exploration, industry, and beyond.

2.2 Legged Mobile Robots

Legged locomotion distinguishes itself through a series of point contacts between the robot and the ground, offering unique advantages in adaptability and maneuverability, particularly in challenging terrains. The fundamental characteristic of legged robots is the ability to traverse varied landscapes by maintaining ground clearance between these contact points, facilitating easy navigation of rough surfaces. This adaptability is further highlighted by the capability to cross holes or chasms if the robot's reach exceeds the width of the obstacle.

A notable advantage of legged locomotion lies in the potential for intricate manipulation of objects within the environment. Drawing inspiration from nature, the dung beetle serves as a remarkable example. This insect showcases the dexterity of legged locomotion by simultaneously rolling a ball while navigating through its environment using its adept front legs (Gong et al. 2023).

However, the prowess of legged locomotion comes with inherent challenges, primarily in power consumption and mechanical complexity. The legs, often featuring multiple degrees of freedom, must support the robot's weight and lift and lower the entire system. The effectiveness of high manoeuvrability hinges on the legs having sufficient degrees of freedom to exert forces in various directions.

Biologically inspired legged robots find their roots in studying successful leg configurations in diverse organisms. Large mammals and reptiles typically have four legs, while insects like ants exhibit six or more legs. Some mammals, including humans, have perfected walking on two legs, showcasing exceptional balance even to the extent of jumping with one leg. However, the increased manoeuvrability associated with fewer legs demands more complex active control to maintain balance, underscoring a trade-off in legged locomotion.

Achieving static walking in legged robots necessitates a minimum of four legs, allowing for a statically stable tripod of legs to maintain contact with the ground. The number of degrees of freedom in legged mobile robots plays a crucial role in their movement. A minimum of two degrees of freedom is typically required to move a leg forward, involving lifting the leg and swinging it forward. Adding a third degree of freedom allows for more intricate maneuvers, while recent advancements in bipedal walking robots incorporate a fourth degree of freedom at the ankle joint. This ankle articulation empowers the robot to shift the force vector of ground contact by manipulating the pose of the sole.

While additional degrees of freedom enhance a robot's manoeuvrability, they come with trade-offs in energy consumption, control complexity, and increased mass. Extra actuators demand additional energy and intricate control systems, contributing to the overall mass of the leg and escalating power and load requirements on existing actuators.

The spectrum of legged locomotion designs spans from single-legged robots to hexapods. Each design brings its own set of challenges and innovations, marking significant strides in the field of mobile robotics.

2.2.1 One-Legged Robot

At the forefront of legged locomotion innovation stands the one-legged robot, embodying a minimalist approach that capitalizes on the fundamental advantages of legged mobility. Despite its seemingly simplistic nature, the design of a single leg brings forth compelling advantages, addressing critical factors such as body mass, leg coordination, and adaptability to challenging terrains.

The rationale behind a one-legged robot is rooted in the significance of minimizing cumulative leg mass. In walking machines, where body mass is critical, having a solitary leg reduces the overall mass, contributing to more efficient locomotion. Coordination, a challenge in robots with multiple legs, becomes a non-issue with a single-legged design. The simplicity of managing a solitary leg eliminates the need for intricate coordination between multiple limbs.

A vital advantage of the one-legged robot lies in its approach to contact points with the ground. Unlike wheeled counterparts that rely on an entire track, a leg, with its single contact point, adapts seamlessly to rough terrains. The single-legged robot manoeuvres through challenging landscapes by relying on a sequence of single contacts, allowing it to navigate rough terrains easily. Additionally, the design permits dynamic crossing of larger gaps, a feat unattainable for multi-legged walking robots limited by their reach.

However, the primary challenge in creating a one-legged robot is the need for balance. Unlike robots with multiple legs that can achieve static walking and stationary stability, a single-legged robot faces inherent challenges in maintaining balance. Static walking becomes impossible, necessitating dynamic stability mechanisms to actively balance the robot during movement.

A notable example of a single-legged hopping robot is the Raibert hopper, celebrated for its advancements in dynamic stability (Zhu et al. 2018). This robot employs continuous corrections to body attitude and velocity by adjusting the leg angle concerning the body. Actuated hydraulically, the Raibert hopper executes high-power longitudinal leg extensions during the stance phase, propelling itself back into the air. While this design showcases remarkable capabilities, it comes with the trade-off of requiring a substantial off-board hydraulic pump to be connected to the robot.

Essentially, the one-legged robot represents a bold exploration of minimalistic yet efficient-legged locomotion. As researchers delve into the intricacies of dynamic stability and balance, the advancements in single-legged robotics contribute to the evolution of legged locomotion and the broader landscape of mobile robotics, offering insights into adaptability and efficiency in challenging environments.

2.2.2 Two-Legged Robot

Over the past decade, remarkable progress has unfolded in bipedal locomotion, with two-legged robots assuming a pioneering role in replicating human capabilities. Endowed with state-of-the-art sensor technologies and sophisticated control systems, these robots exhibit the capacity for walking, verbal expression, emotional articulation, and executing intricate motions. This marks a significant advancement towards mirroring human functions.

A central challenge in bipedal locomotion is the perpetual pursuit of balance. In contrast to their multi-legged counterparts, two-legged robots depend on dynamic stability to perform complex manoeuvres such as running, jumping, traversing stairs, and even executing aerial tricks like somersaults. The complexity of these motions arises from the relatively diminutive size of the robot's feet, necessitating continuous dynamic balance control. Even maintaining a stationary posture demands sophisticated control mechanisms, emphasizing the pivotal role of dynamic stability in the design and operation of bipedal robots (Kawabata & Iba, 2019).

Humanoid robots, designed to emulate human features and capabilities, exhibit diverse forms, ranging from full-sized bipedal robots to specialized robotic arms or heads with human-like sensing and expression. The autonomy of locomotion in humanoid robots involves modules such as local path planning based on environmental observation, global path planning using geometrical information, footstep planning, and a comprehensive motion planner. These modules empower humanoid robots to navigate and interact in dynamic environments, considering aspects such as grasping objects, footstep placement, and full-body motions (Kawabata & Iba, 2019).

Atlas, a notable bipedal robot, distinguishes itself for its versatility and application in search and rescue missions. With 28 hydraulically-actuated degrees of freedom, stereo cameras, and a Lidar system, Atlas can perform diverse tasks, including walking, lifting, carrying, climbing stairs, and navigating challenging terrains. Its anthropomorphic design enables it to mimic human actions, proving invaluable in scenarios where human presence might pose risks (Feng et al., 2015).

Bipedal robots offer a unique advantage, with their anthropomorphic shape closely resembling human dimensions. This characteristic positions them as valuable tools for research in human-robot interaction. WABIAN-2R, developed at Waseda University, Japan, exemplifies this anthropomorphic approach, emulating human motion and showcasing the ability to dance. However, the static stability of bipedal robots within certain limits demands continuous balance correction through servoing, even when stationary, adding to the complexity of achieving balance in bipedal locomotion (Otani et al., 2013).

As the field of bipedal robots evolves, it presents new avenues for exploring humanoid capabilities. Atlas and WABIAN-2R exemplify the expanding landscape of robotic mobility, pushing the boundaries of what these machines can achieve. Research focused on refining balance control, load distribution, and human-robot interaction is key to unlocking the full potential of bipedal robots.

2.2.3 Four-legged Robot

When demands necessitate heightened safety and enhanced payload capability, quadruped robots take the forefront. Characterized by their four legs, quadrupeds inherently possess static stability when stationary, offering advantages in scenarios where maintaining a steady stance is crucial. Standing still on four legs is inherently passively stable; however, complexities arise during walking motions, requiring active shifts in the robot's center of gravity to maintain stability, introducing intricate control and leg coordination challenges.

These substantial robots' control systems and leg coordination are considerably more complex, demanding high computational speed for efficient operation. The motors and power storage systems required for quadrupeds come at a cost in terms of financial investment and energy consumption.

A notable example of quadruped robots is the AIBO robot developed by Sony (Knox & Watanabe, 2018). Sony's innovative approach involves creating a new robot operating system with near real-time capabilities and developing geared servomotors with high torque to support the robot while remaining back-drivable for safety. AIBO incorporates a colour vision system, enabling it to track and chase a brightly coloured ball. Remarkably, the robot demonstrates functionality for at least one hour before necessitating recharging, showcasing advancements in power efficiency.

Quadruped robots, exemplified by AIBO, have the potential to serve as compelling artifacts for research in human-robot interaction. AIBO's walking style and general behaviour, designed to emulate learning and maturation, lead to dynamic behavioural changes that captivate the owner's interest over time. As challenges in high-energy storage and motor technology continue to be addressed, quadruped robots surpassing AIBO's capabilities are poised to become commonplace in diverse human environments.

Another notable instance of quadruped robots is BigDog, developed by Boston Dynamics and commissioned by the American Defense Advanced Research Projects Agency (DARPA) (Ding, 2015). BigDog is a rough-terrain robot designed to walk, run, climb, and carry heavy loads. Its power is derived from an engine that propels a hydraulic actuation system. BigDog's legs are articulated similarly to an animal's, incorporating compliant elements to absorb shocks and recycle energy between steps. This project aims to equip BigDog with the capability to navigate terrains where both humans and animals can traverse, exemplifying the versatility and potential impact of quadruped robots in various applications.

In conclusion, quadruped robots embody a captivating convergence of stability, mobility, and payload capacity. As technological advancements persist, these robots are poised to play crucial roles in diverse fields, contributing to advancements in robotics and reshaping interactions with intelligent machines.

2.2.4 Six-Legged Robots

Within the robotics domain, the number of legs a robot possesses plays a pivotal role in determining its stability and manoeuvrability. A particularly intriguing category is the six-legged robot, renowned for its statically stable characteristics that enable controlled and deliberate movements across various environments. The advantage of static walking techniques in these robots lies in reducing control complexity.

The hexapod, a typical architecture for six-legged robots, has garnered popularity in mobile robotics, providing a robust platform for studying and implementing stable locomotion (Skaburskyte et al. 2017). Hexapod gaits exhibit stability even on rocky and uneven terrain, showcasing versatility in different environments. These robots can employ various gaits, such as the one-leg-at-a-time approach or a quadruped gait, ensuring adaptability to diverse scenarios. An inherent advantage of hexapods is their ability to continue walking even if one or two legs become disabled.

Each leg typically boasts three degrees of freedom in hexapod robots, encompassing hip flexion, knee flexion, and hip abduction. This articulation grants these robots a high degree of versatility and adaptability to navigate through challenging terrains.

A notable exemplar in hexapod robots is LAURON, a six-legged walking robot developed to achieve statically stable walking in rough terrain (Roennau et al. 2014).

Drawing inspiration from the stick insect Carausius Morosus, LAURON V represents the latest iteration, featuring improved kinematics and a robust mechanical structure. Each leg of LAURON incorporates four independent joints, enabling the robot to navigate steep inclines, surmount large obstacles, and manipulate objects with its front legs. The impressive terrain adaptability, autonomy, robustness, and substantial payload capacity make LAURON highly suitable for various field applications. Its intended uses encompass inspection and maintenance tasks in challenging and hazardous areas, such as landmine detection, exploration of volcanoes, or search and rescue missions following natural disasters.

2.2.5 Conclusion: Evolution of Legged Mobile Robots

In conclusion, the exploration of legged mobile robots underscores their unique advantages in adaptability and manoeuvrability across challenging terrains. While presenting opportunities for intricate object manipulation, legged locomotion introduces challenges in power consumption and mechanical complexity. From one-legged robots focusing on minimalistic efficiency to advanced bipedal and quadruped robots, each design brings its own set of challenges and innovations. The evolving landscape of legged robotics, exemplified by hexapods like LAURON, promises advancements in search and rescue missions, exploration, and various industrial applications. Continuous research and refinement in legged locomotion contribute to the dynamic evolution of mobile robotics, unlocking new possibilities for robotic exploration.

2.3 Wheel-Based Locomotion

The wheel is the most prevalent locomotion mechanism in mobile robotics and various artificial vehicles, owing to its proven efficiency and straightforward mechanical implementation. Its simple design allows for seamless integration into diverse robotic systems, showcasing remarkable versatility (Zheng et al. 2023).

In wheeled robot designs, balance is generally not a primary research focus. These robots are meticulously engineered to ensure continuous ground contact for all wheels, guaranteeing stable balance. While three wheels suffice for stability, it is noteworthy that two-wheeled robots can also achieve stability, presenting a spectrum of design possibilities. However, incorporating a suspension system becomes imperative when more than three wheels are employed to maintain ground contact, especially on uneven terrains (Pecie et al. 2021).

Research in wheeled robotics predominantly addresses challenges related to traction, stability, maneuverability, and control (Rubio et al. 2019). Key considerations encompass whether the robot's wheels can provide adequate traction and stability across diverse terrains and if the wheeled configuration allows precise control over the robot's velocity.

The landscape of wheel configurations comprises four major classes, each presenting distinct kinematic characteristics that significantly influence the overall motion of mobile robots (Niloy et al. 2021). The standard wheel and castor wheel possess a primary axis of rotation and exhibit high directionality. Steering these wheels involves vertical axis motion to alter direction. Notably, the standard wheel accomplishes this steering motion with minimal side effects, as its center of rotation aligns with the contact patch with the ground. Conversely, the castor wheel rotates around an offset axis, introducing force to the robot chassis during steering.

Apart from the standard wheel's directional constraints, the Swedish and spherical wheel offer unique features. The Swedish wheel functions similarly to a regular wheel but provides low resistance in alternative directions, allowing movement along various trajectories. In contrast, the spherical wheel, being truly omnidirectional, can actively spin in any direction, employing actively powered rollers against its top surface, akin to a computer mouse.

Regardless of the chosen wheel type, robots designed for all-terrain environments or those featuring more than three wheels often necessitate a suspension system to maintain continuous ground contact (Bruzzone et al. 2022). While some robots incorporate flexibility into the wheel, such as deformable soft rubber tires for primitive suspension, more dynamic suspension systems become crucial for applications involving significantly non-flat terrains.

The wheel's omnipresence in mobile robotics underscores its efficiency and adaptability. Exploring various wheel types and configurations addresses challenges in traction, stability, and control, expanding the horizons of robotic mobility (Trojnacki & Dąbek. 2019). As researchers delve into the nuances of wheeled locomotion, the wheel remains a cornerstone in the evolution of mobile robotics, propelling advancements in diverse applications and terrains.

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A meticulous examination of each wheel type will be presented in the ensuing sections, delineating their intricacies, strengths, and potential applications. This comprehensive analysis aims to elucidate the nuanced dynamics governing wheel-based locomotion in mobile robotics, providing insights into the versatility and limitations inherent in each wheel class.

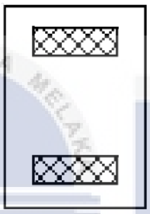
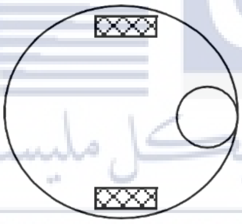
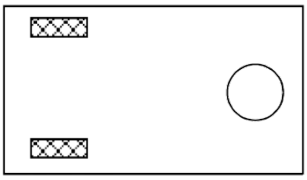
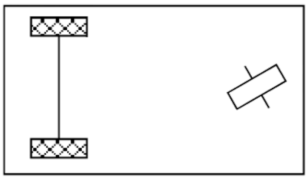
2.4 Wheel Configurations in Mobile Robotics

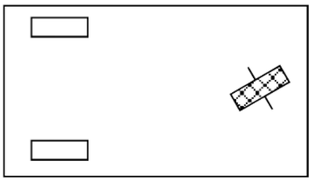
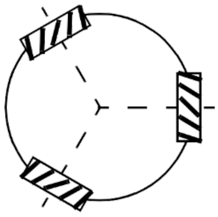
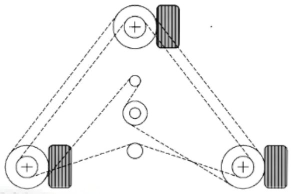
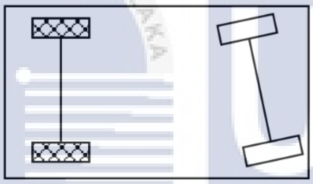
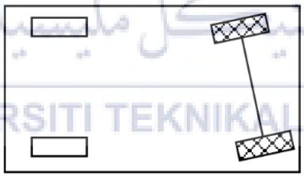
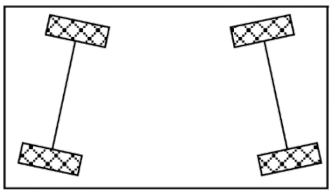
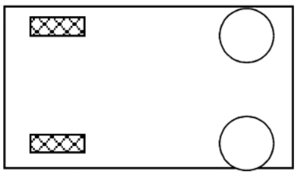
In mobile robotics, the selection of wheel types intricately intertwines with wheel arrangement or geometry. Designing a wheeled robot's locomotion mechanism requires considering these two factors simultaneously. The mobile robot designer is challenged to optimize three fundamental characteristics: maneuverability, controllability, and stability.

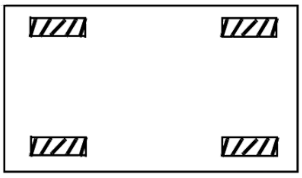
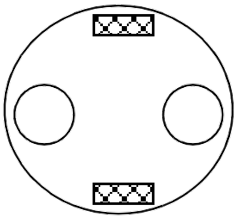
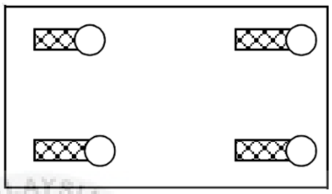
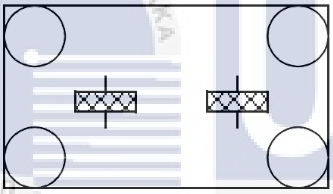
In contrast to automobiles, which predominantly operate in a highly standardized environment on paved roadways, mobile robots are engineered to traverse diverse situations. This diversity in application scenarios eliminates the existence of a singular wheel configuration that maximizes manoeuvrability, controllability, and stability for all environments, as observed in the case of automobiles on roads (Vestman, 2023). Consequently, the wheel configurations of mobile robots exhibit significant variety to cater to the multifaceted challenges presented by different environments.

Table 2.1 provides an insightful overview of wheel configurations, systematically organized by the number of wheels, elucidating the selection of specific wheel types and their geometric placement on the robot chassis. This table is a comprehensive guide, offering a snapshot of the diverse landscape of wheel configurations in mobile robotics.

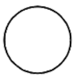
Table 2.1: Wheel configurations for mobile robots

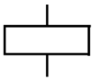
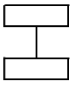
Number of Wheels	Arrangement	Description
2		Front: Steering wheel Rear: Motorized standard wheel
		Two-wheel differential drive
3		Differential drive centered on two wheels with a third point of contact
		Front/rear: One unpowered omnidirectional wheel Rear/front: Two independently driven wheels
		Front: Two connected differential wheels Rear: Steered standard wheel

		Front: One steered motorized wheel Rear: Two free-wheel
		Three motorized Swedish or Spherical wheels
		Three synchronously motorized And steered wheels
4		Front: two steered wheels Rear: Two motorized wheels To prevent slippage or sliding, the two wheels' steering must be different.
		Front: Two motorized wheels Rear: two steered wheels To prevent slippage or sliding, the two wheels' steering must be different.
		Four steered and motorized. Wheels
		Front/rear: Two omnidirectional wheels Rear/front: Two traction wheels

		Four omnidirectional wheels
		Differential drive on two wheels with two extra points of contact
		Four motorized steered castor wheels.
6		One omnidirectional wheel is located at each corner, and two motorized steerable wheels are positioned in the center.
		Two differential drive wheels are at the center, and one omnidirectional wheel is located at each corner.

Symbols for each type of wheel are as follows:

	Unpowered omnidirectional wheel
	Motorized Swedish wheel
	Unpowered standard wheel
	Motorized standard wheel

	Motorized steered castor wheel
	Steered standard wheel
	Connected wheels

The link between wheel types and geometric arrangement plays a pivotal role in determining the overall performance of a mobile robot. Maneuverability, the capability to navigate and traverse tight spaces or intricate terrains, is directly influenced by the chosen wheel configuration. Controllability, another critical factor in the design process, refers to the precise management of the robot's velocity and direction. Stability, a fundamental characteristic ensuring the robot's equilibrium during motion, further adds complexity to the decision-making process (Borkar et al. 2023).

In exploring wheel configurations, the emphasis lies in tailoring the design to the specific requirements of the robot's intended environment. The inherent diversity in mobile robot applications necessitates a flexible approach in selecting wheel types and their arrangement, enabling optimal performance across varied terrains and challenges.

As mobile robotics continues to evolve, the intricate interplay between wheel types and configurations remains a focal point of research and innovation. The adaptability of wheeled robots across different environments underscores the dynamic nature of their design, with each configuration representing a unique solution to the complex interplay of manoeuvrability, controllability, and stability.

This ongoing evolution in mobile robotics reflects the field's commitment to addressing the diverse challenges posed by real-world applications. Researchers and engineers continually strive to enhance the adaptability and performance of wheeled robots, ensuring their effectiveness in a wide range of scenarios. As advancements unfold, the synergy between wheel types and geometric arrangements will continue to shape the future of mobile robotics, offering solutions that push the boundaries of what is achievable in various environments.

2.4.1 Stability in Wheeled Mobile Robots

In the intricate design process of wheeled mobile robots, achieving stability is paramount. Stability, a crucial characteristic, ensures the robot maintains its equilibrium during motion, preventing unintended tipping or loss of control. The number and arrangement of wheels play a pivotal role in determining the static and dynamic stability of the robot.

The minimum requirement for static stability in a wheeled mobile robot is two wheels. In the case of a two-wheel differential-drive robot, static stability can be achieved if the center of mass is positioned below the wheel axle (J. H. Park & Cho, 2018). However, practical considerations often limit the feasibility of this solution, as it necessitates impractically large wheel diameters. Moreover, dynamics, such as high motor torques from a standstill, can cause a two-wheeled robot to strike the floor with a third point of contact. This dynamic interaction adds complexity to the stability challenge.

Conventionally, static stability is assured with a minimum of three wheels. The arrangement of these wheels forms a triangle, and the center of gravity must be contained within this triangular area defined by the ground contact points. This configuration ensures that the robot remains stable under normal operating conditions. Adding more wheels can enhance stability but introduce a hyperstatic nature to the geometry.

The hyperstatic nature arises when the number of contact points exceeds three, demanding flexible suspension, especially when navigating uneven terrain. Flexible suspension systems become imperative to accommodate variations in the terrain and maintain consistent ground contact for all wheels. This adaptability ensures stability when the robot encounters irregular surfaces or obstacles.

The pursuit of stability in wheeled mobile robots is a delicate balance between the number of wheels, their placement, and the dynamic forces at play. While a minimal configuration of three wheels guarantees static stability, the practical implementation requires careful consideration of factors like terrain variability, payload, and dynamic interactions during motion (Tao et al. 2022).

As researchers and engineers delve deeper into the complexities of stability in wheeled mobile robots, innovations in suspension systems, sensor technologies, and control algorithms continue to shape the landscape. The goal is to strike an optimal balance that ensures stability across a spectrum of operating conditions, paving the way for the seamless integration of wheeled robots into diverse environments and applications.

2.4.2 Maneuverability in Mobile Robots

The maneuverability of mobile robots is a critical aspect, influencing their ability to navigate diverse environments effectively (Kim et al. 2018). Some robots boast omnidirectional capabilities, allowing them to move in any direction along the ground plane, irrespective of their orientation around the vertical axis. Achieving this high level of manoeuvrability involves strategically using specialized wheels, such as Swedish or spherical wheels, which can move in multiple directions and are actively powered.

