HYBRID MOBILE ROBOT SYSTEM: INTERCHANGING LOCOMOTION AND MANIPULATION

by

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ABSTRACT

This thesis presents a novel design paradigm of mobile robots: the Hybrid Mobile Robot system. It consists of a combination of parallel and serially connected links resulting in a hybrid mechanism that includes a mobile robot platform for locomotion and a manipulator arm for manipulation, both interchangeable functionally.

All state-of-the-art mobile robots have a separate manipulator arm module attached on top of the mobile platform. The platform provides mobility and the arm provides manipulation. Unlike them, the new design has the ability to interchangeably provide locomotion and manipulation capability, both simultaneously. This was accomplished by integrating the locomotion platform and the manipulator arm as one entity rather than two separate and attached modules. The manipulator arm can be used as part of the locomotion platform and vice versa. This paradigm significantly enhances functionality.

The new mechanical design was analyzed with a virtual prototype that was developed with MSC Adams Software. Simulations were used to study the robot’s enhanced mobility through animations of challenging tasks. Moreover, the simulations were used to select nominal robot parameters that would maximize the arm’s payload
capacity, and provide for locomotion over unstructured terrains and obstacles, such as stairs, ditches and ramps.

The hybrid mobile robot also includes a new control architecture based on embedded on-board wireless communication network between the robot’s links and modules such as the actuators and sensors. This results in a modular control architecture since no cable connections are used between the actuators and sensors in each of the robot links. This approach increases the functionality of the mobile robot also by providing continuous rotation of each link constituting the robot.

The hybrid mobile robot’s novel locomotion and manipulation capabilities were successfully experimented using a complete physical prototype. The experiments provided test results that support the hypothesis on the qualitative and quantitative performance of the mobile robot in terms of its superior mobility, manipulation, dexterity, and ability to perform very challenging tasks. The robot was tested on an obstacle course consisting of various test rigs including man–made and natural obstructions that represent the natural environments the robot is expected to operate on.
To Annette, Timor and my Family
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# TABLE OF CONTENTS

ABSTRACT ..........................................................................................................................II
ACKNOWLEDGEMENT ........................................................................................................V
TABLE OF CONTENTS ...................................................................................................... VII
LIST OF FIGURES ...............................................................................................................IX
LIST OF TABLES ................................................................................................................XI

## CHAPTER 1: INTRODUCTION .......................................................................................1

1.1 Preface .......................................................................................................................1
1.2 Objective ...................................................................................................................2
1.3 Overview of the Dissertation .....................................................................................3
1.4 Contributions .............................................................................................................4

## CHAPTER 2: BACKGROUND ......................................................................................8

2.1 Review of Tracked Mobile Robots .............................................................................11
2.2 Analysis of Issues and Related Research Problems and Proposed Solutions.........14

## CHAPTER 3: MECHANICAL DESIGN PARADIGM ......................................................18

3.1 Description of the Design Concept ...........................................................................18
   3.1.1 Concept Embodiment ......................................................................................19
   3.1.2 Modes of Operation .......................................................................................20
   3.1.3 Maneuverability ............................................................................................21
   3.1.4 Manipulation ..................................................................................................22
   3.1.5 Traction ........................................................................................................24
   3.1.6 Additional Embodiments of the Concept ........................................................24
3.2 Mechanical Design Architecture ................................................................................26
3.3 Motor Layout and Driving Mechanisms .....................................................................30
3.4 Base link 1 - Tracks ....................................................................................................32
3.5 Built-in Dual-operation Track Tension and Suspension Mechanism .........................34

## CHAPTER 4: MODELLING AND DYNAMIC SIMULATIONS ...........................................37

4.1 Robotic System Modelling and Postprocessing .........................................................37
   4.1.1 Virtual Prototyping and Simulations Using ADAMS Software .......................37
   4.1.2 Model Structure ...............................................................................................39
   4.1.3 Simulations and Postprocessing ......................................................................42
4.2 Simulation Results and Discussion ............................................................................42
   4.2.1 Mobility Characteristics Analysis - Animation Results .....................................42
   4.2.2 Analysis of Track Tension and Suspension Mechanism ....................................51
   4.2.3 Analysis of Motors Torque Requirements .......................................................53
   4.2.4 End–Effector Payload Capacity Analysis .......................................................59
CHAPTER 5: CONTROL SYSTEM DESIGN PARADIGM .......................................................... 63