Omnidirectional robots, employing Swedish or spherical wheels, typically face ground clearance challenges due to the mechanical constraints associated with constructing these wheels. An innovative solution to address this ground-clearance problem is the four-castor wheel configuration. In this setup, each castor wheel is not only actively steered but also actively translated. This configuration grants true omnidirectionality to the robot. Even if the castor wheels face a direction perpendicular to the desired travel direction, the robot can still move in the intended direction by steering these wheels (Kasiri & Fani Saberi, 2023). The offset vertical axis from the ground-contact path enables effective robot motion, offering a versatile solution to omnidirectional navigation.

Another popular mobile robot class in the research community achieves high maneuverability, closely approaching that of omnidirectional configurations. These robots may require an initial rotational motion to move in a specific direction. A notable example is the two-wheel differential drive robot, where the two wheels rotate around the center point of the robot. Stability in these configurations may involve one or two additional ground contact points, depending on the application's specifics.

In contrast, Ackerman steering configurations, commonly found in automobiles, present a different approach. These vehicles typically have a turning diameter more significant than the car itself (Liu. 2023). Moving sideways with Ackerman steering necessitates a parking maneuver involving repeated changes in the forward and backward directions. While Ackerman steering might have slightly inferior manoeuvrability, its directionality and steering geometry offer excellent lateral stability during high-speed turns.

Selecting a particular maneuverability configuration depends on the specific requirements of the robot's intended tasks and operating environment. Whether prioritizing true omnidirectionality, high maneuverability with rotational motion, or the stability inherent in Ackerman steering, each configuration brings unique advantages and trade-offs to the complex field of mobile robotics. As researchers continue to explore and refine these configurations, the potential for mobile robots to navigate challenging terrains and dynamic environments continues to expand, unlocking new possibilities for applications in various industries.

2.4.3 Controllability in Mobile Robots

Controlling a mobile robot involves a delicate balance between maneuverability, stability, and controllability. In mobile robotics, a notable inverse correlation exists between controllability and maneuverability. Highly maneuverable designs, such as the four-castor wheel configuration, offer remarkable omnidirectionality, but achieving control over these systems requires substantial computational processing. This is particularly evident in converting desired rotational and translational velocities into individual wheel commands.

Omnidirectional designs often feature a significant number of degrees of freedom at the wheel, introducing complexities in control. For instance, the Swedish wheel incorporates free rollers along the wheel perimeter. While these degrees of freedom enhance maneuverability, they come at the cost of potential slippage, reduced dead-reckoning accuracy, and increased design complexity.

Controlling the direction of travel for an omnidirectional robot proves to be a more challenging task compared to less maneuverable designs. In contrast, vehicles with Ackerman steering can move straight by merely locking the steerable wheels and driving the drive wheels (Gautam et al. 2021). The simplicity of this approach contrasts with the differential-drive vehicle, where precise synchronization of two motors becomes essential, considering variations between wheels, motors, and environmental factors.

The challenge intensifies in configurations like the four-wheel omni drive, exemplified by the Uranus robot with its four Swedish wheels (Klindworth & Selekwa, 2017). Straight-line travel demands precise coordination, with all four wheels being driven at the same speed. This exemplifies the intricate trade-offs in optimizing controllability for highly manoeuvrable robotic systems.

No universal "ideal" drive configuration exists that simultaneously maximizes stability, manoeuvrability, and controllability. Each mobile robot application imposes unique constraints on the design problem, compelling designers to navigate the intricate space of compromises. The task is to choose the most appropriate drive configuration that aligns with the specific demands of the application, acknowledging the inherent trade-offs between manoeuvrability and controllability in the dynamic field of mobile robotics.

2.5 Wheel Drive Configuration

2.5.1 Differential Drive Systems

Differential drive systems are a cornerstone of robotics and vehicular design, particularly mobile robots. This configuration, characterized by two independently driven wheels, offers a versatile mechanism where the relative speed of the wheels dictates the vehicle's direction and orientation. The simplicity of control and design makes the differential drive a compelling choice for applications ranging from compact robotic platforms to larger vehicles.

The fundamental principle underpinning a differential drive system lies in manipulating the rotational speed disparity between the left and right wheels (Sugahara, 2022). This variance enables the vehicle to execute turns efficiently and navigate confined spaces. The design's inherent simplicity facilitates cost-effective implementation and reduces mechanical complexity, contributing to the widespread adoption of differential drive in diverse contexts.

The differential drive configuration's manoeuvrability proves advantageous in environments characterized by spatial constraints or intricate pathways. However, challenges surface, particularly in maintaining precise control during straight-line motion. Minor discrepancies in wheel diameters or variations in frictional properties can lead to deviations from the intended path.

Researchers have delved into innovative solutions to address these challenges and enhance the overall performance of differential drive systems. Integrating sensors for feedback, coupled with advanced control algorithms, emerges as a strategy to ensure accurate speed differentials between the wheels. This approach mitigates deviations during straight-line motion (Martins et al. 2017).

Furthermore, ongoing studies explore optimal wheel placements and configurations to address challenges of uneven terrain or wheel slippage. By refining the foundational principles of differential drive and incorporating technological advancements, researchers strive to elevate the control precision and adaptability of mobile robots operating within dynamic and unpredictable environments. As the field progresses, the continued integration of sensors, control algorithms, and strategic design considerations promises to unlock new frontiers in the capabilities of differential drive systems, reinforcing their significance in the landscape of mobile robotics.

2.5.2 Synchro Drive

In the realm of indoor mobile robot applications, the synchro drive configuration stands out as a compelling arrangement of wheels. This configuration, characterized by three driven and steered wheels, utilizes only two motors. The translation motor sets the speed of all three wheels simultaneously, while the steering motor spins them together about their vertical steering axes. However, it is crucial to note that the wheels are steered concerning the robot chassis, leading to challenges in direct chassis reorientation.

One distinct advantage of synchro drive emerges when omnidirectionality is a primary goal. As long as each vertical steering axis aligns with the contact path of its respective tire, the robot can effortlessly reorient its wheels, enabling movement along a new trajectory without altering its footprint (Tatar et al. 2016). Nevertheless, if intentional chassis reorientation is part of the design, synchro drive proves suitable only when coupled with an independently rotating turret attached to the wheel chassis.

Despite its advantages in achieving omnidirectionality, synchro drive faces limitations regarding dead reckoning accuracy. Synchro-drive systems generally fare better than actual omnidirectional configurations but fall short of the precision of differential-drive and Ackerman steering systems.

Two primary factors contribute to the dead reckoning challenges in synchro drive systems. Firstly, the translation motor typically drives the three wheels using a single belt, introducing slop and backlash in the drive train (Cao et al. 2023). This leads to the closest wheel initiating rotation slightly ahead of the furthest wheel whenever the drive motor engages, resulting in incremental changes in chassis orientation. Over time, these small angular shifts accumulate, leading to significant errors in orientation during dead reckoning.

Secondly, the lack of direct control over the chassis' orientation presents a significant challenge. Depending on the chassis's orientation, the wheel thrust can exhibit high asymmetry, with two wheels on one side and the third wheel alone, or symmetry, with one wheel on each side and one straight ahead or behind. Asymmetric cases introduce errors during tire-ground slippage, further contributing to inaccuracies in dead reckoning for robot orientation.

In conclusion, while synchro drive excels in achieving omnidirectionality, addressing dead reckoning challenges remains a focal point for refinement. Continued research and innovation in mitigating issues related to driving train slop, backlash, and chassis orientation control are essential to unlock the full potential of synchro drive configurations in diverse indoor mobile robot applications.

2.5.3 Omnidirectional Drive

Omnidirectional drive systems are pivotal in the pursuit of complete maneuverability, allowing robots to move freely in any direction (x, y, θ) at any given time. Holonomic robots, exemplifying omnidirectional movement, have garnered significant interest for their unparalleled agility. Here, we explore various configurations of omnidirectional drive systems, each presenting unique advantages and considerations (Hacene & Mendil, 2019).

2.5.3.1 Omnimobile Robot with Spherical Wheels

An intriguing approach to achieving omnidirectional movement involves constructing an omnimobile robot with three spherical wheels, each actuated by an individual motor. In this design, the spherical wheels are suspended by three contact points (Wei et al. 2019), with two provided by spherical bearings and one by a wheel connected to the motor axle. While this concept offers excellent manoeuvrability and simplicity in design, it is constrained to flat surfaces and is suitable for relatively small loads. The challenge lies in sourcing wheels with sufficiently high friction coefficients to ensure effective motion.

2.5.3.2 Omnimobile Robot with Swedish Wheels

The Swedish wheel presents another avenue for building holonomic omnidirectional robots, requiring a minimum of three wheels for construction (Taheri et al. 2015). A notable advantage of the Swedish wheel lies in its ability to facilitate the construction of omnidirectional robots without the need for active steering of wheel modules. This simplicity in actuation allows for straightforward mechanical structures in the actuating parts. However, the Swedish wheel is not without drawbacks. One notable limitation is the potential for vertical vibrations due to discontinuous contact during motion.

2.5.3.3 Omnidirectional Robot with Steerable Wheels

Centered orientable wheels come into play when constructing omnidirectional robots, necessitating a minimum of two modules. Unlike the active caster wheel, the centered orientable wheel requires constant alignment of wheel orientation with the desired velocity direction, as computed by inverse kinematics. This characteristic renders the robot non-holonomic yet omnidirectional (Azizi et al. 2021). Mechanical challenges akin to those of active caster wheels include the need for multiple actuators and intricate mechanical structures. Additionally, the direct attachment of the driving motor to the driving axis may impose limitations on allowable steering angles to prevent wiring problems.

In the pursuit of holonomic robots capable of omnidirectional movement, each configuration presents a trade-off between simplicity, mechanical complexity, and specific environmental constraints. As technology advances, ongoing research aims to overcome these limitations, paving the way for the integration of omnidirectional drive systems in diverse applications, from precision robotics to dynamic and agile autonomous platforms.

2.6 Wheeled Mobile Robot (WMR)

2.6.1 Classification of Wheeled Mobile Robots

According to the Springer Handbook of Robotics Siciliano & Khatib. (2008. pp. 391–410), wheeled mobile robot (WMR) structures can be categorized into five distinct classes. These classifications are established based on a pair of indices, with 'm' denoting mobility and 's' representing degrees of steerability (Delgado-Mata et al. 2012).

Type I or Type (3,0) robots, often called omni-mobile robots, represent a class of robots characterized by their ability to achieve omnidirectional mobility without using traditional steering wheels. These robots employ specially designed wheels, including Mecanum wheels, omni wheels (or universal wheels), orthogonal wheels, and spherical/ball wheels, to attain omnidirectional motion within a plane. The defining feature of Type (3,0) robots is their complete plane mobility (m=3), allowing them to move in any direction without requiring orientation changes. Consequently, these robots excel in navigating in all directions with exceptional agility, making them well-suited for a wide range of applications in mobile robotics (Cuevas et al. 2019).

Type II or Type (2,0) robots are defined by their lack of steering wheels (s=0) and typically include one or several fixed wheels that share a common axle. The unique characteristic of these robots is that their mobility is restricted to a two-dimensional plane (m=2).

Differential drive locomotion is a prevalent choice for this class of platforms, as noted by (Sandeep Kumar Malu et al. 2014). These robots typically feature two traction wheels that can rotate independently around the common axis. The essential advantage of this design is that the instantaneous centre of the rotation permanently resides on the common axis of the traction wheels. Consequently, Type (2,0) robots can move in a direction perpendicular to the common axis and achieve rotation around a vertical axis. While this locomotion system does not allow for sideways motion, it is widely adopted in wheeled mobile robots due to its simplicity in construction and control.

Type III or Type (2,1) robots are distinguished by their absence of fixed wheels and the inclusion of at least one steering wheel. When multiple steering wheels are employed, they must be precisely coordinated in orientation (s=1). The defining characteristic of these robots is their mobility, which is confined to a two-dimensional plane (m=2).

These robots do not incorporate fixed wheels but rely on the manoeuvrability of the steering wheel or wheels. To be classified as Type III, the orientation of multiple steering wheels must align in the same direction. As a result, Type (2,1) robots can achieve motion exclusively within a 2D plane, making them suitable for applications where precise planar movement is required.

Type IV or Type (1,1) robots are characterized by their uncomplicated design, typically involving one or several fixed wheels mounted on a common axle and one or more steering wheels. However, two crucial conditions must be met for these robots. First, the centers of the steering wheels should not coincide with the standard axle of the fixed wheels. Second, the orientations of the steering wheels must be meticulously coordinated (s=1). As a result, Type (1,1) robots can navigate solely within a plane determined by the angle of the steering wheel.

This confinement to a single plane restricts their mobility to one dimension (m=1) and limits their steering to a single degree of freedom (s=1). Notable examples of Type (1,1) robots include tricycles, bicycles, and car-like Wheeled Mobile Robots (WMR), as documented by (Mydlarz & Skrzypczyński, 2020).

Type (1,2) robots, also known as Type V robots, do not incorporate fixed wheels but are equipped with a minimum of two independent steering wheels. In cases where more than two steering wheels are employed, they are organized into two distinct groups (s=2). The mobility of Type (1,2) robots is confined to a one-dimensional plane (m=1), which is determined by the orientation angles of the two steering wheels.

This locomotion architecture offers flexibility through various actuation strategies. For instance, a generic velocity twist can be achieved by properly configuring the steering angles. However, when the wheel axes are aligned on the same line, the platform's mobility aligns with that of Type II (differential drive locomotion). In other scenarios, the platform's mobility at a particular steering angle configuration is limited to a one-dimensional plane, influenced by a set of non-equal steering angles that define the position of the instantaneous center of rotation, as described by (Tagliavini et al. 2022).

In summary, these five classes of WMRs offer a range of mobility and steering options, making them suitable for diverse applications in the field of mobile robotics.

2.6.2 Holonomy in Mobile Robotics

Holonomy, a fundamental concept in the field of mobile robotics, pertains to the kinematic constraints governing a robot's chassis, categorizing robots into holonomic and nonholonomic based on their mobility characteristics.

In mobile robotics, the terms "holonomic" and "nonholonomic" differentiate robots concerning their kinematic constraints. A holonomic robot has zero nonholonomic kinematic constraints, allowing it unrestricted motion defined solely by its control inputs. This characteristic grants holonomic robots high maneuverability, enabling them to move in any direction within their workspace (Roland Siegwart et al. 2011). Conversely, a nonholonomic robot is constrained by one or more nonholonomic kinematic constraints, limiting its mobility and making its motion less flexible.

An alternative perspective on characterizing holonomic robots involves examining the relationship between a robot's differential degrees of freedom (DDOF) and the degrees of freedom in its workspace. A robot is considered holonomic when the number of its DDOF equals the degree of freedom in its workspace. In such cases, the robot can execute any motion within its workspace without constraint. Conversely, if the count of DDOF is less than the degree of freedom in its workspace, the mobile robot is classified as a nonholonomic system. This classification is crucial in mobile robotics, directly influencing a robot's navigational capabilities and task performance.

Understanding the concept of holonomy is pivotal in designing and controlling mobile robots. Holonomic robots, by offering enhanced maneuverability, can navigate complex environments more effectively. This trait proves advantageous in applications like autonomous vehicles and agile robotic systems. On the other hand, nonholonomic robots necessitate more intricate control strategies to overcome their kinematic constraints.

In the field of mobile robotics, the fundamental classification of robots into holonomic and nonholonomic categories based on kinematic constraints and degrees of freedom holds paramount importance. This distinction significantly influences a robot's mobility and control, providing a foundational understanding of holonomy's practical implications in designing and controlling robotic systems.

2.7 Types of Wheels in Wheeled Mobile Robotics

The property of holonomics in mobile robots is intricately linked to the type of wheels they employ. This section explores the distinctions between holonomic and non-holonomic systems, emphasizing the pivotal role of wheels, and provides an in-depth analysis of the strengths and weaknesses associated with each wheel type.

In the domain of mobile robotics, the classification of a system as holonomic or non-holonomic is intimately connected to the characteristics of its wheels. A non-holonomic mobile robot, exemplified by an Ackerman wheeled system, encounters inherent limitations in its freedom of movement. Conversely, a robot equipped with omnidirectional wheels is classified as holonomic.

2.7.1 Conventional Wheels

One archetype of a non-holonomic system is the differential drive-wheeled robot configured with conventional wheels. These wheels, widely adopted across engineering disciplines, are celebrated for their simplicity, reliability, and versatile applicability. Conventional wheels, as depicted in the figure, serve as fundamental components in various applications, showcasing adaptability to diverse sizes and shapes, and robust load-bearing capabilities.

In mobile robotics, conventional wheels, especially those endowed with omnidirectional capabilities, often integrate caster and steering wheels. This combination, typically featuring a minimum of two wheels, each equipped with a motor, facilitates movement in multiple directions, enhancing the system's overall versatility.

While conventional wheels excel in traction and stability on flat surfaces, they grapple with limitations in terms of maneuverability and true omnidirectionality, particularly on rough or uneven terrains. Challenges such as getting stuck or slipping may arise, prompting the introduction of steerable wheels. However, traditional steerable wheels, constrained by non-holonomic characteristics, fall short of achieving genuine omnidirectional motion.

Conventional wheels, especially during differential steering scenarios where rotation occurs around the vertical axis, are susceptible to increased friction. This heightened friction over time adversely impacts positioning accuracy, elevates energy consumption, and accelerates tire wear. A strategic mitigation, as proposed by (Crenganis et al., 2021), involves implementing a dual-wheel system, alleviating the impact of excessive frictional forces.

The steering wheel, a variant of the conventional wheel, distinguishes itself through its unique mechanical design. It rotates around its vertical axis, guided by a motor, allowing for distinct steering capabilities. Steering wheels are employed in various contexts, showcasing applications ranging from plane front wheels to clinic chairs, television tables, and self-contained portable robots.

The caster wheels, which are akin to steering wheels, differ in working principles. Caster wheels find applications not only in robotics but also in service, medical equipment, and manufacturing. They facilitate near-omnidirectional mobility for mobile robots bearing heavy payloads with minimal sensitivity to ground conditions. Caster wheels can be categorized into fixed and pivot wheels, with pivot wheels providing unrestricted movement due to their 360-degree passive rotation around the vertical axis.

Enhancing near-omnidirectional motion is achievable through modifications to the wheel mechanism, as demonstrated by the use of active caster wheels. This modification, exemplified by a wheeled mechanism with a passive steering axis, generates holonomic and omnidirectional capabilities. Despite its structural simplicity, this configuration, as explained by (Aziz Safar, 2015), offers versatility and flexibility.

A kinematic analysis and motion planning study conducted by (Jung et al. 2015) examined a planar multi-articulated omnidirectional mobile robot equipped with three caster wheels. The study delved into kinematic modeling and identified singular configurations that could lead to unstable motion. The insights from this analysis contribute to designing control algorithms ensuring stable motion in diverse scenarios.

2.7.2 Mecanum Wheels

The Mecanum wheel, often referred to as the Swedish or Ilon wheel, originated in 1973 through the inventive work of Bengt Ilon at Mecanum AB in Sweden. Since its inception, this wheel design has captivated the robotics community, prompting extensive research and development.

Early studies by (Muir & Neuman, 1987) and (Agulló et al. 1987) delved into the intricacies of Mecanum wheels, providing a foundational understanding of this innovative technology. Over the years, numerous systems have emerged based on the unique mechanism of Mecanum wheels. Notable examples include Mohd Salih et al.'s Omnidirectional Wheeled Mobile (OMR) with four independent Mecanum wheels and the pioneering work of F. G. Pin and S. M. Killough, who constructed the first three-wheeled OMR featuring Mecanum wheels.

The Mecanum wheel distinguishes itself through its distinctive structure, where passive rollers are strategically arranged at an angle along the outer rim of the wheel. This roller arrangement is pivotal for the wheel's operation. Notably, wheels with a roller angle (γ) of 45 degrees are typically called Mecanum wheels. In comparison, those with a γ of 0 degrees are commonly known as Swedish wheels, as (Indiveri, 2009) documented in 2009.

The working principle of the Mecanum wheel offers several advantages, such as a compact and robust design and high payload capacity for robots. These wheels provide omnidirectional motion, allowing a robot to move in three degrees of freedom (3-DOFs) at the vehicle's center. This motion is achieved by controlling the velocity and direction of the wheel's rotation (Aziz Safar, 2015).

The free-rolling sub-wheels positioned at an angle offset from the wheel's rotation, as highlighted by Han et al. (2009), facilitate sideways movements achieved by spinning the wheels on the front and rear axles in opposite directions. Notably, forward and backward movements with Mecanum wheels are comparable to those of conventional wheels.

Despite their advantages, Mecanum wheels introduce challenges. The intricate mechanism design leads to horizontal and vertical vibrations, impacting positioning accuracy (Kanjanawanishkul, 2015). Furthermore, slipping can lead to odometry errors (Xie et al. 2015). Operation on uneven terrain or inclined surfaces presents challenges, as the rim contacts the ground instead of the rollers. A solution proposed by (Ramirez-Serrano & Kuzyk, 2010) involves splitting the rollers into two or three slides mounted centrally, effectively addressing the terrain compatibility issue. Additionally, Mecanum wheels exhibit slower motion than Omni-wheels during robotic turns (Kundu et al. 2017).

Various studies have sought to mitigate these challenges. For instance, Bae & Kang (2016) conducted design optimization of Mecanum wheels to reduce vertical vibrations by considering equivalent stiffness. Despite successfully eliminating vertical vibrations, it was noted that the complete elimination of horizontal vibrations proved challenging.

Sun et al. (2021) focused on designing a control system for path following in Mecanum-wheeled omnidirectional mobile robots. They introduced a non-singular terminal sliding mode (NTSM) control approach, demonstrating its effectiveness in ensuring stability during path following, even in the presence of disturbances and uncertainties.

In another endeavour, Xie et al. (2015) introduced AuckBot, a heavy-duty omnidirectional robot equipped with Mecanum wheels. The study detailed the design and development of the robot, highlighting the application of intelligent navigation methodologies in enhancing control precision and efficiency. The results underscored the effectiveness of Mecanum wheels in improving manoeuvrability and flexibility.

2.7.3 Universal Omni Wheels

Omni-wheels stand as a pioneering innovation in robotic mobility, offering a unique combination of a primary active wheel and passive freely rotating rollers (Shabalina et al. 2019). This design, characterized by an active wheel and rollers with independent rotation axes, enables versatile and omnidirectional motion in robots. A subtype of omni-wheels, the universal wheels, incorporates passive rollers positioned at a 90-degree angle to the shaft, with their axes perpendicular to the wheel shaft (Barreto S. et al. 2014).

The disk-shaped Omni-wheel, resembling a conventional wheel, boasts free rollers around its outer circumference, allowing it to move in any direction. The ingenious design of Omni-wheels facilitates forward, backward, and sideways movement by orchestrating a circle using the rollers. Importantly, these wheels eliminate lateral direction forces associated with nonholonomic constraints, ensuring almost identical traction to standard wheels while inducing pure rolling in the lateral direction. This characteristic makes them suitable for driving systems requiring holonomic motion (Soni et al. 2014). Despite their cost-effectiveness compared to Mecanum wheels (Pasupuleti et al. 2021), achieving the coveted 3-DOF mobility with Omni wheels necessitates at least three units of independent Omni wheels.

However, Omni-wheels come with inherent challenges. Vibrations resulting from the contact points between rollers and the ground, as well as gaps between rollers, have been identified by Park et al. (2016). Additionally, Omni-wheels exhibit lower load capacity and encounter difficulties in obstacle traversal. To mitigate vibration concerns, a double wheel type comprising two rollers has been proposed to enhance ground contact points.

Addressing the vertical vibration problem, Park et al. (2016) conducted a comprehensive analysis employing the Taguchi method to optimize the manufacturing process and product quality. Factors influencing vibration, including angular velocity, gap, load, elasticity of the flexible body, alignment angle, geometry errors, and fixable body thickness, were considered.

The taxonomy of Omni-wheels encompasses conventional Omni-wheels, half wheels, alternate wheels, and the prevalent double wheel type, designed specifically to overcome inter-wheel constraints and friction challenges.

Researchers have explored specific applications of Omni-wheeled robots. For instance, Samarasinghe & Parnichkun (2019) employed the linear quadratic regulator (LQR) method for pitch control in a robot equipped with a single active Omni-wheel, showcasing the stability achieved through LQR. In another study, Komori et al. (2016) designed an active Omni-wheel using a differential gear mechanism, enhancing motion control in any direction and contributing to the development of omnidirectional vehicles Yunardi et al. (2021) focused on designing a high-mobility robot with three omnidirectional wheels for chasing and catching a ball, showcasing holonomic implementation.

In addressing issues of vibration and slip in a four-wheeled Omni-wheelchair designed for indoor environments, Kundu et al. (2017) developed an innovative suspension system demonstrating reduced slip and vibration, thereby improving overall performance.

2.7.4 Orthogonal Wheel

The concept of orthogonal wheels, introduced by Pin and Killough (1994), has evolved into a fascinating avenue of exploration within mobile robotics. Comprising a pair of sliced spherical wheels arranged orthogonally, these wheels offer a unique blend of advantages, particularly in applications requiring low-speed precision and controlled movement.

Orthogonal wheels, fundamentally composed of a pair of sliced spherical wheels strategically placed at the driving axle in an orthogonal arrangement, provide normal traction in one direction, ensuring continuous ground contact while allowing pure free rolling in the perpendicular axis. Two layouts, longitudinal and lateral, cater to specific operational requirements, prioritizing continuous ground contact to mitigate vibration and friction issues. Caution is advised in high-speed and heavy-load conditions, making them suitable for precision-focused applications such as soccer competitions (Shao et al. 2016).

While the unique advantages of orthogonal wheels in specific applications are evident, the full potential of these wheels in complex systems necessitates further investigation. Future research endeavors could focus on optimizing the design of these wheels for different applications and evaluating their performance in more challenging environments. The potential for achieving omnidirectional and holonomic capabilities in mobile robots by integrating multiple orthogonal wheel assemblies opens new avenues for exploration.

The study conducted by Mourioux et al. (2006) explores an omnidirectional robot with spherical orthogonal wheels, laying essential concepts and analyses. This foundational research aids in developing robots with orthogonal wheels and a deeper understanding of their kinematic models. Integration of three pairs of assemblies, resembling a three-wheeled omni-wheel vehicle architecture, enables omnidirectional movement without reorientation, showcasing high maneuverability.

The evolution of orthogonal wheel designs has seen remarkable developments. The MY wheel, introduced by Ye & Ma (2009), features a unique arrangement where passive rotational axes of two sliced balls are inclined at 45 degrees in two parallel planes perpendicular to the active axis. This design ensures continuous ground contact, improving wheel intensity and load-carrying capacity. Subsequent studies by Ye et al. (2011) delved into kinematic performance, proposing methods to reduce trajectory errors, providing solutions for challenging environments.

In the pursuit of refinement, an improved version, MY2, introduced by Ye et al. (2012), enhances carrying capacity and obstacle-crossing ability. Composed of two spherical bodies using four 90-degree cones with spherical caps, this design includes a differential structure for orientation maintenance during motion, addressing obstacles and varying terrains.

Continuing this trajectory of improvement, the MY3 wheel, developed by Yu et al. (2016), consists of two balls with equal diameters sliced into four spherical crowns. The design allows alternate ground contact for continuous active motion, offering advantages such as improved load-carrying capability, insensitivity to fragments and dirt, and enhanced traction with polyurethane (PU) crown covers.

The practical applications of these evolved designs are evident in studies applying the MY3 wheel to an omnidirectional Automated Guided Vehicle (AGV). Wang et al. (2016) showcase promising outcomes in higher payload capacity and insensitivity to fragments and dirt, contributing valuable insights into the practical application of advanced orthogonal wheel designs in real-world scenarios.

2.7.5 Spherical and Ball Wheels

The integration of omnidirectional wheels in mobile robotics has ushered in enhanced maneuverability and adaptability across various terrains. Among these innovations, the spherical wheel, commonly known as the Omni-ball system, distinguishes itself through its unique design and versatile capabilities. This discussion delves into the evolution of spherical wheels, their diverse applications, and ongoing innovations aimed at addressing challenges and expanding their functionalities.

The concept of the ball wheel mechanism, a precursor to spherical wheels, was first pioneered by West & Asada (1995). Their work introduced a three-ball wheel system for omnidirectional mobile robots, featuring two hemispherical wheels that rotated passively and an active shaft enabling active rotation. This design facilitated improved traction control and accurate dead reckoning navigation, laying the groundwork for subsequent advancements.

Expanding on this foundation, Ferrière & Raucent (1998) introduced ROLLMOBS, an enhanced version that utilized a classical universal wheel driving a sphere. This optimization led to improved performance, dependent on the sphere's diameter rather than the roller's diameter. ROLLMOBS demonstrated enhanced load capacity, surmountable bump height, and smoother motion without vibrations. Freely rotating rollers in the universal wheel tread allowed the sphere's free motion orthogonal to the roller axis.

Building upon these innovations, Tadakuma et al. (2007) introduced the Omni-ball wheel in 2007, drawing inspiration from the ROLLMOBS structure. This mouse-like-wheel-shaped design incorporated principles from traditional spherical wheels like the Coweye wheel, Omnitrack, and ball universal wheel. However, the Omni-ball wheel addressed the limitation of self-actuation, expanding possibilities for omnidirectional movement.

Spherical wheels, including the Omni-ball system, are designed to overcome challenges such as vibrations, ground contact discontinuity, obstacle traversal, and payload limitations. Their simple structure enhances reliability and ease of maintenance, making them suitable for diverse applications in mobile robotics. The ball and socket joint principle allows movement in any direction, with the control system adjusting wheel orientation and speed for desired movements.

Studies such as Runge et al. (2016), have demonstrated the promising stability, efficiency, and maneuverability of spherical wheels. Their ability to move in any direction, coupled with adaptable control systems, makes them suitable for applications where precise movement is crucial. However, it's important to note that these wheels cannot serve as main driving wheels in autonomous robots directly due to motor limitations.

Comparative studies, exemplified by Taheri & Zhao (2020), highlight the advantages of the Omni Spherical Wheel (OSW) over other omnidirectional wheel types. OSW provides smoother motion and a broader range of maneuvering across various terrains, addressing issues related to friction and rotation force requirements. This geometric advancement positions OSW mechanisms as an ideal choice for ground-wheeled mobile robots, offering improved motion capabilities.

Recent innovations in spherical wheel designs include the Ospheel, a modular omnidirectional spherical sectioned wheel introduced by Hayat et al (2020). This design, driven by two actuators, provides independent rotation about two perpendicular axes, enhancing torque transmission, obstacle overcoming, and outdoor applicability. The

Ospheel represents a notable advancement in torque-efficient, obstacle-tolerant applications.

Additionally, Ghariblu's (2010) addressed vibration and load capacity limitations associated with traditional omni-wheels. A robot with three omni wheels standing on three ball wheels showcased multi-directional movements with high stability and mobility. Subsequent modifications in 2011, adjusting ball diameters for operation in rough terrains and adding a suspension system, further improved stability and mobility, overcoming challenges faced by ball-wheel omnidirectional robots.

2.8 Mechanical Design Principles in Differential Drive Mobile Robot (DDMR)

A differential drive mobile robot is a paradigm of simplicity, versatility, and effectiveness in navigating diverse terrains. The essence of "differential drive" lies in its propulsion mechanism, where each wheel operates independently, granting the robot precise control over its movements. This design choice ensures simplicity and imparts a high degree of manoeuvrability, rendering it suitable for applications spanning indoor environments to challenging outdoor terrains.

2.8.1 Differential Drive Systems Overview

Differential drive systems in mobile robots are standard locomotion system with two independently controlled driving wheels and a balancing wheel (Crenganis et al. 2021). These systems are non-holonomic, meaning they have differential constraints that cannot be fully integrated (Yufka & Ozkan, 2015). Control of nonholonomic wheeled mobile robots, including those with differential drive, has been extensively studied (Poonawala & Spong, 2017). Research has focused on various aspects, such as trajectory planning, obstacle avoidance, and motion control (Lazarowska, 2020; Samodro et al. 2023). Studies have also proposed control algorithms, like receding horizon control, for the navigation of differential drive mobile robots (Seder et al. 2017). Differential drive systems find applications in formation control and landmark visibility maintenance (Chen et al. 2018). The differential drive system is a fundamental and extensively studied locomotion system in mobile robotics, with a wide range of applications and control strategies.

The operation of a differential drive mobile robot is characterized by the autonomous manipulation of two drive wheels and a balancing wheel (T. et al. 2018). This unique system empowers the robot to navigate its surroundings by autonomously altering the speeds and directions of the two driving wheels, facilitating forward and backward motion and rotation in place.

A distinctive feature of the differential drive system lies in its capability to execute turns through the independent adjustment of each wheel's speed. This autonomy in controlling the left and right wheels allows the robot to pivot around its axis or traverse intricate paths effortlessly. The differential steering approach significantly enhances the robot's agility, enabling it to navigate through confined spaces and overcome obstacles with remarkable precision (Trojnacki & Dąbek, 2019).

2.8.2 Advantages of Differential Drive Systems In Mobile Robots

The use of a differential drive system in a mobile robot offers several advantages, making it a popular choice for various applications. One of the key advantages is the ability to navigate through narrow spaces due to the type of locomotion implemented (Crenganis et al. 2021). This maneuverability is essential for mobile robots operating in confined spaces, such as warehouses, indoor environments, and cluttered outdoor areas. Navigating through narrow spaces enhances the robot's adaptability, enabling access to locations potentially inaccessible to other locomotion systems.

Furthermore, differential drive systems have a notable advantage in terms of construction simplicity, especially compared to more complex holonomic wheeled mobile robots (Poonawala & Spong, 2017). The differential drive system's mechanical simplicity makes it easier to design, build, and maintain, contributing to cost-effectiveness and ease of implementation. This advantage is particularly significant in applications deploying multiple robots, allowing for efficient scalability and deployment of robotic systems.

Moreover, the differential drive system provides rapid response, high stability, tracking accuracy, and good anti-interference, making it suitable for precise path-tracking control (Tiep et al. 2018). This is particularly advantageous in applications requiring accurate and reliable navigation, such as autonomous vehicles and robotic systems operating in dynamic environments. The system's capability of changing direction by varying the angular velocities of the two driving wheels without additional steering mechanisms is another advantage (Wu et al. 2018). This feature simplifies the mechanical design and reduces the control system's complexity, enhancing the mobile robot's overall efficiency and reliability.

Energy efficiency is a crucial consideration in mobile robot design, and the differential drive system offers advantages in this aspect as well. Studies have focused on energy-optimal trajectory planning for car-like robots, aiming to minimize energy consumption during motion (Tokekar et al. 2014). Additionally, energy estimation based on path tracking for a differential drive wheeled mobile robot has been investigated to improve energy efficiency and increase operational time (Fadlo et al. 2021). These efforts highlight the potential for energy savings and prolonged operation through the implementation of differential drive systems in mobile robots.

Furthermore, the differential drive system's ability to pass through existing obstacles has been demonstrated through artificial potential field path planning algorithms (Samodro et al. 2023). This capability is essential for obstacle avoidance and navigation in complex environments, enhancing the robot's adaptability and safety. The system's non-holonomic nature, characterized by differential constraints that cannot be fully integrated, also offers advantages in terms of control and maneuverability. Research has explored the use of differential drive mobile robots in formation control, trajectory tracking, and obstacle avoidance, showcasing their versatility and effectiveness in various robotic tasks (Nascimento et al. 2018; Seder et al. 2017).

In addition to the technical advantages, differential drive systems offer practical benefits in real-world applications. For example, the use of differential drive mobile robots in maze maneuvering and colored object tracking demonstrates their potential for practical tasks such as inventory management and object retrieval in constrained environments

(Aldair & Al-Mayyahi, 2019). Integrating differential drive systems with distance sensors for navigation and obstacle avoidance further enhances their utility in real-world scenarios.

In summary, the advantages of using a differential drive system in a mobile robot include maneuverability in narrow spaces, simplicity of construction, rapid response and stability, energy efficiency, obstacle avoidance capabilities, and adaptability to real-world tasks. These advantages make the differential drive system versatile and effective for a wide range of mobile robotic applications.

2.8.3 Kinematic Modelling

Understanding the mechanical behavior of a differential drive mobile robot is paramount for designing appropriate mobile platforms tailored to specific tasks and developing accurate control software. This understanding is achieved through the study of kinematics, which focuses on the mathematics of motion without delving into the forces influencing the motion (Leena & Saju. 2016). In this context, robot kinematics illuminates the mobile robot's intricate movements, providing insights essential for designing the robot for desired tasks and crafting control software to optimize its hardware.

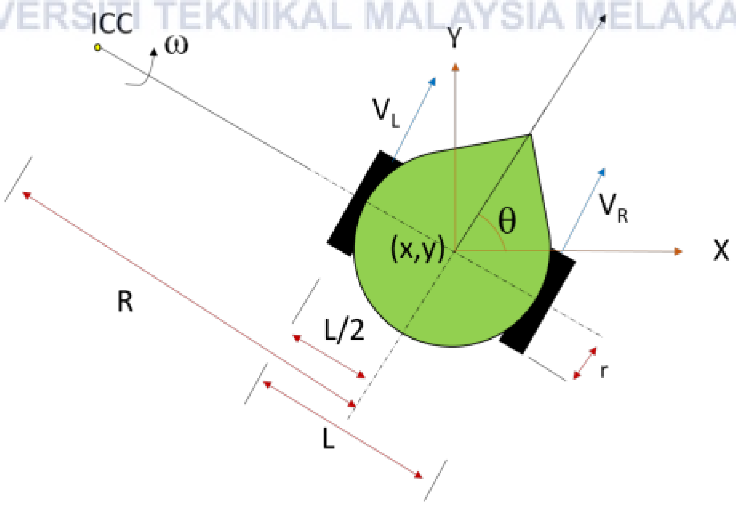


Figure 2.1: Differential drive kinematics (Leena & Saju. 2016)

In Figure 2.1, a differential drive mobile platform is depicted, featuring two controllable wheels. The key variables are expressed using the following notation: X and Y denote the global coordinate system, while the orientation of the robot concerning the global coordinates is represented by the angle θ. The wheels assumed to be in constant contact with the ground to avoid slip, describe arcs in the plane, causing the vehicle to rotate around a point known as the instantaneous center of curvature (ICC). The essential parameters include the radius of the wheels (r) and the vehicle's (L) width. The ground contact speeds of the left and right wheels are denoted by V_L and V_R,, respectively, contributing to the overall rotation of the vehicle characterized by the angular velocity ω.

To articulate the kinematics model of a Differential Drive Mobile Robot (DDMR), five simplifying assumptions are employed, as proposed by Felix-Rendon et al. (2021):

1) The robots are assumed to move in a planar area, simplifying the analysis to two-dimensional motion.
2) The guide axis, representing the direction of movement, is considered perpendicular to the plane of motion, streamlining the mathematical formulation.
3) The wheels are assumed to move without restrictions, facilitating a straightforward kinematic representation.
4) The direction of movement remains constant during small time intervals, allowing for a more manageable analysis of the robot's kinematics.
5) The robot is treated as a rigid body, enabling the application of rigid body dynamics principles to the analysis.

These assumptions are grounded in acknowledging that individual velocities are time-variant components, subject to change over time. Within the time interval t_1 to , t_2, these velocities are deemed constant, as articulated by Kothandaraman. (2016). By making these assumptions, the kinematics model achieves a balance between mathematical tractability and a practical representation of the differential drive mobile robot's dynamic behaviour.

Table 2.2 presents a comprehensive overview of the mechanical parameters and the controlled and observed variables crucial for developing the robot's kinematic model and control system. These parameters are pivotal in understanding and manipulating the robot's dynamic behaviour.

Table 2.2: Differential drive wheeled robot parameter (Kothandaraman. 2016)

Robot Parameter	Symbol	Unit
Wheel radius	r	m
Half distance between wheels	$\frac{L}{2}$	m
Robot translation velocity	V	m/s
Right wheel linear velocity	V_R	m/s
Left wheel linear velocity	V_L	m/s
Right wheel angular velocity	ω_R	rad/s
Left wheel angular velocity	ω_L	rad/s
Robot velocity in the x-axis	V_x	m/s
Robot velocity in the y-axis	V_y	m/s
Robot angle calculated from the x-axis	θ	degree
Robot angular velocity	ω	degree/s
Robot position in x-axis	x	m
Robot position in y-axis	y	m

In a two-wheeled robot employing a differential drive system, the linear velocity of the robot's wheels is a crucial parameter that influences the overall system state. The left and right wheel's linear velocity can be calculated from the motor angular velocity and the wheel radius, as described by Equation 2.1 and Equation 2.2:

$$V_R = \omega_R \mathrm{r} \qquad \text{Equation 2.1}$$

$$V_L = \omega_L r \qquad \text{Equation 2.2}$$

Even though the two motors can move independently, the calculated linear velocities play a pivotal role in determining the overall system state. These velocities directly impact the robot's motion, influencing its speed and direction. The equations serve as fundamental tools for understanding and predicting the dynamic behavior of a differential drive robot, enabling precise control over its movements by manipulating the motor angular velocities and wheel radius.

A set of equations based on the Instantaneous Center of Curvature (ICC) concept describes the kinematic behavior of a mobile robot with a differential drive system. The

ICC concept helps elucidate the robot's motion in different scenarios, leading to the formulation of kinematic equations:

1) Straight Linear Motion (Case V_R = V_L):
    - When the linear velocities of the right and left wheels are equal (V_R = V_L), the robot moves straight in a linear direction.
    - The radius of curvature (R) is infinite, and the angular velocity (ω) is zero.

2) Rotation in Place (Case V_R = -V_L):
    - When the linear velocities of the right and left wheels are equal in magnitude but opposite in sign (V_R = -V_L,), the robot rotates in the same place along its axis about its center point.

    The radius of curvature (R) is zero.

3) Turning about Left Wheel (Case V_L = 0):
    - When the linear velocity of the left wheel is zero (V_L = 0), the robot turns about the left wheel with a radius of curvature (R) equal to half the width of the robot, R = $\frac{1}{2}$.

4) Turning about Right Wheel (Case V_R = 0)
    - When the linear velocity of the right wheel is zero (V_R = 0), the robot turns about the right wheel with a radius of curvature (R) equal to half the width of the robot, R = $\frac{1}{2}$.

Kinematic equations for the mobile robot as per the ICC concept are as following:

$$\omega \cdot \left(R + \frac{L}{2}\right) = V_R$$ Equation 2.3

$$\omega \cdot \left(R - \frac{L}{2}\right) = V_L$$ Equation 2.4

At any instance in time, we can solve for R and ω:

$$\omega = \frac{(V_R - V_L)}{L}$$ Equation 2.5

$$R = \frac{L}{2} \cdot \frac{(V_R + V_L)}{(V_R - V_L)}$$ Equation 2.6

Using the equation for the angular velocity, the instantaneous velocity V of the point midway between the robot's wheels is given by:

$$V = \omega \cdot R$$

$$= \frac{V_R + V_L}{2}$$ Equation 2.7

2.8.4 Forward Kinematic

In autonomous navigation, understanding the Instantaneous Center of Curvature (ICC) concept is crucial for determining the robot's position and orientation as it moves. When the robot's wheel speeds change, causing it to rotate, the ICC becomes the point around which it pivots. Let's consider the robot's initial position (x,y) and orientation angle θ with respect to the X-axis.

As the robot changes its configuration, reaching a new position (x', y')with an updated orientation angle θ', the ICC plays a pivotal role in describing this motion. The ICC is the point around which the robot rotates during this transformation.

$$ICC = [x - R\sin\theta, y + R\cos\theta]$$ Equation 2.8

and the new position at time t + δt would be:

$$\begin{pmatrix} x' \\ y' \\ \theta' \end{pmatrix} = \begin{pmatrix} \cos(\omega\delta t) & -\sin(\omega\delta t) & 0 \\ \sin(\omega\delta t) & \cos(\omega\delta t) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x - ICC_x \\ y - ICC_y \\ \theta \end{pmatrix} + \begin{pmatrix} ICC_x \\ ICC_y \\ \omega\delta t \end{pmatrix}$$ Equation 2.9

By using equation 2.9, can find the robot's position at any instant. The above equations can be described as the position of the robot moving in a particular direction θt at a given velocity V by:

$$P_x = x_t = \int V \cdot \sin\theta \cdot d\theta$$
$$P_y = y_t = \int V \cdot \cos\theta \cdot d\theta \qquad \text{Equation 2.10}$$
$$\theta = \int \omega \cdot dt$$

2.8.5 Dynamic Modelling

Dynamic modelling of differential drive mobile robots is crucial for understanding and controlling their motion. The dynamic model captures the relationship between the robot's motion and the forces and torques acting on it. Various approaches and methodologies have been employed to develop accurate and comprehensive models for differential drive mobile robots.

One approach to dynamic modelling involves using the Lagrange method, which has been applied to derive the dynamic model of a mobile robot with a differential drive (Tiep et al. 2018). The Lagrange method provides a systematic framework for formulating the equations of motion, considering the robot's kinematics and dynamics. By utilizing this approach, researchers have developed detailed dynamic models that accurately represent the behaviour of differential drive mobile robots.

The Lagrange equation is given by:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) + \left(\frac{\partial L}{\partial q_i}\right) = F - \Lambda^T(q)\lambda \qquad \text{Equation 2.11}$$

Where L = T − V is the Lagrangian function; T is the kinematic energy of the robot; V is the potential energy; F is the generalized force; q_i are the generalized coordinates; Λ is the constraint matrix, and λ is the Lagrange multiplier vector associated with the constraints. The kinetic energy of the DDMR is known as:

$$\begin{cases} T_c = \frac{1}{2}m_c{v_c}^2 + \frac{1}{2}I_c\dot{\theta}^2 \\ T_R = \frac{1}{2}m_w{v_R}^2 + \frac{1}{2}I_m\dot{\theta}^2 + \frac{1}{2}I_w{\dot{\theta}_R}^2 \\ T_L = \frac{1}{2}m_W{v_L}^2 + \frac{1}{2}I_m\dot{\theta}^2 + \frac{1}{2}I_w{\dot{\theta}_L}^2 \end{cases}$$ Equation 2.12

where

T_c: the kinematic energy of a robot platform.

T_R: the kinematic of right wheel.

T_L: the kinematic of left wheel.

m_c: the mass of the robot platfrom without the wheel and motor.

m_w: the mass of wheel (including motor).

I_c: the moment of inertia of robot.

I_w: the moment of inertia of each driving wheel with a motor about the wheel axis.

I_m: the moment of inertia of each driving wheel with a motor about the wheel diameter.

The coordinates of wheels can be determined as follow:

$$\begin{cases} x_R = x_p + l\sin\theta \\ y_R = y_p + l\cos\theta \end{cases}$$ Equation 2.13

$$\begin{cases} x_L = x_p - l\sin\theta \\ y_L = y_p + l\cos\theta \end{cases}$$ Equation 2.14

Total kinematic energy of the robot can be determined:

$$T = \frac{1}{2}(m_c + 2m_w)\left({\dot{x}_p}^2 + {\dot{y}_p}^2\right) - m_c d\dot{\theta}(\dot{y}_a\cos\theta - \dot{x}_a\sin\theta) + \frac{1}{2}I\dot{\theta}^2 + \frac{1}{2}I_w({\dot{\theta}_L}^2 + {\dot{\theta}_R}^2)$$

Equation 2.15

Consider L=T at the Lagrangian function, the equations of robot's motion are given by:

$$m\ddot{x}_p - md\ddot{\theta}\sin\theta - md\dot{\theta}^2\cos\theta = C_1$$ Equation 2.16

$$m\ddot{y}_p - md\ddot{\theta}\cos\theta - md\dot{\theta}^2\sin\theta = C_2$$ Equation 2.17

$$I\ddot{\theta} - md\ddot{x}_p\sin\theta + md\ddot{y}_p\cos\theta = C_3$$ Equation 2.18

$$I_w\ddot{\theta}_R = \tau_R + C_4$$ Equation 2.19

$$I_w\ddot{\theta}_L = \tau_L + C_5$$ Equation 2.20

where

$$m = m_c + 2m_w, I = I_c + m_c d^2 + 2m_w l^2 + 2I_m$$ Equation 2.21

The motion of the robot can be represented as:

$$M(q)(\ddot{q}) + V(q, \dot{q}) = B(q)\tau - \Lambda^T(q)\lambda$$ Equation 2.22

where

$M(q)$: the inertia moment matrix, symmetric positive definite matrix.