5.1 On-Board Wireless Sensor/Actuator Control Paradigm ........................................... 64
   5.1.1 On-Board Inter-segmental RF Communication Layout .................................. 64
   5.1.2 RF Hardware for the Hybrid Mobile Robot .................................................... 66
5.2 Electrical Hardware Architecture ........................................................................... 71
   5.2.1 Controllers, Drivers, Sensors and Cameras Layout ...................................... 71
   5.2.2 Power System and Signal Flow Design and Implementation ...................... 72
   5.2.3 Sensor Processor Board .............................................................................. 79
5.3 Robot DOF Coordination and Operator Control Unit (OCU) ............................... 80

CHAPTER 6: EXPERIMENTAL SETUP AND RESULTS .................................................... 84

6.1 Research Hypothesis Validation ............................................................................ 84
6.2 Performance Metrics as Design Targets ............................................................... 85
6.3 Robot Configurations for Manipulation ............................................................... 87
6.4 Mobility/Maneuverability Characteristics Testing and Validation ...................... 88
6.5 Traction Configurations ....................................................................................... 90
6.6 Traversing Cylindrical Obstacles ......................................................................... 90
6.7 Stair Climbing and Descending .......................................................................... 91
   6.7.1 Stair Climbing .............................................................................................. 91
   6.7.2 Stair Descending .......................................................................................... 91
   6.7.3 Stair Descending – Other Configurations ................................................... 94
6.8 Step Obstacle Climbing ....................................................................................... 96
   6.8.1 Climbing with Tracks .................................................................................. 96
   6.8.2 Climbing with Link 2 ................................................................................ 96
6.9 Step Obstacle Descending ................................................................................... 98
   6.9.1 Descending with Links 2 and 3 .................................................................. 99
   6.9.2 Descending with Base link Tracks ............................................................... 100
6.10 Ditch Crossing .................................................................................................... 102
6.11 Platform Lifting and Carrying Capacity Testing ................................................. 103
6.12 Simultaneous Locomotion and Manipulation ..................................................... 104
   6.12.1 Simultaneous Climbing and Manipulation ................................................. 104
   6.12.2 Simultaneous Descending and Manipulation ............................................ 105
6.13 Mobility Configurations for Rubble Pile Climbing ............................................. 106
6.14 Robot Configurations for Manipulation .............................................................. 108
   6.14.2 Adaptive Manipulation ............................................................................ 111
6.15 Robot DOF Speed Runs Testing and Measurement ............................................. 113

CHAPTER 7: CONCLUSIONS .......................................................................................... 114

7.1 Summary ............................................................................................................. 114
7.2 Future Research ................................................................................................. 118

REFERENCES .............................................................................................................. 120

APPENDIX A: HYBRID MOBILE ROBOT SPECIFICATIONS ............................................ 129
LIST OF FIGURES

Fig. 2.1: Review of tracked mobile robots ................................................................. 13

Fig. 3.1: (a) closed configuration; (b) open configuration; (c) exploded view ........... 20
Fig. 3.2: Configurations of the mobile platform for mobility purposes .................. 22
Fig. 3.3: Configuration modes for manipulation ...................................................... 23
Fig. 3.4: Configurations for enhanced traction ......................................................... 24
Fig. 3.5: Additional possible embodiments of the design concept ......................... 25
Fig. 3.6: Deployed-links configuration mode of the mobile robot ......................... 28
Fig. 3.7: Stowed-links configuration mode of the mobile robot (top/bottom covers removed) ................................................................................................................. 29
Fig. 3.8: Open configuration mode and general dimensions (front and top views – all covers removed)................................................................. 32
Fig. 3.9: Isometric view of base link track showing internal pulley arrangement ...... 33
Fig. 3.10: Side view of base link track showing general pulley arrangement and track tension/suspension mechanism ......................................................... 35
Fig. 3.11: A picture of the physical prototype: (a) stowed-links configuration mode; (b) open configuration mode. ........................................................................................ 36