$V(q, \dot{q})$: the Coriolis and centrifugal matrix.

$B(q)$: input matrix.

τ: input vector.

2.8.6 Wheel Torque

Consider the robot moving on an inclined plane of angle θ, the wheel's radius is R, f is the frictional force, T is the torque, and a is the robot's acceleration.

Summation X-axis force,

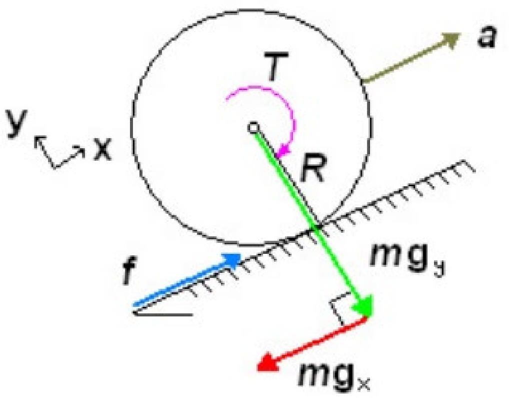


Figure 2.2 Schematic of robot wheel (Tuleshov et al. 2022)

$$\sum Fx = Ma = Mg\sin\theta + f$$ Equation 2.23

$$Ma = Mg\sin\theta + \frac{T}{R}$$ Equation 2.24

Solving,

$$T = MR\ (a + g\sin\theta)$$ Equation 2.25

The torque required for each actuator can be obtained by dividing the total torque by a number of actuators (n).

$$T = \frac{M(a+g\sin\theta)}{n}$$ Equation 2.26

2.8.7 Belt System

The robot's traction system, depicted in Figure 2.3, comprises two DC motors connected to two wheels using rubber belts to create a pulley system, which plays a critical role in its locomotion and manoeuvrability. Jabeur & Seddik (2020) present the control inputs of the robot's dynamic model, shown in Table 2.3, as the torques delivered by the two DC motors incorporated in the left and right wheels.

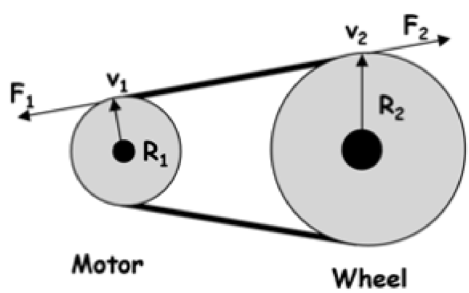


Figure 2.3: The robot pulley system (Jabeur & Seddik, 2020)

Table 2.3: Pulley system parameters (Jabeur & Seddik, 2020)

	Motor Shaft	Driven Wheel
Radius	R_1	R_2
Force exerts	F_1	F_2
Speed contact point	V_1	V_2
Angular speed	ω_1	ω_2

Consider speed and force of the belt same at two points:

$$V_1 = V_2 \quad \text{Equation 2.27}$$

$$F_1 = F_2 \quad \text{Equation 2.28}$$

Since linear speed is equal to the product of the radius and the angular speed,

$$R_1\omega_1 = R_2\omega_2 \quad \text{Equation 2.29}$$

and

$$\frac{\omega_1}{\omega_2} = \frac{R_2}{R_1} \quad \text{Equation 2.30}$$

Since torque is equal to the product of force and radius,

$$\frac{\tau_1}{\tau_2} = \frac{R_1}{R_2} \quad \text{Equation 2.31}$$

Rearrange equation we get,

$$\frac{\tau_1}{\omega_1} = \frac{\tau_2}{\omega_2} \quad \text{Equation 2.32}$$

This shows that the input power is equal to the output power in an ideal pulley system. Therefore, the torque increases if we reduce the speed and vice versa.

2.9 Summary

This chapter provides an in-depth exploration of mobile robot locomotion. It begins by discussing the fundamentals of locomotion and the essential characteristics of robot locomotion systems. The literature review then delves into legged mobile robots, including one-legged, two-legged, four-legged, and six-legged robots, and their evolution over time. It also covers wheel-based locomotion, including stability, maneuverability, and controllability in mobile robots, and the different wheel configurations in mobile robotics, such as conventional wheels, mecanum wheels, universal omni wheels, and orthogonal wheels. This chapter also discusses the different types of wheel drive configurations, including differential drive systems, synchro drive, and omnidirectional drive, and the classification of wheeled mobile robots based on their holonomy. This chapter also emphasizes the importance of understanding the mechanical intricacies of mobile robots for tailoring mobile platforms to specific tasks and developing precise control software.

CHAPTER 3

METHODOLOGY

This chapter is a comprehensive guide outlining the methods and strategies employed throughout the project, from its inception to finalizing the report. Encompassing all essential elements, this topic meticulously details every component and aspect essential for the project's completion, presenting them with precise specifications. The chapter unfolds in four distinct parts. Firstly, it delineates the overall project flow by establishing a detailed flow chart. Subsequently, the second part delves into the 3D modelling and simulation software, elucidating the processes involved. The third segment explains the methodology guiding the project's fabrication, outlining the steps and techniques applied. Lastly, the fourth part delves into the method used to analyze and evaluate the data garnered from the project, ensuring a thorough examination of the project's outcomes.

3.1 Project Planning

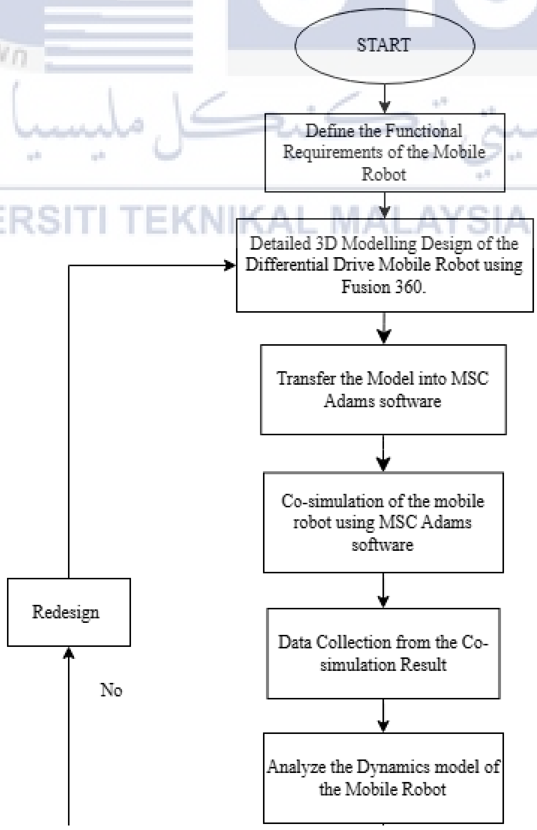
The inclusion of a flow chart in this research project plays a crucial role in conveying the sequential steps involved in the mechanical design and development of the differential drive mobile robot. The description appropriately highlights the significance of a flow chart as a visual representation that systematically outlines the workflow, showcasing the logical progression from one stage to another.

The articulation of the primary purpose of the flow chart is commendable. It effectively communicates that the flow chart is a vital communication tool, surpassing textual descriptions by providing a concise and visual overview of the entire project workflow. This clarity is essential for various stakeholders, including researchers, instructors, and collaborators, to comprehensively grasp the intricacies of design, simulation, and evaluation processes.

The mention of the flow chart's utility in project management and quality control is apt. It rightly emphasizes its role as a roadmap for tracking progress, identifying potential bottlenecks, and ensuring precision in each project phase. This aspect aligns well with industry standards for effective project management practices.

The description successfully conveys the dynamic nature of the flow chart, highlighting its role as a guide that accommodates adaptability and iteration. This is crucial in research projects where flexibility is often required, and tasks may need to be revisited or adjusted based on evolving insights. The emphasis on maintaining a streamlined and organized workflow contributes to transparency and underscores the flow chart's role in achieving the project's objectives.

The flow chart of the overall project is shown in Figure 3.1.



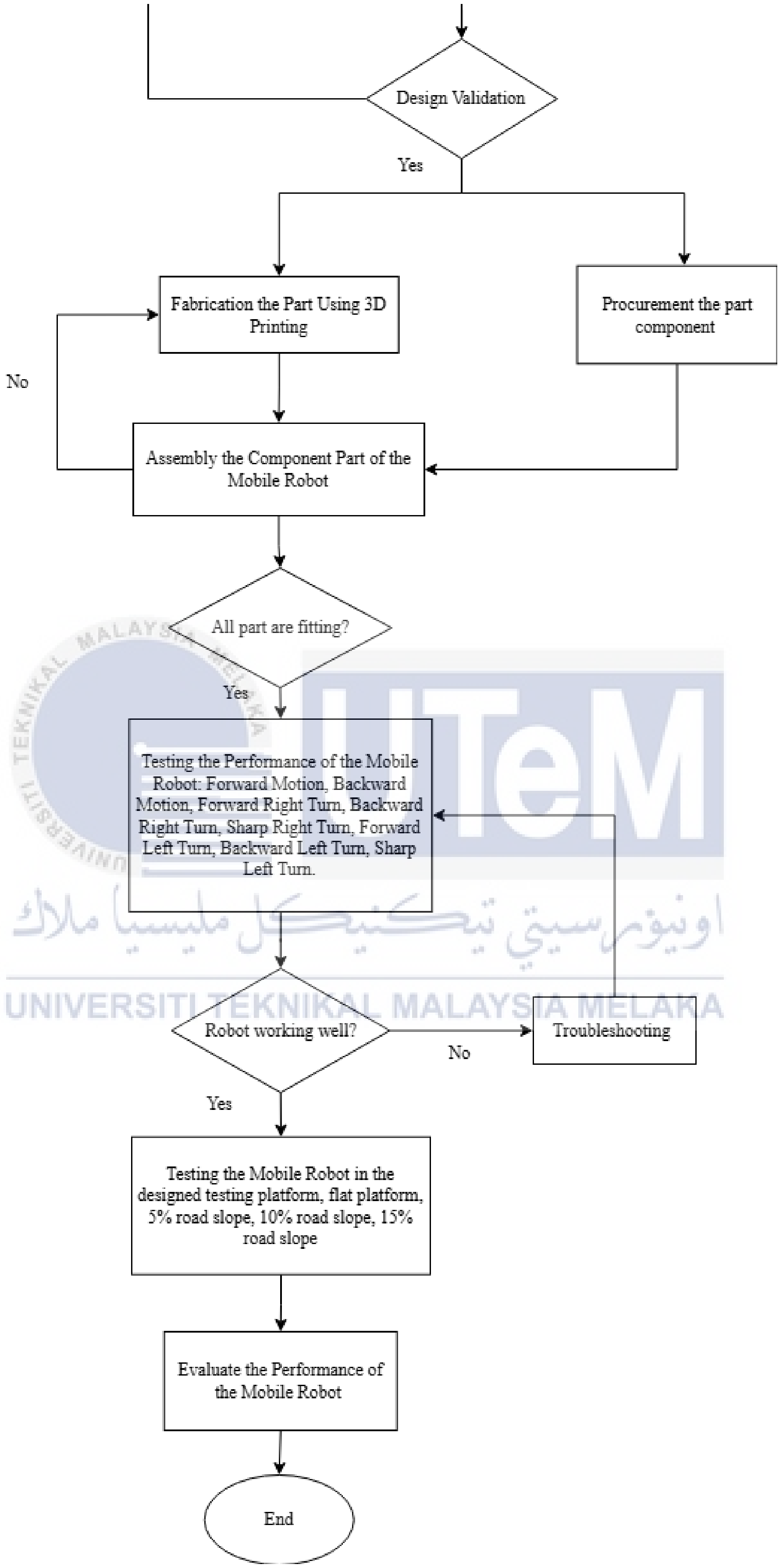


Figure 3.1: Project Flow Chart

3.2 3D Modelling and Simulation Software

In executing the differential drive mobile robot project, the utilization of two distinct software tools, Fusion 360 and ADAMS, is integral to the overall design and development process. Each software tool serves a specific function, playing a critical role in different facets of the project. This section provides a comprehensive overview of these software tools, elucidating their functionalities and how they synergistically contribute to successfully realizing the project objectives.

3.2.1 Fusion 360

The integration of Fusion 360 software is pivotal in this project's comprehensive design and development of the differential drive mobile robot. Fusion 360, a state-of-the-art computer-aided design (CAD) tool, facilitates a seamless and efficient design process.

In the initial stages, Fusion 360 provides a robust platform for creating detailed and intricate 3D models of the mobile robot. The software's parametric modelling capabilities enable the student to refine the design iteratively, ensuring optimal functionality and structural integrity. Through this iterative process, Fusion 360 is a versatile tool for conceptualizing and refining the mechanical aspects of the differential drive system.

Furthermore, Fusion 360's cloud-based collaboration features enhance the project's efficiency by enabling real-time supervisor collaboration. This ensures that the design specifications are consistently updated and accessible to all stakeholders, fostering a collaborative and streamlined design process.

The integration of Fusion 360 extends beyond the design phase into the simulation and analysis of the mobile robot. The software's simulation capabilities allow for a virtual evaluation of the robot's performance, offering insights into its dynamics, stress distribution, and overall functionality. This virtual testing using Fusion 360 contributes to a more informed decision-making process before the physical prototype is constructed.

Additionally, Fusion 360's compatibility with other simulation tools, such as MSC Adams, facilitates a seamless transition between the design and analysis phases of the project. This interoperability enhances the project's scientific rigour by allowing for a more accurate representation of the robot's behaviour in diverse operational scenarios.

3.2.2 MSC ADAMS

The utilization of MSC Adams software is instrumental in advancing the project's objectives by providing a sophisticated platform for simulating and analyzing the performance of the designed differential drive mobile robot.

MSC Adams is a powerful multibody dynamics simulation tool, allowing for a comprehensive virtual evaluation of the mobile robot's behaviour. The software facilitates the creation of dynamic models that accurately represent the mechanical interactions between various robot components. This includes simulating forces, torques, and motion profiles within the differential drive system.

One of the primary applications of MSC Adams in this project is the simulation of the movement and response of the differential drive mobile robot to external stimuli. Through dynamic analysis, the software enables the assessment of the robot's stability, maneuverability, and overall performance under different operating conditions. This virtual testing significantly reduces the need for physical prototypes, saving time and resources while providing valuable insights into the robot's behaviour.

Furthermore, MSC Adams allows for the exploration of torque characteristics, aligning with the project's objective to evaluate the performance efficiency of the differential drive mobile robot. The software enables a detailed examination of torque distribution throughout the system, identifying potential inefficiencies and optimization opportunities.

The seamless integration between Fusion 360 and MSC Adams enhances the project's workflow. The 3D models created in Fusion 360 can be directly imported into

MSC Adams, ensuring a smooth transition from the design phase to dynamic simulation and analysis.

In conclusion, the incorporation of MSC Adams in this project signifies a commitment to a rigorous and scientific approach in assessing the performance of the differential drive mobile robot. The software's advanced simulation capabilities contribute to a more informed and efficient design process, ultimately enhancing the project's overall success and the potential impact of the developed robotic system.

3.3 Component Integration

A few main components are needed in designing the mobile robot platform to perform all the processes, such as the main control, motor controller, and the encoder for the motor. All these components will fit into the body of the mobile robot and be linked with each other by using the Phyton software, which is the operating system of Ubuntu 18.04; apart from using the software, these components will be connected using simple wiring. The wiring diagram will be stated in Chapter 4.

3.3.1 Maker Uno

The Maker Uno serves as the main control unit of the mobile robot. It is a microcontroller board based on the Arduino Uno, designed for simplicity and ease of use in educational and prototyping applications. The Maker Uno features an ATmega328P microcontroller and provides a variety of digital and analog I/O pins for interfacing with sensors, actuators, and other components. It also supports USB communication for programming and serial communication, making it an ideal choice for controlling the mobile robot. The specifications are shown in Table 3.1.

Table 3.1: Specifications of Maker Uno

No	Specification	Details
1	Microcontroller	ATmega328P
2	Operating Voltage	5V
3	Input Voltage (recommended)	5V
4	Digital I/O Pins	14 (6 PWM outputs)
5	Analog Input Pins	6
6	Clock Speed	16 MHz
7	Flash Memory	32 KB
8	SRAM	2 KB
9	EEPROM	1 KB
10	Communication	USB

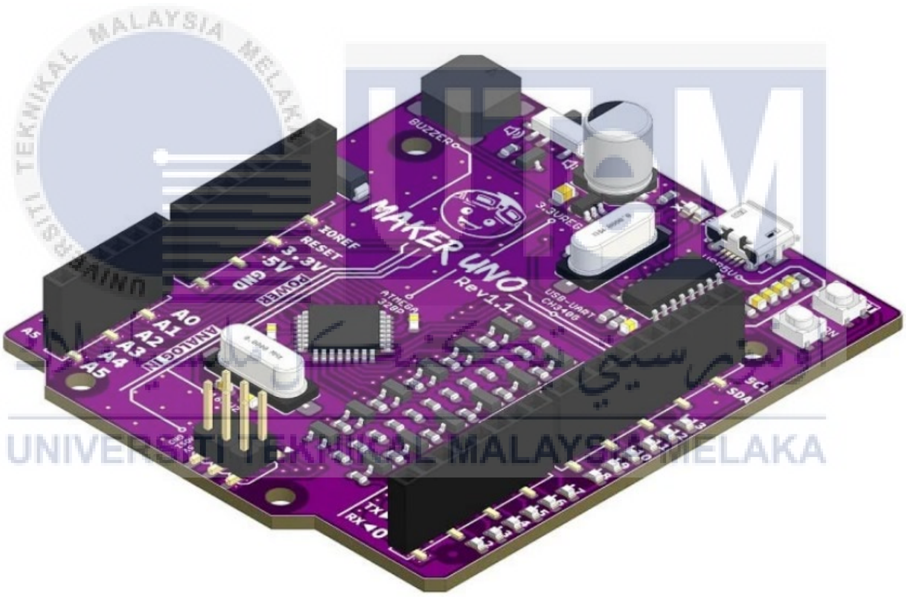


Figure 3.2: Maker Uno

3.3.2 IG32E-264K Planetary DC Geared Motor with Encoder

The IG32E-264K is a high-torque, low-speed DC geared motor with an integrated encoder. This motor is designed for applications that require reliable and precise motion control. The planetary gear design provides high torque and efficiency, making it suitable for driving the wheels of the mobile robot. The integrated encoder allows for precise measurement of the motor's speed and position, enabling accurate control of the robot's movements. The specifications are shown in Table 3.2.

Table 3.2: Specifications of IG32E-264K Planetary DC Geared Motor with Encoder

No	Specification	Details
1	Motor Type	DC Geared Motor
2	Gear Ratio	264:1
3	No-load Speed	24 RPM
4	No-load Current	150 mA
5	Stall Torque	1.2 Nm
6	Rated Current	900 mA
7	Operating Voltage	12V
8	Encoder	1848 pulses per rotation, single channel output

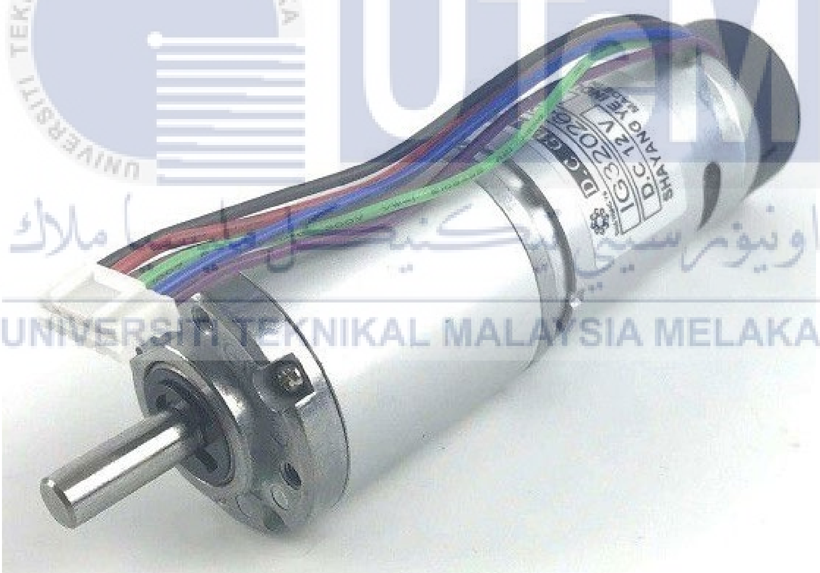


Figure 3.3: IG32E-264K Planetary DC Geared Motor with Encoder

3.3.3 L298N Dual H-Bridge Motor Controller

The L298N is a dual H-Bridge motor controller capable of driving two DC motors independently. It allows for control over both the speed and direction of the motors, making it a versatile component for mobile robotics applications. The L298N can handle high currents and voltages, making it suitable for driving the IG32E-264K motors. It includes protection features such as over-temperature and short-circuit protection to ensure reliable operation. The specifications are shown in Table 3.3.

Table 3.3: Specifications of L298N Dual H-Bridge Motor Controller

No	Specification	Details
1	Motor Controller Type	Dual H-Bridge
2	Operating Voltage	7-30V
3	Output Current	1A per channel
4	Peak Output Current	2A per channel
5	Control Logic Voltage	5V
6	Logic Current	0-36 mA
7	Maximum Power	25W

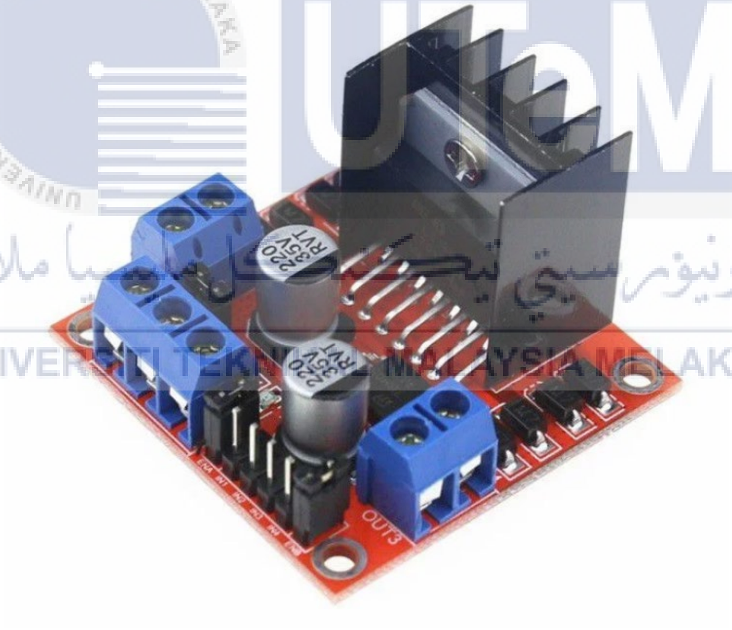


Figure 3.4: L298N Dual H-Bridge Motor Controller

These components collectively form the essential hardware infrastructure for the mobile robot, enabling it to perform various tasks with precision and reliability. The integration of these components with the software and wiring connections will be elaborated on in subsequent chapters.

3.4 Design Stage

The design stage is critical in developing the differential drive mobile robot, laying the foundation for its structural integrity, functionality, and overall performance. In this pivotal stage, meticulous attention is given to conceptualizing and refining the robot's mechanical aspects, with a particular emphasis on the implementation of Fusion 360 software for the creation of detailed 3D models.

The design process involves iterative refinement, leveraging Fusion 360's parametric modelling capabilities to ensure optimal performance and adherence to project specifications. The intricacies of the differential drive system, including component placement, structural design, and overall geometry, are carefully considered during this stage.

3.4.1 Studying the Characteristics of the Differential Drive Mobile Robot

The initial phase of the design process begins with a comprehensive study of the characteristics inherent to the differential drive mobile robot. A meticulous examination is undertaken to grasp the intricacies of its manoeuvrability, torque requirements, and operational constraints. Understanding maneuverability is essential, as it directly influences the robot's ability to navigate and perform tasks effectively within its designated environment.

The scrutiny extends to assessing torque requirements, a critical factor in determining the power and force necessary for optimal functionality. This aspect plays a pivotal role in shaping decisions related to motor selection, gearing mechanisms, and overall power distribution within the system.

Operational constraints are thoroughly examined to identify limitations and challenges the robot may encounter during its intended tasks. These constraints can encompass spatial restrictions, environmental considerations, and any requirements the intended application dictates. This foundational knowledge forms a robust basis for informed decision-making throughout the subsequent design stages, ensuring that the differential drive mobile robot is technically sound and aligned with the practical demands of its operational context.

3.4.2 Requirement Analysis

In the design process of the differential drive mobile robot, a pivotal phase involves conducting a thorough requirement analysis. The primary focus is on crafting a robot with compact dimensions, specifically tailored for operation within human workspaces. This involves meticulous consideration of spatial constraints, aiming to optimize the robot's size for seamless manoeuvrability in confined areas, including navigating through doorways.

The requirement analysis is rooted in the project's problem statement, emphasizing the need for a mobile robot capable of efficiently operating in spaces where larger robotic systems may face limitations. By tailoring the design to be small in dimension, the mobile robot becomes inherently more versatile, offering enhanced accessibility and adaptability within various environments.

The specific attention given to manoeuvrability within constrained spaces, such as doorways, becomes a guiding principle for subsequent design decisions. It influences choices related to the size and configuration of the robot's components, ensuring that the overall design aligns precisely with the identified requirements.

3.4.3 Defining Mobile Robot Size and Component Dimensions

In the meticulous process of designing the differential drive mobile robot, a crucial step involves precisely defining its size and component dimensions. Considering the intended application within a human workspace is paramount, shaping the entire framework of the robot's structure.

The mobile robot's overall dimensions are meticulously established at approximately 350 mm x 450 mm. This deliberate sizing results from a thoughtful analysis of the specific requirements of human workspaces, ensuring that the robot fits seamlessly into such environments and maintains optimal functionality within the defined spatial constraints.

In addition to the overall size, a gear ratio of 1:1 is specified, providing a balanced distribution of power and control within the robot's mechanical system. This gear ratio selection aligns with the intended applications and ensures the robot exhibits the desired performance characteristics.

Furthermore, standard part sizes for procurement, encompassing essential components such as belts, wheels, motors, and others, are determined based on these specifications. This approach streamlines the sourcing and assembly processes, enhancing efficiency and ensuring compatibility between various robot elements.

3.4.4 Exploring Component Positions

Exploring component positions is a critical phase in the design process of the differential drive mobile robot, involving meticulous optimization of the layout to enhance functionality, structural integrity, and ease of assembly. Key components such as gears, motors, motor housings, and wheels are strategically positioned, carefully considering their interplay for efficient operation.

In the context of this project, a specific example illustrates the precision in component placement. Two standard wheels are positioned in the middle of the mobile robot, while two casters are strategically located at the front and back middle sections. This deliberate arrangement aims to achieve optimal stability for the mobile robot during operation.

The placement of standard wheels in the middle ensures balanced weight distribution and facilitates smooth maneuverability. Complementing this, the strategic positioning of casters at the front and back middle enhances stability, minimizing the risk of tipping and ensuring the robot can navigate various surfaces seamlessly.

3.4.5 Defining Problems and Proposed Improvements

The design process has identified several challenges, prompting a comprehensive analysis to propose innovative solutions that enhance the overall performance of the differential drive mobile robot.

Firstly, dimensional constraints pose a significant challenge, especially concerning the in-line alignment of motors with wheels. This configuration results in larger dimensions and hinders the robot's ability to navigate standard doorways. To address this, the proposed solution involves implementing a Belt System. This departure from the traditional in-line setup allows for a parallel connection between the motor and wheel, effectively mitigating the dimensional challenges. This strategic adjustment is anticipated to reduce the mobile robot's overall size and enhance manoeuvrability, particularly in confined spaces.

Additionally, the design process identifies belt slippage between gears as a potential issue. To address this, a belt tensioning mechanism has been introduced. This mechanism includes a screw nut installed in the motor housing that can be adjusted to increase or decrease tension as necessary. This solution ensures a more robust and reliable power transmission within the robot's mechanical system by enabling precise control over the belt tension. The adjustable tensioning mechanism not only overcomes the issue of belt slippage but also extends the belt's lifespan by preventing excessive wear and tear. The belt tensioning mechanism is shown in Figure 3.5.

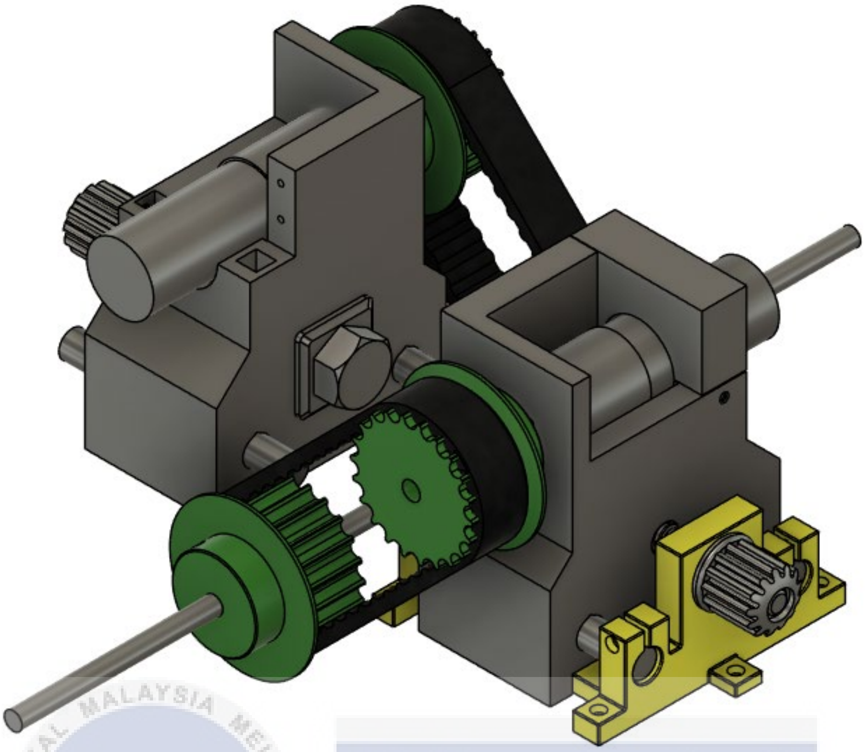


Figure 3.5: Belt tensioning mechanism

Furthermore, considering the limitations of the printing area, the project emphasizes the need to separate body parts during 3D modelling. Specifically, this consideration becomes crucial for efficient manufacturing in instances like the MakerBot Replicator 2X, with a specified maximum print size of 285 x 153 x 155 mm.

Finally, the assembly method is meticulously considered. The incorporation of a fastening joining method, with a specific focus on preparing positions for screw threads in the body part design, underscores the project's commitment to streamlining the construction process. These comprehensive solutions collectively contribute to the overall optimization of the mobile robot, addressing fundamental challenges and advancing its functionality in diverse operational scenarios.

3.4.6 Preliminary Design

The preliminary design phase marks a crucial step in developing the differential drive mobile robot. This stage involves sketching the initial layout of the robot, serving as a foundational visual representation of the proposed design. This preliminary design offers a quick and essential evaluation of the overall structure and the strategic placement of key components within the robot.

The sketch provides a tangible and accessible overview of the mobile robot's envisioned form, facilitating a rapid assessment of its feasibility and adherence to the project's objectives. The layout considers factors such as dimensions, component positioning, and overall aesthetics, providing valuable insights into the initial configuration.

During this stage, any necessary adjustments are promptly identified and implemented. This iterative process addresses potential design flaws or inefficiencies before progressing to more detailed 3D modelling. It allows for a dynamic and responsive approach, enabling designers to refine the concept based on visual feedback and preliminary evaluations.

3.4.7 Detail 3D-Modelling Design using Fusion 360

The pinnacle of the design process is reached during the detailed 3D modelling phase, a critical stage that employs Fusion 360 software. In this phase, the preliminary design is translated into a digital form, with meticulous attention paid to component dimensions, assembly considerations, and optimization for efficient performance.

The 3D modelling phase progresses systematically. It begins with the individual drawing of each component, including gears, belts, shafts, wheels, and motors. Each part is crafted to meet specific design specifications, ensuring precision and accuracy in the virtual representation.

The subsequent step involves drawing the body parts of the mobile robot, thoughtfully segmented into bottom, middle, and upper sections. This segmentation facilitates a comprehensive understanding of the robot's structure and aids in efficiently assembling the final model.

Figure 3.6 depicts the completed model of the mobile robot created in Fusion 360.

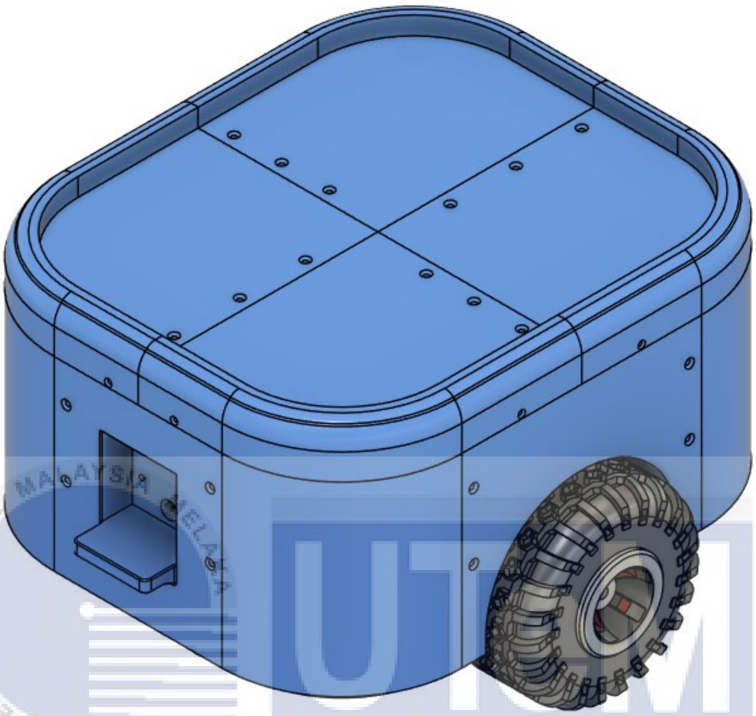


Figure 3.6: The completed model of the differential drive mobile robot

3.5 Simulation Stage

The Simulation Stage in developing the Differential Drive Mobile Robot involves several intricate processes to analyze and test the robot's performance in a virtual environment.

3.5.1 Export the Mobile Robot Model to Adams

Initiating the simulation process, the completed 3D model of the mobile robot, meticulously crafted in Fusion 360, undergoes a crucial preservation step. It is saved in the Parasolid format (.xt), a format optimized for compatibility before being seamlessly exported to Adams. This meticulous transition between platforms ensures a fluid integration, laying the groundwork for comprehensive simulation analysis.

The adoption of the Parasolid format is strategic, serving as a universal bridge between the intricate details of the 3D model and the analytical capabilities of Adams. By preserving the model in this format, the simulation stage can draw upon the nuances of the design, enabling a nuanced exploration of the robot's behaviour and dynamics.

This exportation process begins a sophisticated virtual exploration, allowing for in-depth scrutiny of the mobile robot's performance under various conditions. The compatibility achieved through the Parasolid format ensures a smooth transition to Adams, setting the stage for subsequent phases in the simulation stage.

3.5.2 Defining Materials, Joints, Contacts

The Simulation Stage in Adams is a meticulous process that involves defining key elements to facilitate a comprehensive analysis of the Differential Drive Mobile Robot's behaviour in a virtual environment.

In Adams, the simulation is initiated by defining the materials for each component of the mobile robot. This critical step ensures accurate representation, considering the influence of material properties on the robot's dynamics. The definition of materials establishes the groundwork for simulating realistic interactions and responses during the analysis.

Following material definition, joints are strategically added to connect different parts of the mobile robot. This includes incorporating fixed and revolute joints, essential for simulating the mechanical connections within the robot's structure. The joints play a crucial role in determining how the components interact, influencing the overall dynamics and movements of the mobile robot. The example of fixed and revolute joints is shown in Figure 3.7.

Thank you for reaching out.

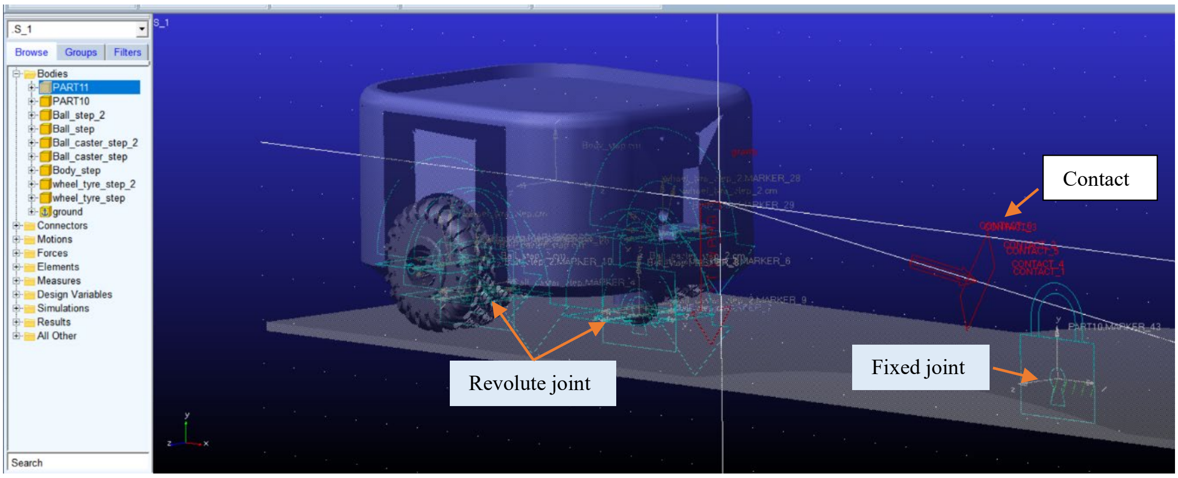


Figure 3.7: Fixed and revolute joint on the mobile robot

Integral to the simulation is creating the ground platform, serving as a foundational base for the robot's movements. This platform becomes the reference point for assessing the robot's behaviour and responses in various scenarios. Subsequently, contacts between the wheels and the ground are established, replicating realistic friction. This simulation element is vital, mimicking the conditions necessary for the mobile robot's locomotion. Without these contacts, the robot would be rendered immobile.

State variables are defined to provide a comprehensive understanding of the robot's behaviour. These include left and right wheel velocities and joint torque. These variables act as input and output for the control system, capturing the dynamic interplay between the robot's components during simulation.

3.5.3 Design and Co-Simulation of the Testing Platform

In this phase, the simulation environment is enriched by creating various testing platforms, with a specific emphasis on sloped terrains. Three distinct scenarios are considered, each representing different slope configurations:

1. Flat Platform: This scenario is a baseline for evaluating the robot's fundamental capabilities on a level surface.

2. Slope with a 5% Incline: This scenario simulates a moderate 5% slope terrain. The aim is to assess the robot's ability to traverse inclined surfaces efficiently. A 5% slope is representative of common real-world gradients encountered in everyday environments, such as gentle hills or ramps, making it crucial for evaluating practical mobility.

3. Slope with a 10% Incline: This scenario involves a steeper slope with a 10% angle. The purpose is to evaluate the robot's performance under more demanding terrain conditions, pushing its capabilities to the limit. A 10% slope simulates more challenging environments, such as steeper hills or ramps, which are less common but still within the range of everyday encounters, especially in urban settings.

4. Slope with a 15% Incline: This most challenging scenario involves a steep slope with a 15% angle. The objective is to test the robot's maximum capacity for handling severe inclines. A 15% slope represents the upper limit of typical urban and off-road conditions, providing a rigorous test of the robot's stability and power.

These testing platforms are strategically designed to represent real-world scenarios the mobile robot might encounter. Including sloped terrains allows for a comprehensive assessment of the robot's stability, maneuverability, and overall performance across varied landscapes.

The co-simulation of the designed Differential Drive Mobile Robot is crucial to this phase. The robot's behaviour is observed and analyzed within the established testing platforms, providing a comprehensive understanding of its torque performance. This real-world simulation approach allows a nuanced exploration of the robot's responses to diverse terrains, critically validating its capabilities.

During the co-simulation process, real-time observations are made, capturing variations in torque exerted by the joints and components of the mobile robot. This comparative analysis identifies strengths, weaknesses, and potential challenges in torque responses across different scenarios. The Flat Platform scenario serves as a baseline, while the 5%, 10%, and 15% inclines increase difficulty levels, allowing for an in-depth assessment of the robot's adaptability.

The torque analysis provides insights into the robot's ability to generate the required torque for efficient locomotion and contributes to scenario-specific understandings. It sheds light on how the mobile robot navigates and responds to varying terrains, offering valuable information for further refinement and optimization.

The co-simulation approach is strategically aligned with real-world scenarios, ensuring that the torque performance analysis accurately reflects the robot's challenges in practical environments. This iterative process of observation, analysis, and refinement contributes to the continual improvement of the robot's design, enhancing its adaptability and efficiency across diverse terrains.

3.5.4 Defining Input/Output State Variables

In the Adams Simulation Stage, a crucial step involves the definition of input and output variables, establishing a clear communication pathway between the simulation and the control system of the Differential Drive Mobile Robot.

Adams is a dynamic interface between the simulated mobile robot and its control system. The output generated by Adams functions as the input for the control system, while the feedback variable from the control system acts as the input for Adams. This bidirectional communication is essential for comprehensively evaluating the robot's behaviour.

In the context of this research, specific input and output variables are meticulously defined to capture the essential dynamics of the mobile robot:

Input Variables:

1. Left Wheel Velocity: The rotational speed of the left wheel, 140 degree/s
2. Right Wheel Velocity: The rotational speed of the right wheel, 140 degree/s

These variables are input state variables, representing the controlled parameters influencing the robot's movement during simulation. The chosen rotational speeds reflect the motor's maximum capacity, allowing for an in-depth assessment of the robot's performance under optimal conditions. This setup ensures that the simulation accurately represents the robot's potential in real-world scenarios, providing valuable insights for its design and operational efficiency.

Output Variables:

1. Joint Torque: The applied torque at the joints.

These variables and other kinematic parameters are designated as output state variables. They provide comprehensive insight into the robot's orientation, stability, and the forces exerted at its joints during simulation.

3.6 Data Collection

The culmination of the simulation process is the collection of results, which is crucial for evaluating the Differential Drive Mobile Robot's performance. The outcomes are presented graphically, comprehensively analyzing the system's behaviour. The Adams plug-in, Adams PostProcessor, generates these graphical results, enabling performance evaluation at any stage of the co-simulation process.

Simulated results, specifically torque values, are collected using the ADAMS postprocessor. Once the co-simulation concludes, the Adams View plug-in is activated, allowing customization of the results for flexible data analysis and presentation.

The Adams View sub-block permits modification of the animation mode during simulation, enhancing the ability to observe and analyse the robot's real-time dynamics. This interactive mode provides a 360-degree perspective, comprehensively understanding the robot's behaviour.

The effectiveness of the mobile robot is validated through graphical representations and real-time dynamic simulations. The Adams View window displays these dynamic simulations, providing detailed views of the robot's movements and responses. This 360-

degree observation ensures that any flaws or nuances not evident in the graphs are identified and addressed, leading to a thorough assessment of the mobile robot's performance.

3.7 Fabrication

The fabrication phase of the Differential Drive Mobile Robot involved producing approximately 32 parts, excluding standard components and electronic elements. Polylactic acid (PLA), a commonly used material in 3D printing, was chosen for this process due to its balance of durability and flexibility.

The fabrication was divided into three major sections: upper, middle, and bottom. This systematic division ensured a structured and efficient assembly of the mobile robot, with each section contributing uniquely to the overall design and functionality. The upper section served as a protective cover and housed critical components, the middle section provided structural support, and the bottom section integrated the drive mechanisms.

In the 3D printer settings, the infill density was calibrated to 10% to minimize material usage and reduce the time needed for the printing phase (Suteja. 2021). This approach optimised resource efficiency while maintaining the structural integrity required for the robot's components.

By choosing PLA and employing a strategic fabrication process, the project achieved a balance between material efficiency and the mechanical robustness necessary for the Differential Drive Mobile Robot's operational demands.

3.8 Post Processing

Following the completion of the 3D printing phase, the mobile robot parts progress through a crucial stage known as post-processing. This essential step is designed to elevate the quality of the fabricated components and optimize their overall performance. The post-processing journey encompasses key steps contributing to refining and perfecting the manufactured parts.

Firstly, the components undergo a meticulous inspection and quality assurance process. Each 3D-printed part undergoes a comprehensive examination to detect imperfections, inconsistencies, or deviations from the original design specifications. This rigorous scrutiny is imperative to ensure that the fabricated parts meet and surpass the required functionality and structural integrity standards.

Another integral aspect of post-processing involves the careful removal of support structures. These structures are introduced during the 3D printing process to support the creation of complex geometries. Post-processing meticulously addresses the removal of these supports, resulting in a final appearance that is clean and polished to meet aesthetic standards.

Furthermore, the surface smoothing step becomes paramount, especially considering the potential presence of layer lines or rough textures on the surfaces of the 3D-printed parts. Techniques such as sanding or polishing are employed during post-processing to achieve a smoother finish. This not only enhances the visual appeal of the components but also contributes to improved functionality.

In essence, post-processing serves as a comprehensive refinement phase, ensuring that the mobile robot parts are free from defects, exhibit a polished appearance, and meet the desired standards for both aesthetics and functionality.

3.9 Assembly

The assembly phase commences with carefully placing threaded inserts into pre-prepared holes within the mobile robot components. These threaded inserts serve a crucial function by providing threaded receptacles, facilitating the installation of screws, bolts, or other fixings. This meticulous process ensures a secure and stable connection between the various parts of the mobile robot.

Once the threaded inserts are in place, the assembly proceeds systematically by bringing together all the individual components of the mobile robot. Each part is fitted according to the predefined design specifications, aligning with the fabrication and post-processing stages. This step involves connecting the upper, middle, and bottom sections, ensuring a seamless integration contributing to the mobile robot's structural integrity and overall functionality.

The assembly process demands precision and attention to detail to guarantee that each part is correctly positioned and securely fastened. The incorporation of electronic components and standard parts is also completed during this phase, contributing to the comprehensive functionality of the mobile robot.

By adhering to the assembly instructions and design specifications, the Differential Drive Mobile Robot takes shape, transforming from a collection of individual components into a fully integrated and operational system.

3.10 Mobile Robot Performance Testing

The evaluation of the Differential Drive Mobile Robot's performance is a pivotal phase, involving rigorous tests to scrutinize its functionality across diverse manoeuvres and operational scenarios.

3.10.1 Forward Motion

Forward motion is achieved by commanding both drive wheels to rotate in the same direction and at the same speed. Specifically, the motors receive signals to rotate the wheels forward, causing them to push against the ground and propel the robot forward. To ensure the robot moves in a straight line, encoders provide continuous feedback, allowing the control system to adjust and maintain equal speeds for both wheels.