Fig. 4.1: Virtual product development diagram ...................................................... 39
Fig. 4.2: ADAMS virtual prototype model structure ................................................ 41
Fig. 4.3: Configurations for manipulation ............................................................... 43
Fig. 4.4: Surmounting circular obstacles ................................................................. 44
Fig. 4.5: Stair climbing ............................................................................................ 45
Fig. 4.6: Stair descending ......................................................................................... 46
Fig. 4.7: Step obstacle climbing with tracks ........................................................... 46
Fig. 4.8: Step obstacle climbing with links 2 and 3 .................................................. 47
Fig. 4.9: Step descending ......................................................................................... 48
Fig. 4.10: Ditch crossing .......................................................................................... 49
Fig. 4.11: Lifting tasks ............................................................................................... 50
Fig. 4.12: Flip-over scenario .................................................................................... 51
Fig. 4.13: Top ((a) - track tension) and bottom ((b) - suspension) spring array force distribution ........................................................................................................ 53
Fig. 4.14: Link 2 motor torque requirement – step obstacle climbing with tracks (via joint 1) ................................................................................................................. 55
Fig. 4.15: Link 2 motor torque requirement – Step obstacle climbing with link 2 ...... 56
Fig. 4.16: Link 3 motor torque requirement – (a) Step obstacle climbing with tracks (via joint 2); (b) Step obstacle climbing with link 3 ...................................................... 57
Fig. 4.17: Driving pulley motor torque requirement – incline condition.................. 58
Fig. 4.18: Platform COG vs. load capacity ............................................................. 61
Fig. 4.19: Possible configurations for manipulation ................................................. 62
Fig. 5.1: Embeddable flat antennas for video and data RF communication. 66
Fig. 5.2: On-board wireless communication layout and design details (all covers removed). 67
Fig. 5.3: Hardware architecture: (a) right base link track; (b) left base link track; (c) link 3 – gripper mechanism. 69
Fig. 5.4: XBee OEM RF module. 70
Fig. 5.5: Sensors and cameras layout. 72
Fig. 5.6: Li-Ion battery packs assembly. 74
Fig. 5.7: Power/signal distribution board for base link tracks. 76
Fig. 5.8: Power/signal distribution board for gripper mechanism. 78
Fig. 5.9: Sensor processor board. 80
Fig. 5.10: Operator control unit (OCU) architecture and robot degrees of freedom. 83

Fig. 6.1: Configurations for manipulation. 87
Fig. 6.2: Configurations of the hybrid robot for mobility purposes. 89
Fig. 6.3: Configurations for enhanced traction. 90
Fig. 6.4: Surmounting circular obstacles. 92
Fig. 6.5: Stair climbing. 93
Fig. 6.6: Stair descending. 94
Fig. 6.7: Stair descending – other configurations. 95
Fig. 6.8: Step obstacle climbing with tracks. 97
Fig. 6.9: Step obstacle climbing with links 2 and 3. 98
Fig. 6.10: Step descending with links 2 and 3. 99
Fig. 6.11: Step descending with base link tracks – tracks flip on the table. 100
Fig. 6.12: Step descending with base link tracks – tracks rotate on the table. 101
Fig. 6.13: Ditch crossing. 102
Fig. 6.14: Lifting capacity testing. 103
Fig. 6.15: Simultaneous climbing and manipulation. 105
Fig. 6.16: Simultaneous descending and manipulation. 106
Fig. 6.17: Combined mobility configurations for rubble pile climbing (cont’d). 108
Fig. 6.18: Configurations for manipulation. 110
Fig. 6.19: Adaptive manipulation configuration steps. 112
LIST OF TABLES

Table 2.1: Table of Comparison ................................................................. 17
Table 3.1: Robot Design Specifications ................................................... 35
Table 5.1: Robot Motion Specifications ................................................... 83
Table 6.1: Robot DOF Speed Measurements ............................................. 113
CHAPTER 1

INTRODUCTION

1.1 Preface

The use of mobile robots is growing very rapidly in numerous applications such as planetary exploration, police operations (e.g., EOD – Explosive Ordnance Disposal), military operations (e.g., reconnaissance missions, surveillance, neutralization of IED), hazardous site exploration, and more. The use of Unmanned Ground Vehicles (UGVs) in Urban Search and Rescue (USAR) and Military Operations on Urbanized Terrain (MOUT) is gaining popularity because the mobile robots can be sent ahead or in place of humans, act on the surroundings with a manipulator arm or other active means attached to an arm, collect data about its surroundings, and send it back to the operator with no risks posed to humans.

In the past decade, new designs of mobile robots have emerged and were demonstrated by both academia and industry. This work presents a new paradigm to mobile robot design for locomotion and manipulation purposes for a wide range of applications and practical situations. Typically, a mobile robot’s structure consist of a mobile platform that is propelled with the aid of a pair of tracks, wheels or legs, and a manipulator arm attached on top of the mobile platform to provide the required manipulation capability (neutralization of bombs or landmines, manipulation of hazardous materials, etc). However, the presence of an arm limits the mobility. On the other hand, there are several designs of mobile robots that have pushed further the mobility state of the art such as PackBot [3],[4] and Chaos [24] including the ability to
return itself when flipped-over, but this may not be possible if the robot is equipped with a manipulator arm. This gap is bridged in my approach by providing a new mobile robot design that provides locomotion and manipulation capabilities simultaneously and interchangeably.