3.10.2 Backward Motion

Backward motion is similar to forward motion but in the opposite direction. Both motors are commanded to rotate the wheels in reverse at equal speeds. The robot moves backwards as the wheels push against the ground reversely. Encoders monitor the wheel speeds to ensure synchronization, maintaining a straight backward trajectory.

3.10.3 Forward Right Turn

A forward-right turn is executed by creating a speed differential between the two wheels, with the left wheel rotating faster than the right. The left motor is commanded to increase its speed relative to the right motor, causing the robot to describe an arc curving to the right while moving forward. This differential in wheel speeds results in a smooth turning motion to the right.

3.10.4 Backward Right Turn

A speed differential is created to perform a backward right turn while both wheels rotate in reverse. The left motor rotates the left wheel faster than the right motor, causing the robot to turn to the right while moving backwards. This maneuver allows the robot to describe an arc curving to the right in a reverse motion.

3.10.5 Forward Left Turn

A forward left turn is achieved by creating a speed differential where the right wheel rotates faster than the left. The right motor is commanded to increase its speed relative to the left motor, causing the robot to describe an arc curving to the left while moving forward. This differential in wheel speeds facilitates a smooth left turn.

3.10.6 Backward Left Turn

The backward left turn is performed similarly to the backward right turn but in the opposite direction. The right motor rotates the right wheel faster in reverse than the left motor, causing the robot to turn to the left while moving backwards. This results in the robot describing an arc curving to the left while reversing.

3.10.7 Sharp Left Turn

A sharp left turn involves rotating the wheels in opposite directions, similar to a sharp right turn but in the opposite direction. The right motor is commanded to rotate the right wheel forward while the left motor rotates the left wheel backwards. This counter-rotation causes the robot to spin around its center to the left without moving forward or backwards, enabling a very tight turn to the left.

3.10.8 Sharp Right Turn

A sharp right turn, or turning in place, involves rotating the wheels in opposite directions. The left motor is commanded to rotate the left wheel forward while the right motor rotates the right wheel backwards. This counter-rotation causes the robot to spin around its center to the right without moving forward or backwards, allowing for a very tight turn.

3.11 Mobile Robot Experiment

Conducting a torque analysis experiment for the Differential Drive Mobile Robot involves a comprehensive assessment of its performance under various terrain conditions, mirroring the scenarios simulated during co-simulation. The experiment is executed across three distinct terrain configurations: a flat platform, a slope with a 5% incline, and steeper slopes with 10% and 15% inclines. The robot's torque performance is systematically evaluated in each terrain setting to understand its dynamic response and capabilities.

The experiment begins by placing the mobile robot on the designated terrain, ensuring it is securely positioned for accurate torque measurements. As the robot navigates through these diverse terrains, torque sensors capture real-time data reflecting the forces exerted by the motors and wheels. This data encompasses the torque required to propel the robot forward and backward and execute turns on each terrain type.

Analyzing the torque data allows a nuanced understanding of how the robot adapts to varying terrain challenges. Factors such as incline, surface irregularities, and obstacles contribute to fluctuations in torque requirements. The experiment aims to elucidate how the differential drive system responds to these challenges, providing valuable insights into the robot's performance and refining its control algorithms.

3.12 Evaluate the Performance of the Differential Drive Mobile Robot

The evaluation of the Differential Drive Mobile Robot's performance involves a meticulous comparison between the simulated results and the real-world outcomes obtained through the conducted experiments. After the torque analysis experiment is implemented in real-world scenarios, the robot's performance data is collected, encompassing variables such as torque requirements, navigational accuracy, and responsiveness under different terrain conditions.

The evaluation process begins by systematically comparing the quantitative results obtained from the co-simulation in MSC Adams with the empirical data acquired from the physical experiments. Parameters such as torque distribution, wheel velocities, and the robot's ability to navigate diverse terrains are scrutinized for alignment between the simulated and real-world performances.

Discrepancies between the simulation and real-world results are carefully analyzed to identify potential sources of variation. Factors such as material properties and environmental conditions are considered in the evaluation process. These comparative findings imply adjustments to the simulation model or the physical robot may be implemented.

Additionally, qualitative aspects of the robot's performance, such as stability, maneuverability, and overall functionality, are subjectively assessed and compared. Observations from real-world experiments contribute to a holistic understanding of the robot's capabilities beyond numerical metrics.

The evaluation process is a crucial feedback loop, guiding further refinements to the robot's design, control algorithms, and overall system integration. By aligning simulated expectations with real-world performance, the evaluation ensures that the Differential Drive Mobile Robot meets or exceeds the anticipated standards and functionalities in practical applications. This iterative assessment continuously improves the robot's design and performance for enhanced real-world deployment.

3.13 Summary

This chapter marks a pivotal phase in developing and evaluating the Differential Drive Mobile Robot. Through rigorous experimentation and analysis, the real-world torque analysis experiment provided invaluable insights into the robot's dynamic performance across diverse terrains, facilitating a nuanced understanding of its adaptability and responsiveness. The evaluation process involved a meticulous comparison between simulated and empirical results, shedding light on areas of alignment and potential variations. This iterative feedback loop guided refinements to the robot's design, control algorithms, and overall system integration, ensuring that the mobile robot meets or exceeds anticipated standards for torque distribution, maneuverability, and functionality in practical applications. As the chapter concludes, synthesizing simulated and real-world data positions the project for further advancements, contributing to the ongoing pursuit of an optimized and robust Differential Drive Mobile Robot.

CHAPTER 4

RESULT AND DISCUSSION

The purpose of this chapter is to present and interpret the research findings derived from the study. This chapter is integral to understanding the efficacy and implications of the developed differential drive system in mobile robotics. The results gathered from various simulations and performance tests will be systematically presented, followed by a comprehensive discussion that interprets these findings in the context of the research objectives.

4.1 Final Design of The Mobile Robot

The final design of the mobile robot prioritised functionality and structural integrity. The robot comprises three primary sections: the upper, middle, and bottom. Each section was meticulously designed and fabricated to ensure seamless integration and optimal performance.

4.1.1 Fabrication

The initial stage involved creating detailed CAD models of the robot's components using Fusion 360 design software. These models served as comprehensive blueprints for the fabrication process. Figure 4.1 displays the fabrication of all 32 mobile robot parts, which involved several meticulous steps utilising polylactic acid (PLA) as the primary material for 3D printing.

Figure 4.1: Fabrication parts of the mobile robot

4.1.2 Assembly

Post-processing began with a meticulous inspection and quality assurance process. Each 3D-printed part underwent a comprehensive examination to detect imperfections, inconsistencies, or deviations from the original design specifications. This rigorous scrutiny ensured the fabricated parts met and surpassed the required functionality and structural integrity standards. Any components with defects were reprinted or corrected.

Tools and materials required for assembly, such as screws, bolts, and Allen keys, were prepared and organised. The assembly phase commenced with threaded inserts placed into pre-prepared holes within the mobile robot components. These inserts provided threaded receptacles for screws, bolts, and other fixings, ensuring a secure and stable connection between the various parts of the mobile robot. Each part was fitted according to the predefined design specifications, aligning with the fabrication and post-processing stages to ensure seamless integration and optimal performance.

Figure 4.2 shows a view of all the structural parts after assembly. The upper section of the mobile robot serves as a protective cover for the internal components. The load-placing capacity has been improved to prevent the load from easily falling out of the mobile robot.

Figure 4.2: Complete assemble of the mobile robot

Figure 4.3 shows the top view of the mobile robot. From this perspective, it is evident that half of the tyre is exposed on both sides of the mobile robot. Due to time and material supply constraints, the robot's size was minimised, resulting in the tyre thickness being exposed. The robot body was thus designed to be as compact as possible to address these constraints.

Figure 4.3: Top view of the mobile robot.

4.1.3 Wiring Connection

Once the structural assembly was completed, electronic components such as the control unit, sensors, and wiring were integrated into the robot. Careful handling was essential during this step to prevent damage to sensitive parts. Figure 4.4 below depicts the complete wiring connection diagram for the mobile robot. This diagram includes six components: the microcontroller, encoder board, DC motor controller, battery source (a 12V Li-Po battery), and two brushed DC motors. The wiring diagram illustrates how the Li-Po 12V battery powers the brushed DC motors, motor driver, and Arduino Uno microcontroller, which interfaces with a computer via a micro-USB cable.

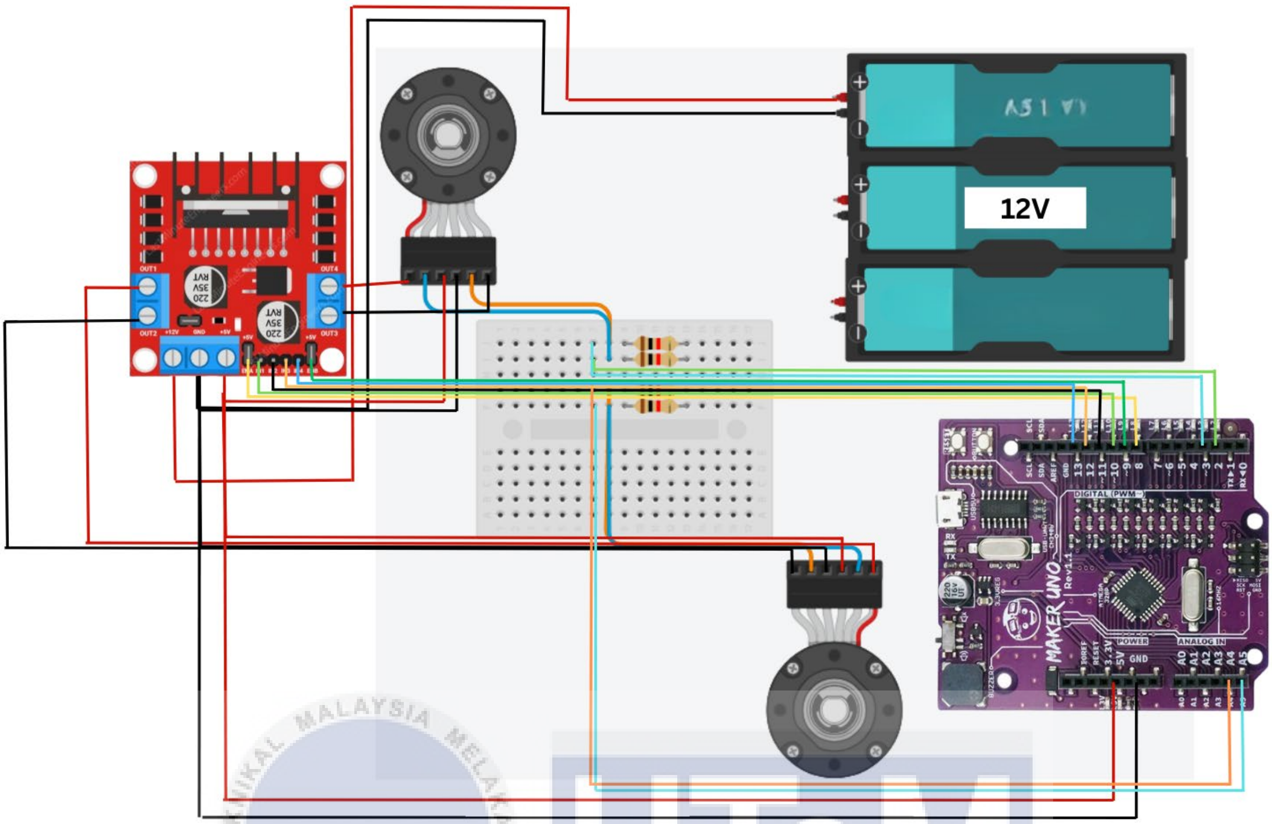


Figure 4.4: Wiring diagram

4.2 Fundamental Robot Movements

4.2.1 Forward Motion

The forward motion of the differential drive mobile robot was simulated in MSC Adams and validated through real-world experiments. The robot's movement in the simulation was smooth and consistent, with both wheels maintaining equal speeds. This was confirmed experimentally, where the robot moved straight without veering, demonstrating the control system's effectiveness in synchronizing wheel speeds. Encoder feedback was crucial in maintaining this synchronization, ensuring the robot's trajectory remained straight. Figures 4.5 and 4.6 compare the simulation and real-world experiment results.

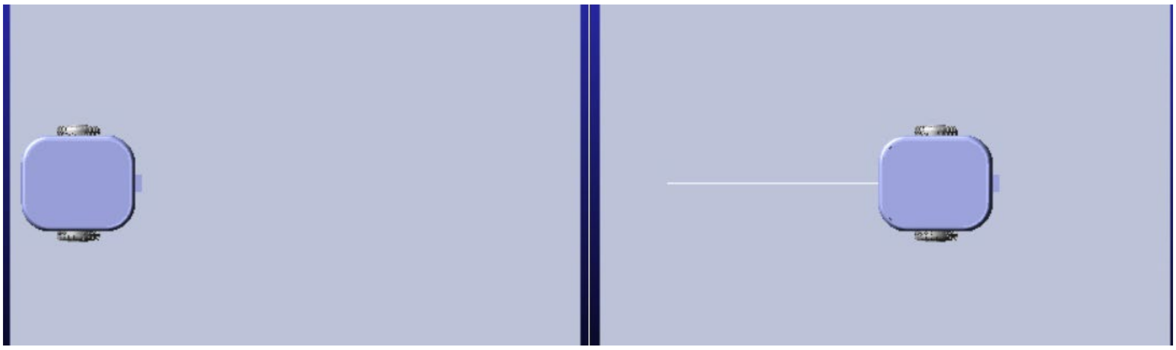


Figure 4.5: Forward Moton Simulation in Msc Adams

Figure 4.6: Forward Motion Real-World Testing

4.2.2 Backward Motion

Backward motion is achieved by reversing the direction of both drive wheels while keeping their speeds equal. The MSC Adams simulation showed the wheels rotating in reverse at equal speeds, resulting in a straight trajectory. Real-world tests confirmed this behaviour, with the robot moving backwards in a straight line. Encoder feedback was critical in adjusting wheel speeds to achieve precise movement, highlighting the control system's robustness. Figures 4.7 and 4.8 illustrate the comparison between the simulation and real-world results.

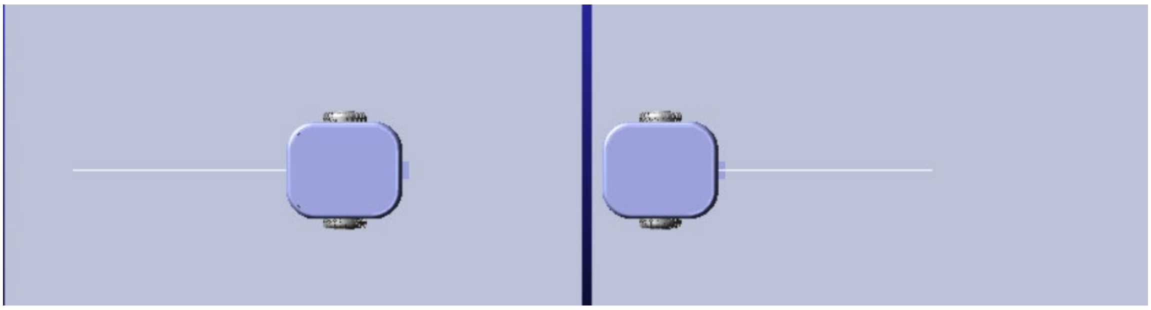


Figure 4.7: Backward Moton Simulation in Msc Adams

Figure 4.8: Backward Motion Real-World Testing

4.2.3 Forward Right Turn

A forward-right turn creates a speed differential between the two wheels, with the left wheel rotating faster than the right. The simulation in MSC Adams showed the robot turning smoothly to the right while moving forward, describing a clear arc. Experimental validation confirmed that the robot could replicate this motion, successfully turning while maintaining forward movement. The control system managed the speed differential effectively, allowing for precise and predictable turns. Figures 4.9 and 4.10 show the robot performing the forward right turn in simulation and real-world settings.

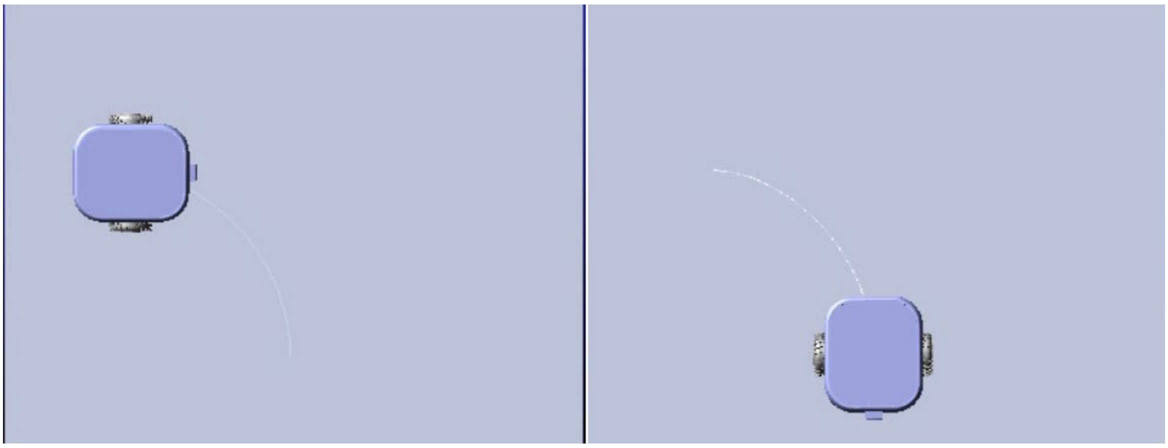


Figure 4.9: Forward Right Turn Simulation in Msc Adams

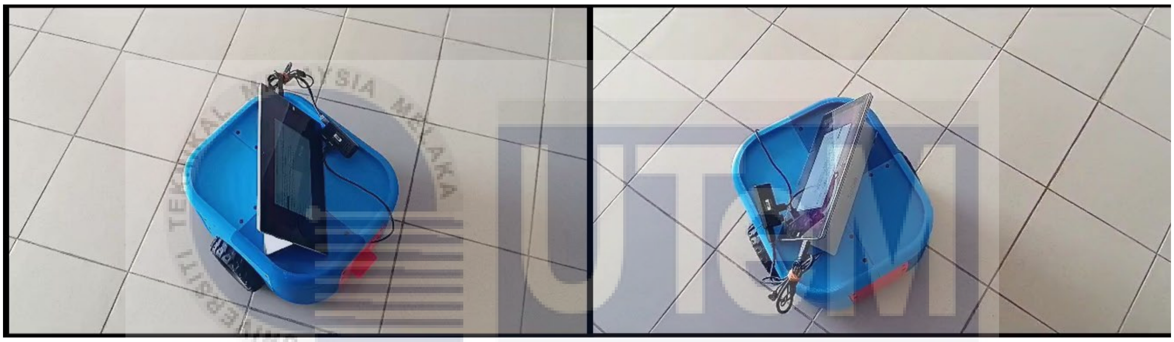


Figure 4.10: Forward Right Turn Real-World Testing

4.2.4 Backward Right Turn

The backward right turn was simulated by increasing the speed of the left wheel while both wheels rotated in reverse. The MSC Adams simulation demonstrated the robot turning right in reverse, forming a distinct arc. This motion was validated in real-world tests, where the robot accurately followed the same trajectory. The experimental results closely matched the simulation, confirming the control system's ability to handle reverse turns with precision. Figures 4.11 and 4.12 illustrate the simulation and real-world outcomes.

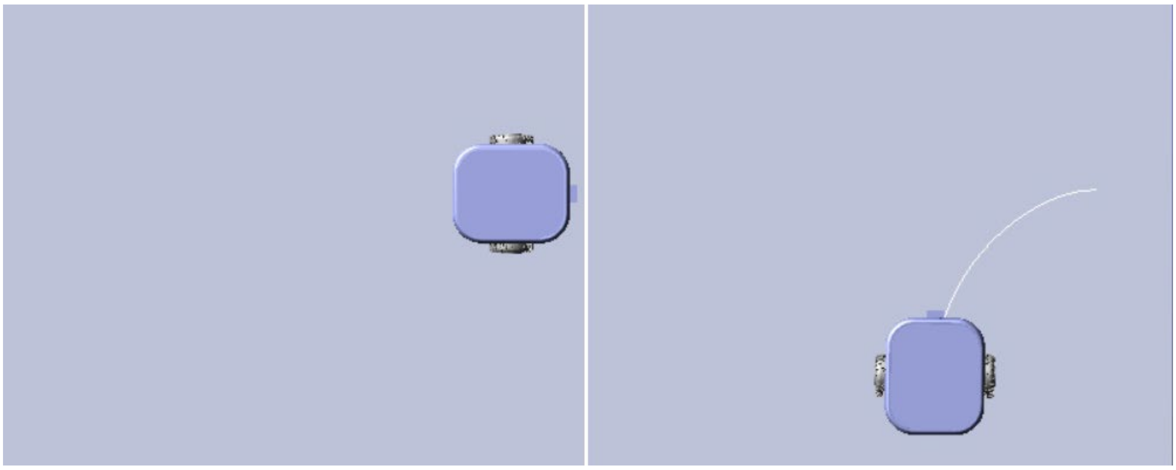


Figure 4.11: Backward Right Turn Simulation in Msc Adams

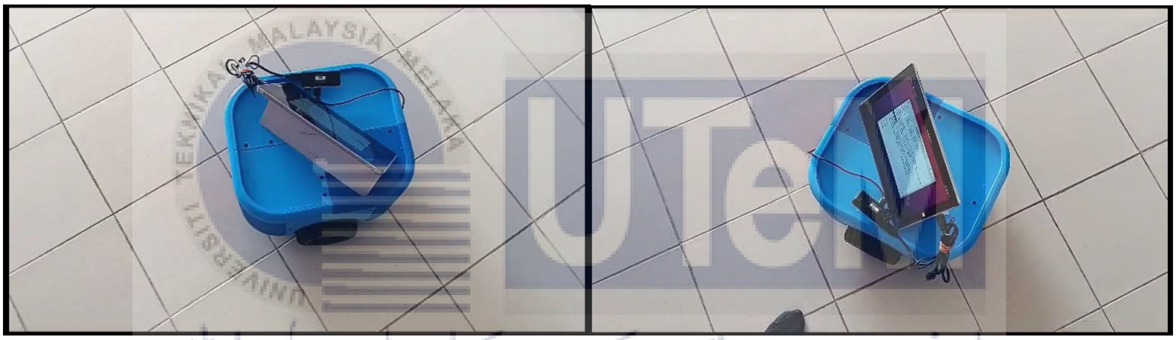


Figure 4.12: Backward Right Turn Real-World Testing

4.2.5 Forward Left Turn

The forward left turn was tested by creating a speed differential where the right wheel rotates faster than the left. The MSC Adams simulation showed the robot turning left while moving forward, forming a clear arc. Experimental validation confirmed that the robot could achieve this motion, demonstrating consistent and smooth turning behaviour. The control system's management of the speed differential ensured accurate and reliable turns. Figures 4.13 and 4.14 illustrate the forward left turn in simulation and real-world tests.

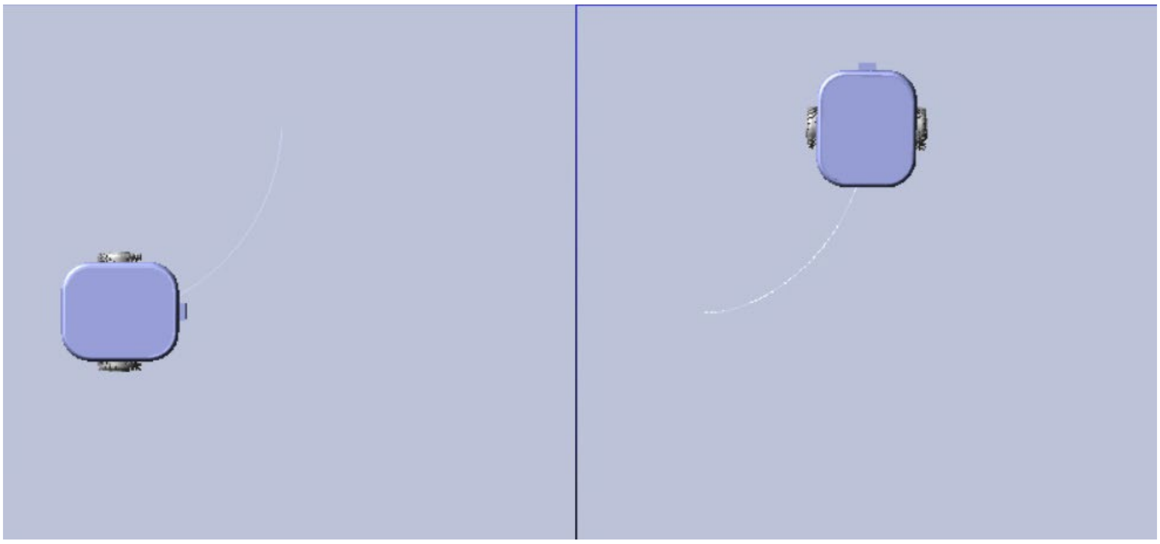


Figure 4.13: Forward Left Turn Simulation in Msc Adams

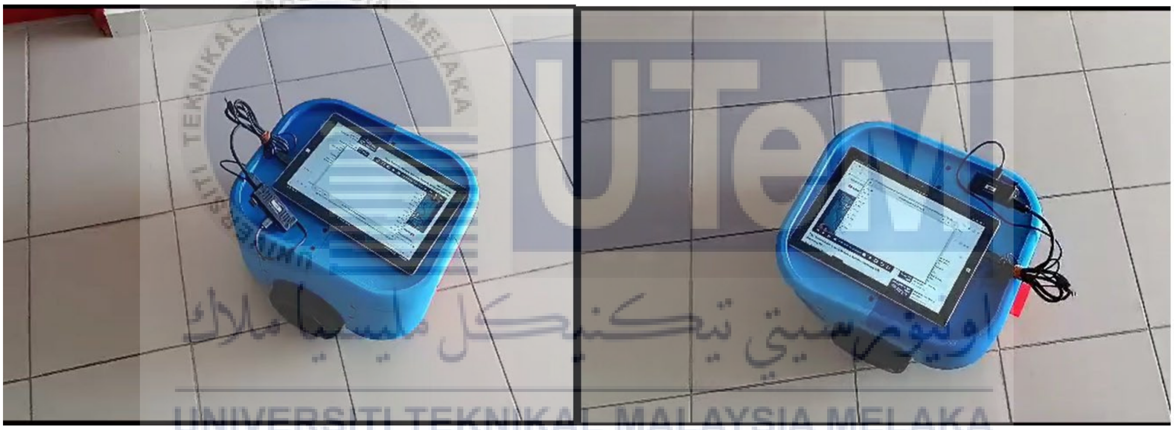


Figure 4.14: Forward Left Turn Real-World Testing

4.2.6 Backward Left Turn

The backward left turn was performed similarly to the backward right turn, with the right wheel rotating faster in reverse. The MSC Adams simulation depicted the robot turning left in reverse, creating a distinct arc. Real-world experiments validated this motion, with the robot accurately following the simulated trajectory. This confirmed the control system's effectiveness in handling reverse turns and maintaining precise movement. Figures 4.15 and 4.16 show the simulation and real-world results for the backward left turn.

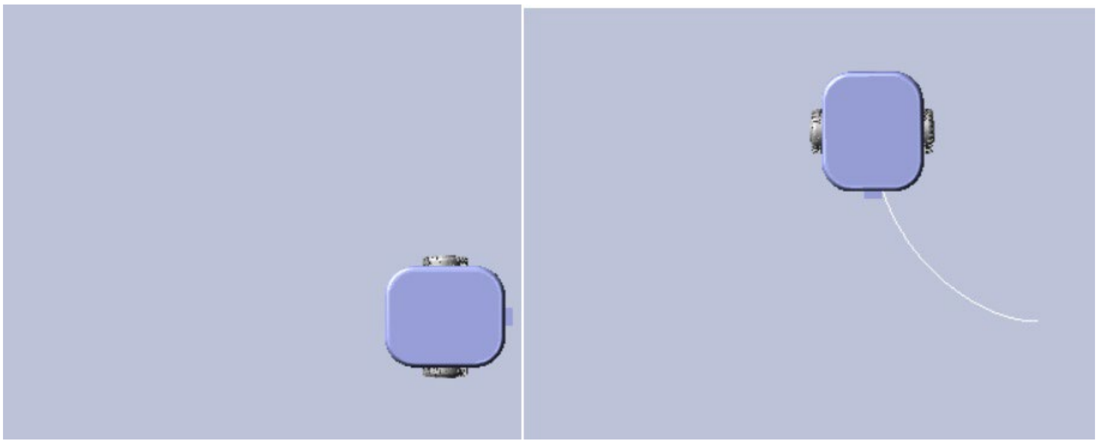


Figure 4.15: Backward Left Turn Simulation in Msc Adams

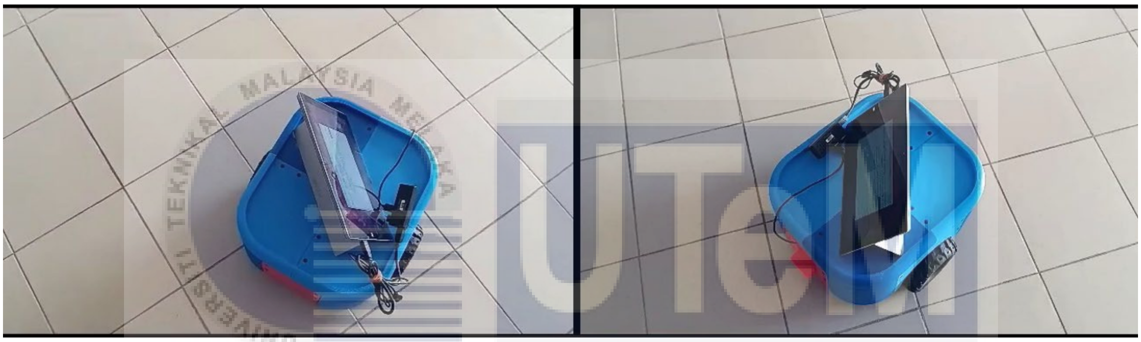


Figure 4.16: Backward Left Turn Real-World Testing

4.2.7 Sharp Right Turn

A sharp right turn, or turning in place, involves rotating the wheels in opposite directions. The MSC Adams simulation showed the robot spinning in place to the right, rotating around its center without forward or backward movement. This behaviour was replicated in real-world experiments, where the robot executed the sharp turn effectively. The ability to turn in place is critical for manoeuvrability in confined spaces, and the control system's performance in this scenario was validated through simulation and experimentation. Figures 4.17 and 4.18 present the simulation and real-world test results.

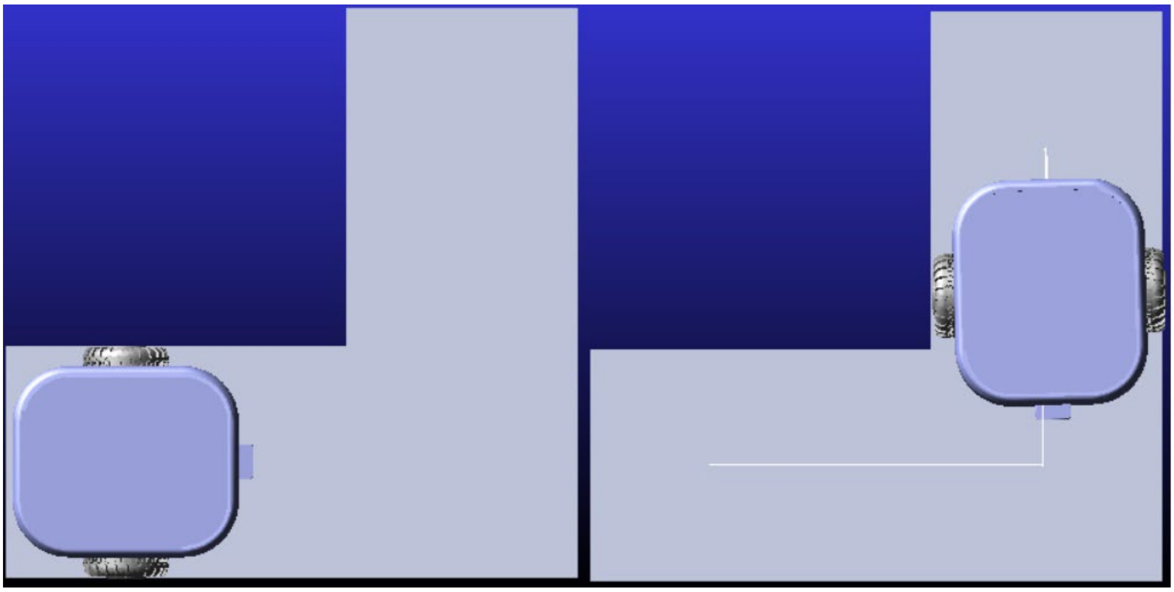


Figure 4.17: Sharp Right Turn and Sharp Left Turn Simulation in Msc Adams

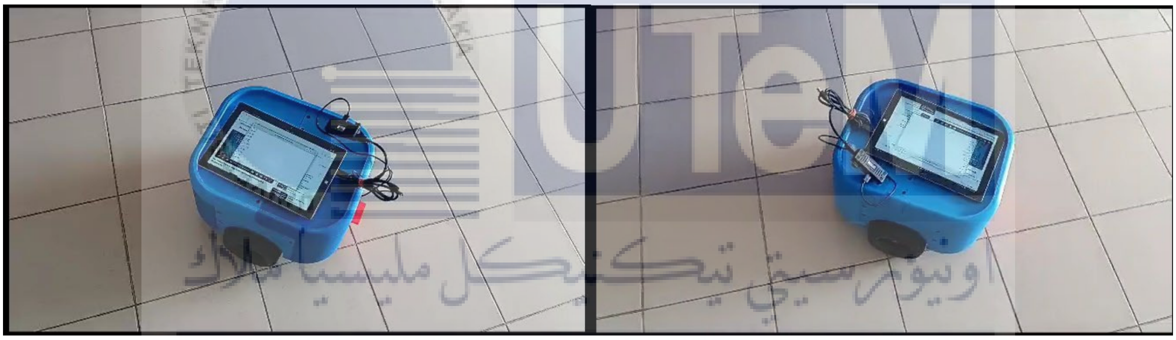


Figure 4.18: Sharp Right Turn Real-World Testing

4.2.8 Sharp Left Turn

A sharp left turn involves rotating the wheels in opposite directions, similar to a sharp right turn but in the opposite direction. The MSC Adams simulation showed the robot spinning in place to the left, rotating around its center without forward or backward movement. This behaviour was confirmed in real-world tests, where the robot performed the sharp turn accurately. The ability to turn in place enhances the robot's manoeuvrability, and the control system's performance was validated through simulation and experimentation. Figures 4.17 and 4.19 present the results from the simulation and real-world testing.

Figure 4.19: Sharp Left Turn Real-World Testing

4.2.9 Discussion

The results from both MSC Adams simulations and real-world experiments consistently demonstrated the differential drive mobile robot's ability to execute various motions precisely. Forward and backward movements were straight and controlled, highlighting the control system's effectiveness and the importance of encoder feedback in maintaining synchronization. The various turning manoeuvres, including sharp turns, were executed smoothly, validating the robot's manoeuvrability and the control system's ability to manage speed differentials between the wheels.

The differential drive configuration offers significant advantages in mobility. Through both simulation and real-world testing, it was evident that the robot could either turn in a conventional manner or rotate around its center. This capability is particularly useful for navigating confined spaces, allowing the robot to pass through pathways that fit its length. This flexibility enhances the robot's ability to operate in diverse environments and perform complex manoeuvres efficiently.

Overall, the experiments confirmed that the differential drive robot could perform complex movements reliably in real-world conditions, as predicted by the simulations. This validation underscores the robustness of the design and control system, ensuring that the robot can operate effectively in diverse environments. The close match between simulated and experimental results further supports the accuracy of the MSC Adams model in predicting real-world behaviour.

4.3 Platform Testing

The following sections present an analysis of torque requirements and motion observations for a differential drive mobile robot under different slope conditions. The torque magnitudes were measured using MSC Adams software simulations and validated through real-world experiments. Each case includes a description of the simulation setup, the corresponding real-world scenario, and an in-depth analysis based on torque versus time graphs for the left and right wheels.

4.3.1 Case 1: Flat platform

In the first case, the differential drive mobile robot was tested on a flat platform using MSC Adams software. The simulation provided a detailed model of the robot's dynamics and interactions with the flat surface. This setup was mirrored in the real world by placing the robot on an even, level ground, ensuring no inclines or obstacles interfered with the robot's motion. Figures 4.20 and 4.21 show the differential drive mobile robot tested on a flat platform in simulation and real-world conditions.

Figure 4.20: The differential drive mobile robot tested on a flat platform in simulation.

Figure 4.21: The differential drive mobile robot tested on a flat platform in real-world conditions.

On a flat platform, the robot moved smoothly and steadily without any noticeable deviations in its path. The simulation and real-world tests showed consistent linear motion, indicating that the robot's control system was well-calibrated for flat surfaces. The robot's speed remained constant, and there were no abrupt changes in direction or speed, demonstrating effective handling of the flat terrain.

The torque versus time graphs for the left and right wheels on the flat platform are shown in Figure 4.22.

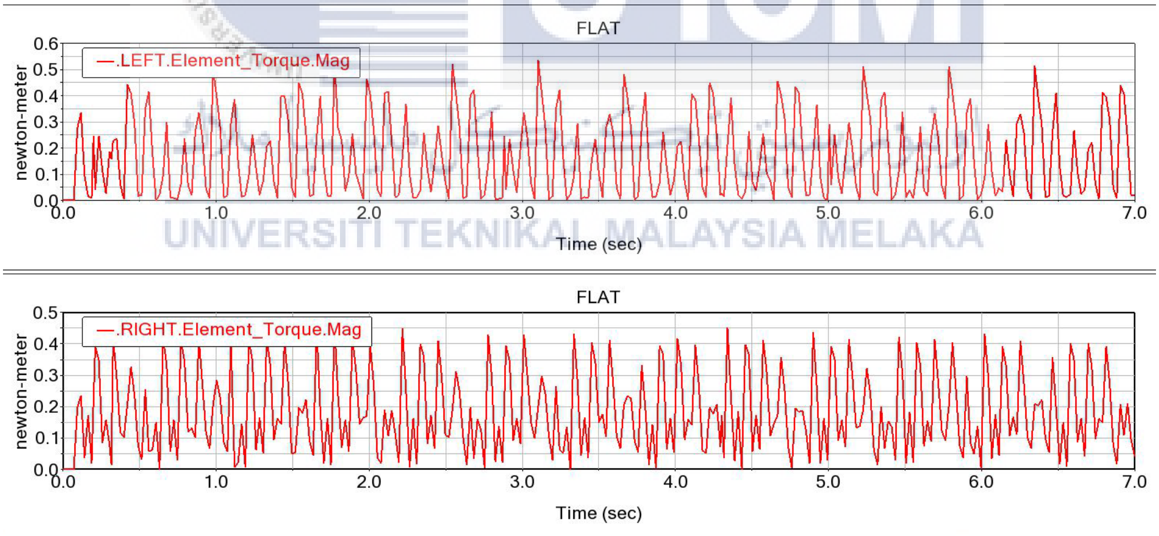


Figure 4.22: Torque versus time graphs for the left and right wheels on the flat platform

On a flat platform, the torque exerted by both the left and right wheels showed a relatively steady and consistent oscillation pattern. The torque values for the left wheel ranged between 0.0 and 0.45 Nm, while the right wheel exhibited a slightly broader range, from 0.0 to 0.39 Nm. This minor disparity indicates a generally even load distribution, with both wheels operating efficiently under minimal resistance. The consistency in the torque pattern suggests smooth and stable motion, confirming that the robot's control system handles flat surfaces effectively without significant fluctuations or additional strain.

4.3.2 Case 2: 5% road slope

In the second case, the robot was subjected to a 5% incline in the MSC Adams simulation environment. The setup was designed to test the robot's ability to navigate a gentle slope. In the real world, this scenario was replicated by placing the robot on a 5% inclined surface, ensuring the incline was uniform and the surface consistent with the simulation conditions. Figures 4.23 and 4.24 show the differential drive mobile robot tested on a 5% slope in simulation and real-world conditions.

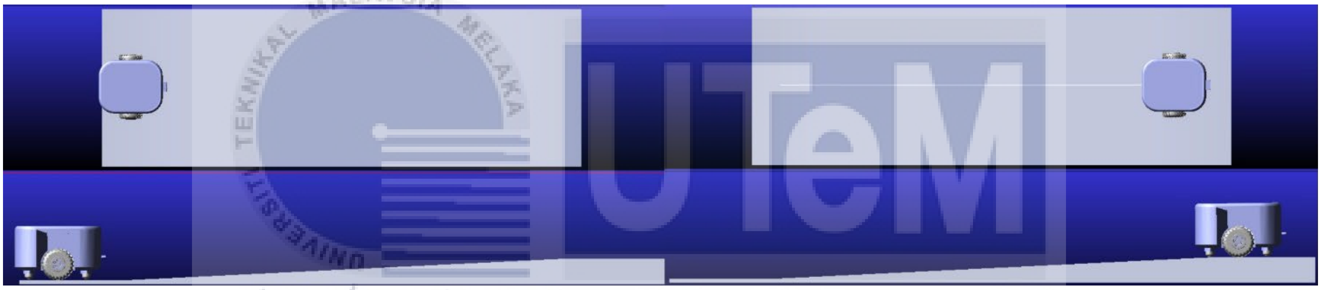


Figure 4.23: The differential drive mobile robot on a 5% slope in the simulation

Figure 4.24: The differential drive mobile robot on a 5% slope in real-world conditions.

On the 5% slope, the robot maintained a relatively smooth motion, although slight adjustments were more noticeable compared to the flat platform. The robot exhibited minor oscillations as it compensated for the incline. Both the simulation and real-world tests showed that the robot could ascend the slope without significant difficulty, maintaining a stable trajectory with minimal deviations.

The torque versus time graphs for the left and right wheels on a 5% slope are presented in Figure 4.25.

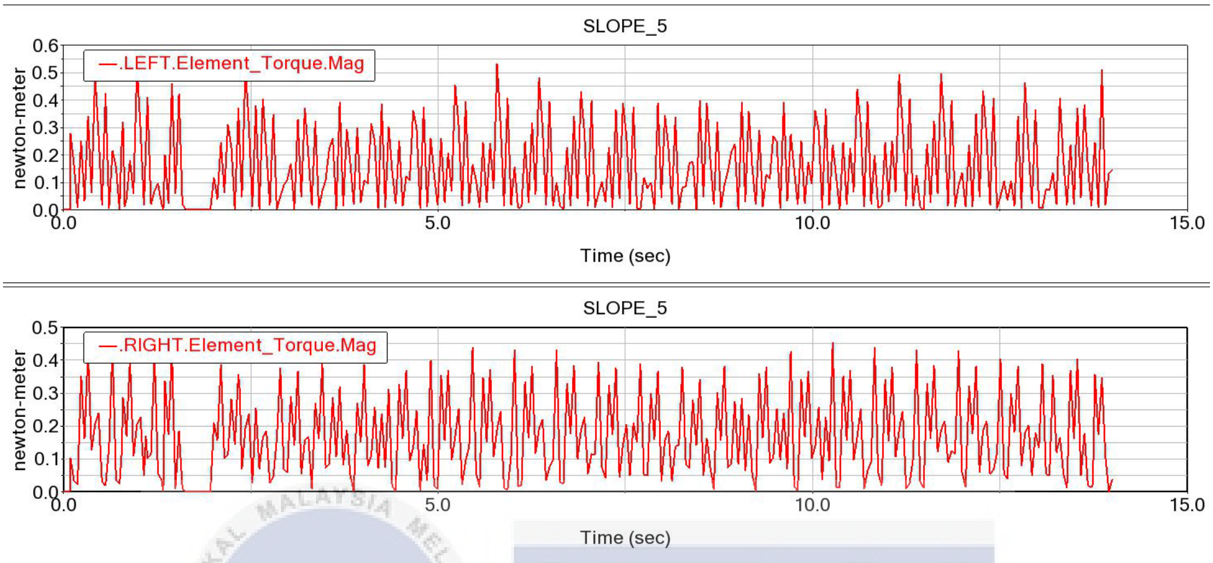


Figure 4.25: The torque versus time graphs for the left and right wheels on a 5% slope.

Introducing a 5% slope resulted in more frequent oscillations in the torque patterns for both wheels compared to the flat platform. The torque values for the left wheel ranged from 0.0 to 0.43 Nm, while the right wheel ranged from 0.0 to 0.40 Nm. The increased oscillation frequency highlights the additional effort required to navigate the incline. This increased activity indicates that the robot's motors are adjusting more frequently to maintain motion against the slope's gravitational pull, reflecting a need for enhanced control precision. Despite these more frequent adjustments, the load remains evenly distributed across both wheels.

4.3.3 Case 3: 10% road slope

For the third case, the robot navigated a 10% slope in the MSC Adams simulation. This setup tested the robot's performance on a moderately steep incline. In the real world, this scenario was replicated by placing the robot on a 10% inclined surface with similar characteristics to those used in the simulation. Figures 4.26 and 4.27 show the differential drive mobile robot tested on a 10% slope in simulation and real-world conditions.

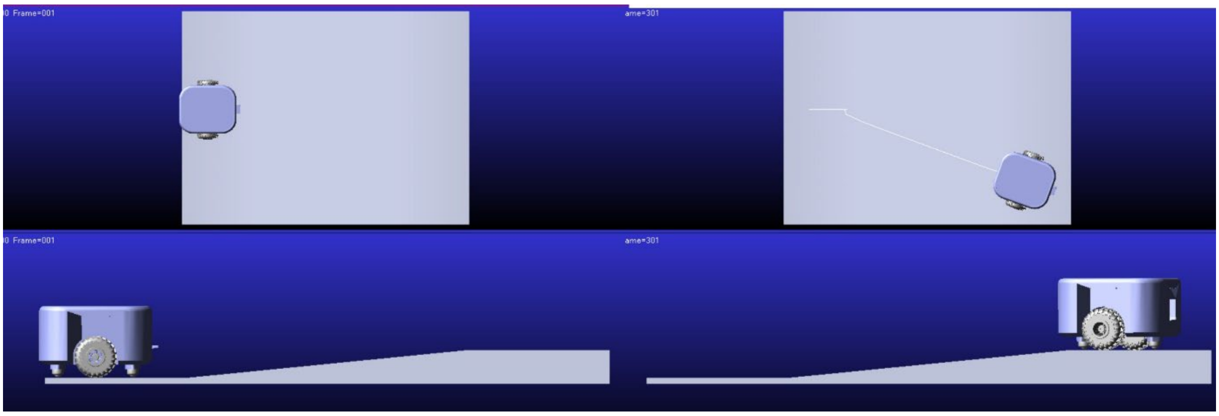


Figure 4.26: The differential drive mobile robot on a 10% slope in simulation.

Figure 4.27: The differential drive mobile robot on a 10% slope in real-world conditions.

On the 10% slope, the robot's motion exhibited more noticeable oscillation. The robot managed to climb the slope in the simulation, but it struggled significantly during the transition between the flat ground and the slope in real-world tests. The design characteristics of the differential drive mobile robot caused difficulties in maintaining a consistent trajectory and speed, with adjustments observed. This transition issue indicates that the robot's real-world performance on a 10% slope is compromised, unlike the simulation results that showed successful ascent.

The torque versus time graphs for the left and right wheels on a 10% slope are shown in Figure 4.28.

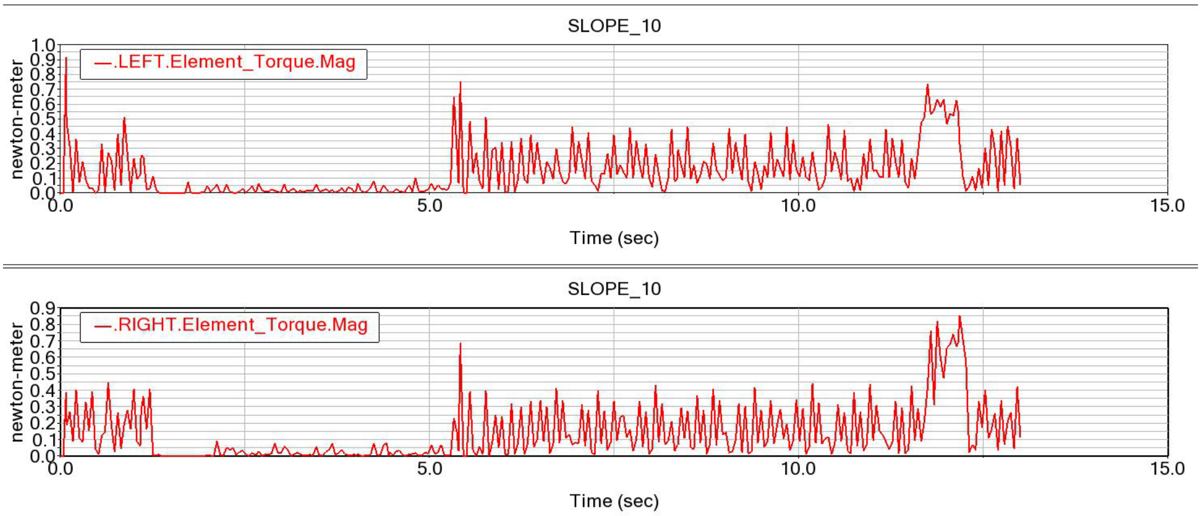


Figure 4.28: The torque versus time graphs for the left and right wheels on a 10% slope

At a 10% slope, a noticeable increase in torque values was observed. The left wheel experienced torque variations between 0.0 and 0.44 Nm, while the right wheel ranged from 0.0 to 0.42 Nm. The magnitude and frequency of these variations are significantly higher than those seen on the 5% slope, indicating a greater resistance encountered by the robot. This increased resistance necessitates higher torque to maintain movement, highlighting the greater physical demands placed on the robot's motors. The larger fluctuations suggest that the robot's control system makes it more difficult to manage the increased load, leading to a less stable motion pattern than the lower slopes.

4.3.4 Case 4: 15% road slope

In the final case, the robot was subjected to a challenging 15% incline in the MSC Adams simulation environment. This scenario tested the limits of the robot’s ability to handle steep slopes. The robot was placed on a 15% inclined surface in the real world, designed to match the simulation conditions as closely as possible. Figures 4.29 and 4.30 show the differential drive mobile robot tested on a 15% slope in simulation and real-world conditions.

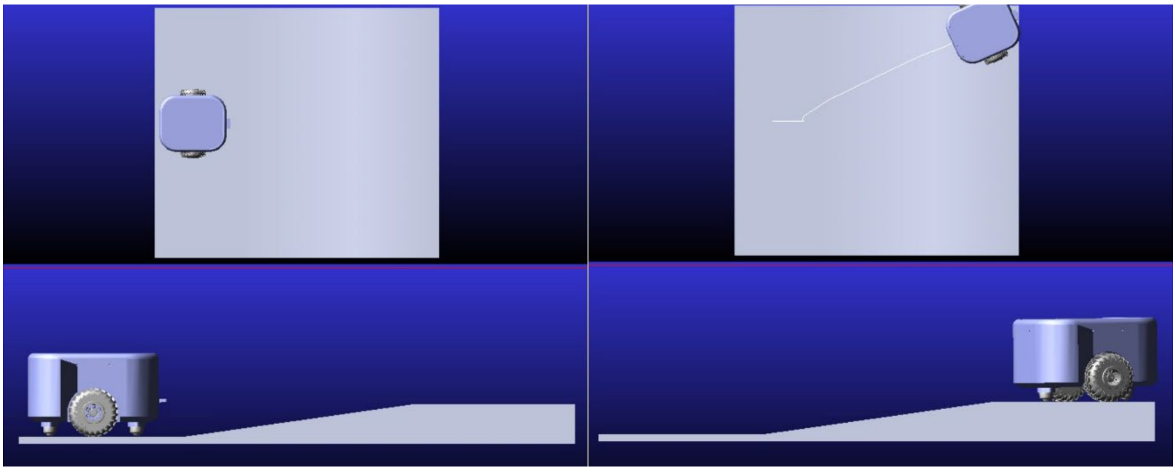


Figure 4.29: The differential drive mobile robot on a 15% slope in simulation.

Figure 4.30: The differential drive mobile robot on a 15% slope in real-world conditions.

On the 15% slope, the robot's motion was significantly more erratic. In the simulation, the robot managed to ascend the slope but not in a straight line. However, in real-world tests, it struggled greatly, particularly during the transition from the flat ground to the slope. The increased resistance of the steep incline caused noticeable strain on the robot's motors, leading to irregular motion patterns. Frequent stops and adjustments were required, and the robot was often unable to continue forward movement. The design characteristics of the differential drive mobile robot were not suited to handle such a steep incline in real-world conditions, resulting in substantial performance issues.

The torque versus time graphs for the left and right wheels on a 15% slope are presented in Figure 4.31.

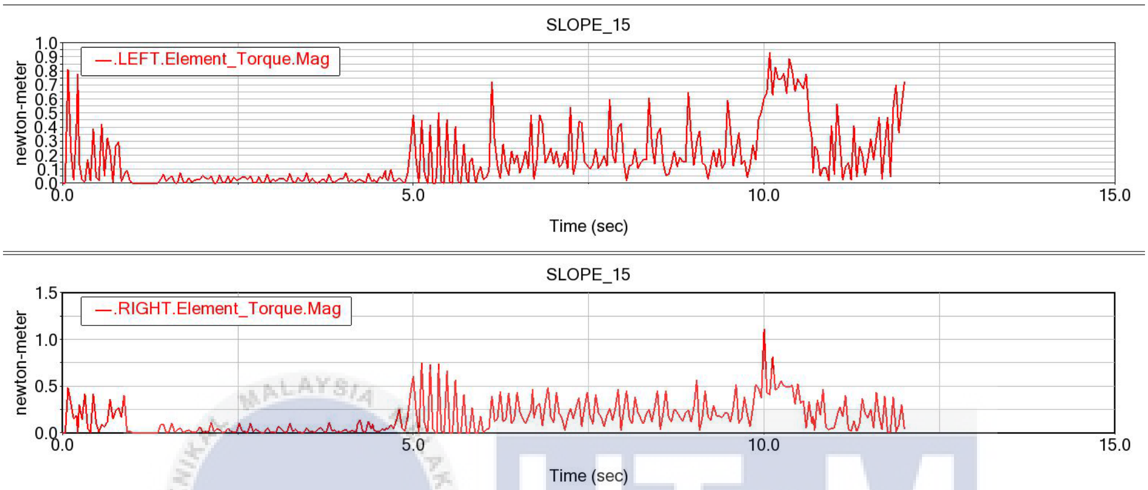


Figure 4.31: The torque versus time graphs for the left and right wheels on a 15% slope

The 15% slope presented the most challenging conditions. The left wheel's torque ranged from 0.0 to 0.54 Nm, while the right wheel varied from 0.0 to 0.48 Nm. The torque patterns in this scenario were highly irregular, with significant peaks and troughs throughout the test duration. This irregularity points to the robot struggling to maintain a consistent motion, as the steep incline introduces substantial gravitational resistance. The extreme variations in torque suggest that the robot's motors are operating near their performance limits, with frequent adjustments needed to counteract the slope's demands. Such conditions likely lead to increased wear and tear on the mechanical components, necessitating potential improvements in motor capacity and control algorithms.

4.3.5 Discussion

The data clearly demonstrates the impact of slope gradients on the torque requirements and motion stability of a differential drive mobile robot. As the slope increases, the torque required by both wheels rises significantly, reflecting the increased effort needed to overcome gravitational resistance. The robot operates smoothly on flat surfaces with minimal torque variations, suggesting optimal performance under these conditions. However, as the slope increases, the control system's ability to maintain stable motion diminishes, evidenced by the more frequent and irregular torque oscillations and deviations in the robot's trajectory.

This analysis reveals the limitations of the current motor and control system configuration when dealing with steeper inclines. The increased torque demand on slopes of 10% and 15% indicates that the robot's motors are nearing their operational thresholds, leading to less stable and more erratic performance. The irregular patterns observed suggest that the control system may require optimization to handle such conditions more efficiently, ensuring smoother adjustments and better overall stability.

4.3.6 Path Deviation on 10% and 15% Slopes

In both the 10% and 15% slope scenarios, the simulation results revealed significant deviations from the expected straight-line path, which were not ideal for the mobile robot's performance. Specifically, the robot's path tilted to the right on a 10% slope and to the left on a 15% slope, as shown in Figure 4.32. Ideally, the mobile robot should maintain a straight-line trajectory as commanded, but these deviations highlight an inherent issue in the design and operation of the robot on inclined surfaces.

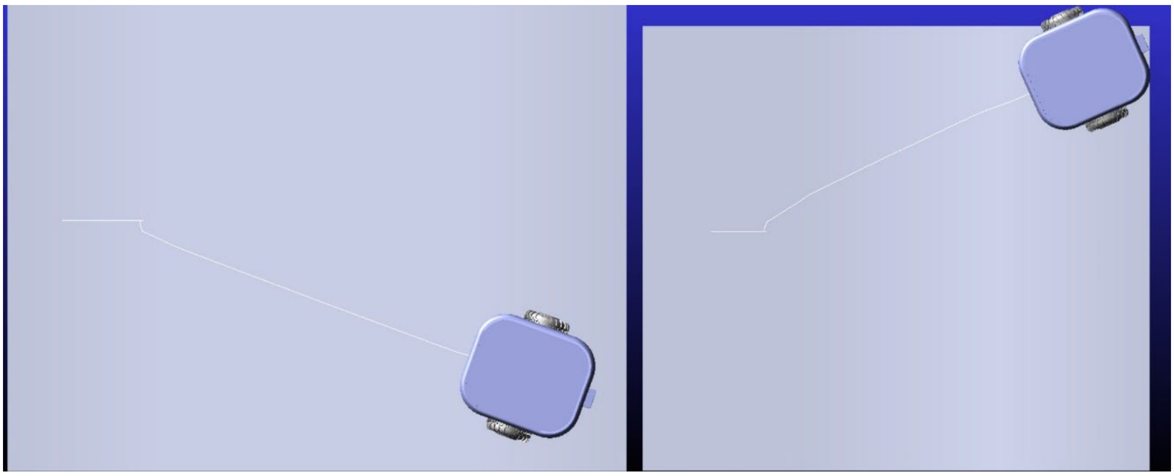


Figure 4.32: Robot's path on a 10% slope (left) and on a 15% slope (right)

The observed path deviation can be attributed to the loss of traction experienced by the drive wheels during the transition from flat ground to the slope. This traction loss is a direct consequence of the robot's design characteristics, specifically the placement of the front and back caster wheels in the center of the robot and its elongated length. Figure 4.33 illustrates the mobile robot's design, emphasising the caster wheels' position.

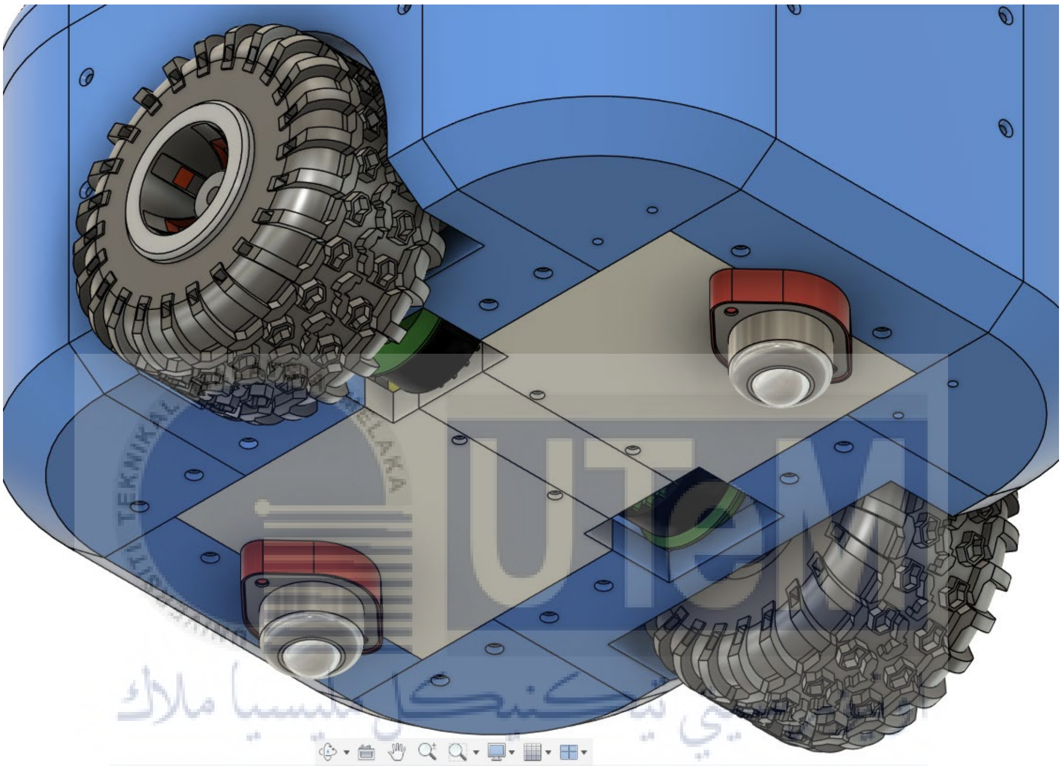


Figure 4.33: The caster wheels' position.

As the mobile robot approaches the slope, the front caster wheel is the first to make contact with the incline. This initial contact creates a lifting effect on the robot due to the disparity in height between the flat surface and the slope. As a result, the drive wheels temporarily lose traction with the ground, effectively floating in the air. This loss of traction is detrimental to maintaining a straight-line path, as the drive wheels are crucial for propulsion and direction control. The floating of the drive wheels and the resulting path deviation are depicted in Figure 4.34.

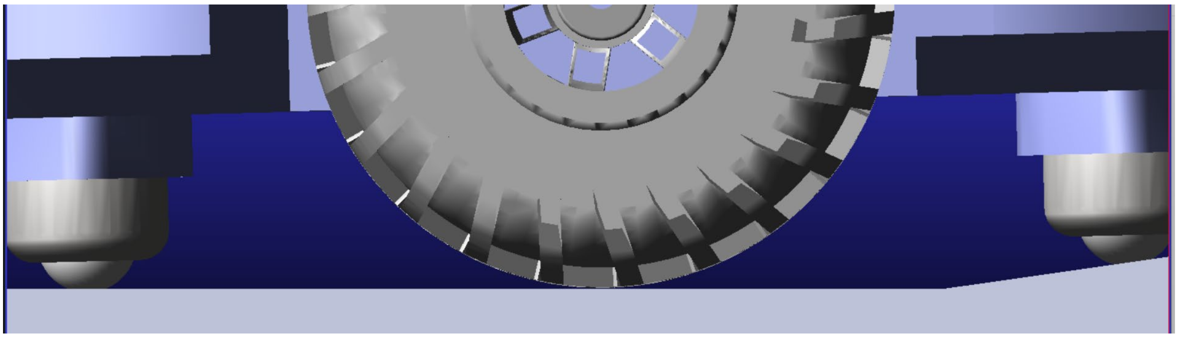


Figure 4.34: Floating of the drive wheel.

The transition-induced traction loss is also evident in both wheels' torque versus time graphs. Figure 4.28 shows the torque graphs for the 10% slope and Figure 4.31 for the 15% slope. These graphs illustrate irregular torque patterns during the transition period, indicating the drive wheels' struggle to regain traction and maintain consistent propulsion.

The deviations in the robot's path on 10% and 15% slopes underscore the challenges posed by its design when navigating inclined surfaces. The lifting effect caused by the initial contact of the front caster wheel with the slope leads to a temporary loss of traction for the drive wheels. This loss of traction results in erratic torque patterns and path deviations as the robot struggles to maintain its commanded trajectory.

4.4 Summary

In summary, the robot's movements were tested in simulations and real-world experiments, demonstrating consistent and controlled behaviour in fundamental motions such as forward, backwards, and turning manoeuvres. However, when subjected to different slopes (Flat platform, 5%, 10%, and 15%), the robot's torque requirements increased, and its motion stability decreased. Notably, on 10% and 15% slopes, the robot deviated from its intended straight-line path due to a loss of traction during the transition from flat ground to the slope, attributed to its design characteristics. These results underscore the need for design and control system optimizations to enhance the robot's performance on inclined surfaces.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This research project aimed to achieve three primary objectives: designing, simulating, and evaluating a differential drive mobile robot with an integrated belt drive system.

5.1 Conclusion

The first objective, to design and develop a differential drive mobile robot with an integrated belt drive system, was successfully achieved. The design process focused on ensuring durability, ease of control, and adaptability to various terrains while minimizing the size of the mobile robot. The resultant robot demonstrated effective performance in fundamental movements such as forward and backward motion and turning manoeuvres. The inclusion of the belt drive system enhanced the mechanical efficiency and torque transmission capabilities, proving the feasibility of the design. The reliability of the design was evident through repeated tests under various conditions, showcasing its dependability and longevity. This phase laid a solid foundation for subsequent analyses, ensuring the robot met the intended design specifications and operational criteria.

The second objective was to simulate and analyze the designed differential drive mobile robot's performance using MSC Adams software. The simulation phase provided comprehensive insights into the dynamic behaviour of the differential drive mobile robot. The simulations replicated various operational scenarios, including different terrains and slopes. The results from these simulations were instrumental in predicting the robot's performance and identifying potential issues. The comparison of simulated data with empirical test results highlighted the reliability of the simulation models, although some discrepancies underscored the need for iterative refinement in the design and control parameters. This phase enabled a thorough understanding of the robot's dynamics, helping to fine-tune its design before physical implementation. The software's ability to model complex interactions and predict outcomes under diverse conditions proved invaluable in preemptively addressing potential challenges, thereby streamlining the development process.

The third objective focused on evaluating the performance efficiency of the differential drive mobile robot, particularly its torque characteristics. Experimental data showed that the robot maintained stable torque output and controlled movements on flat surfaces. However, increased torque requirements and reduced stability were observed on inclined surfaces, indicating a need for design and control adjustments. The loss of traction during transitions onto slopes pointed to the limitations of the current wheel and caster design. This evaluation gained significant insights into the robot's torque distribution and handling capabilities under various conditions. Furthermore, the results from this phase can serve as a guideline for users in determining the optimal factory layout if they intend to deploy this differential drive mobile robot in an industrial setting. Understanding the robot's performance constraints and operational efficiencies can assist in planning the layout to maximize productivity and minimize operational disruptions. Despite these challenges, the robot demonstrated overall effective performance, validating the initial design choices and highlighting improvement areas. The practical implications of these findings are substantial, offering a blueprint for future deployments and enhancements.

The research successfully achieved its objectives by designing, simulating, and evaluating a differential drive mobile robot with an integrated belt drive system. The insights gained provide a solid foundation for further enhancements aimed at optimizing the robot's performance across various terrains.

5.2 Recommendation

Redesigning the caster wheels' placement is recommended to address the traction loss issue observed on inclined surfaces. By adjusting the positioning of these wheels, the robot can achieve better stability and traction. Additionally, integrating a suspension system could help maintain consistent ground contact, especially on uneven terrains. This enhancement would mitigate the identified instability, allowing the robot to adapt more effectively to various surfaces, thus broadening its operational scope. Improved ground contact would lead to enhanced manoeuvrability and stability, ensuring the robot performs reliably under diverse conditions.

Changing the drive wheels to smaller dimensions can minimize the size and length of the mobile robot, making it more compact and versatile. A decrease in wheel size may also improve the robot's ability to climb steeper slopes by reducing the overall weight and enhancing the torque-to-weight ratio. This adjustment allows for better navigation in confined spaces and enhances the robot's suitability for various operational environments. By optimizing the robot's dimensions, this modification can contribute to improved agility and efficiency, addressing specific functional requirements more effectively.

Upgrading the wheels to those with a higher coefficient of friction will significantly improve the contact between the wheels and the ground, leading to better traction. Enhanced traction will increase the robot's stability and control, particularly on inclined and uneven surfaces. This modification is crucial for ensuring the robot can operate efficiently in diverse terrain conditions, providing reliable performance and reducing the risk of slippage. Improved traction directly correlates with better handling and safety, enabling the robot to perform more complex tasks with higher precision and reliability.

By implementing these recommendations, future iterations of the differential drive mobile robot can achieve greater adaptability and performance, contributing to the broader field of mobile robotics. The advancements suggested here aim to guide further research and development efforts, ensuring that the robot continues evolving and meeting various industrial applications' demands.

5.3 Sustainable Design and Development

In this research project, the design and development of a differential drive mobile robot are approached with a strong emphasis on sustainability, aligning with several United Nations Sustainable Development Goals (SDGs). This commitment to environmentally conscious design reflects the philosophy of creating physical objects, the built environment, and services that adhere to social, economic, and ecological sustainability principles.

Sustainable design is not merely an add-on but an integral part of this project's philosophy. It involves considering the full lifecycle of the mobile robot, from material selection and manufacturing processes to operational efficiency and end-of-life disposal. This holistic approach ensures that the development of the differential drive mobile robot aligns with the broader goals of reducing environmental impact, promoting social responsibility, and achieving economic viability. Specifically, the project supports SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation through advanced robotic technology and SDG 12 (Responsible Consumption and Production) by promoting sustainable manufacturing practices.

The use of 3D printing to fabricate parts of the robot is a key sustainable element. 3D printing minimizes material waste using additive manufacturing processes, where materials are added layer by layer only where needed, in contrast to traditional subtractive manufacturing, which often involves cutting excess material. Whenever possible, the project opts for eco-friendly and recyclable materials. Using biodegradable or recyclable polymers for 3D printed parts reduces the environmental footprint, directly contributing to SDG 13 (Climate Action) by mitigating the impact of industrial activities on the environment.

Energy efficiency is another critical aspect of the project. The differential drive system is designed to optimize power consumption, ensuring the robot operates efficiently without excessive energy use. This is achieved by carefully selecting motors and control systems that balance performance with energy efficiency. Furthermore, the robot's power system is designed to be compatible with renewable energy sources, such as solar charging stations, further reducing its carbon footprint and supporting SDG 7 (Affordable and Clean Energy).

Operational sustainability is enhanced by the compact design of the robot, which not only allows it to navigate tight spaces effectively but also reduces material use and energy consumption. A smaller, lighter robot requires less power and can be more easily transported, reducing its environmental impact. The project also leverages advanced simulation tools like MSC Adams, which minimize the need for physical prototypes, conserving materials and energy. Simulations allow for extensive testing and optimization in a virtual environment, leading to more efficient and sustainable designs.

In conclusion, this research project integrates sustainable design principles at every stage. By focusing on material efficiency, energy optimization, lifecycle management, and operational sustainability, the project aims to advance robotic technology in an environmentally responsible, socially beneficial, and economically viable manner. This comprehensive approach ensures that the development of mobile robots contributes positively to sustainable development goals, paving the way for future innovations that respect and preserve our planet's resources.

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