The new design is based on compounded locomotion and manipulation. The design approach is that the platform and manipulator arm are interchangeable in their roles in the sense that both can support locomotion and manipulation in several modes of operation as discussed in Subsection 3.1.2. Moreover, the design architecture enables the robot to flip over and continue to operate.

The development of the hybrid mobile robot system covers mechanics of systems design, system dynamic modeling and simulations, design optimization, computer architecture, and control system design.

1.2 Objective

The objective of this work was to develop a new paradigm for the design of mobile robots in order to solve foremost existing problems and overcome barriers in the use of mobile platforms for rough terrain applications. The major issues addressed were related to design of mobile robots operating on rough terrain. The aim was to significantly increase robot’s mobility and manipulability functionalities while significantly increasing its reliability, and reducing its complexity and cost. Extensive experimental results with the aid of a physical prototype that embodies the proposed design paradigm show that the proposed solution for a mobile robotic system design
significantly exceeds the mobility and manipulation capabilities demonstrated by other existing systems.

The hypothesis of the design paradigm is that the interchangeability of the locomotion and manipulation functions significantly benefits the mobile robot’s overall operation and function.

A physical prototype of the hybrid mobile robot system was developed and integrated as an experimental tool to run extensive testing required to assess the system’s mobility and manipulation capabilities. The test results successfully corroborated the hypothesis. Specifically, it was shown that the simulation results coincide with the experimental results of the hybrid mobile robot system.

1.3 Overview of the Dissertation

This dissertation is organized as follows. Chapter 2 provides a background to the field of mobile robots along with examples of existing types of design architectures. It also introduces a conceptual function-oriented analysis that outlines a summary of existing issues related to tracked mobile robots, their related research problems and proposed solutions. The new design paradigm resulting from the analysis of the issues identified in Chapter 2 is described in Chapter 3 along with presentation of several other possible embodiments of the proposed design approach. To realize the proposed design, a detailed mechanical design embodiment of the mechanically hybrid mobile robot is also described in detail. It includes the design of embedded and interchangeable track tension and suspension mechanism. In Chapter 4, the mechanical design is modeled and thoroughly analyzed in order to study the robot’s functionality and optimize the design.
by defining suitable and optimal operating parameters such as required motor torques, manipulator end-effector capacity, etc. Chapter 5 outlines the development of a new systematic approach for a modular control architecture that dramatically increases the functionality of the mobile robot. This is done by enabling wireless (RF) communication between the robot’s subsystems and modules such as the actuators and sensors. The experimental setup and results that corroborate the hypothesis of this work are discussed in Chapter 6. The setup includes an obstacle course that consists of various test rigs including man-made and natural obstructions. The experiments performed demonstrate the robot’s superior mobility, functionality and durability characteristics. Chapter 7 presents the conclusions.

1.4 Contributions

The proposed research work provides solutions to a series of major issues related to design and operation of mobile robots operating on rough terrain. The proposed paradigm for mobile robot system design leads to functionality and capability that far exceeds those of state-of-the-art existing systems. The research objectives, as presented in Subsection 1.2, were achieved through the following major contributions:

- A new design paradigm for a mobile robot system where the mobile robot’s locomotion platform and the manipulator arm are designed and packaged as one entity rather than two separate and attached modules. Specifically, the locomotion platform can be used as a manipulator arm and vice versa. This design approach results in a hybrid mechanism that is able to provide locomotion and manipulation capability simultaneously and interchangeably, using the same actuators. The robot
links’ interchangeability to provide the functions of the mobile platform and manipulator arm leads to fewer components while at the same time the actuator strength capacity for manipulation purposes considerably increases due to the hybrid nature of the mechanical structure. This approach results in a simpler and more robust design, significant weight reduction, greater end-effector payload capability, and potentially lower production cost.

- New design features that significantly enhance the mobile robot’s overall functionality and operation over rough terrain:
  - The ability to deploy/stow the manipulator arm from either side of the platform;
  - Integration of passive wheels into the robot joints in order to support the robot links when used for locomotion/traction;
  - Robot links with revolute joints that are able to provide continuous 360° rotation.
  - Embed RF antennas without sticking out or protruding from the platform.
  - A new design method where all mobile robot links and the end-effector are nested into each other to allow complete symmetry of the platform’s geometry. This design architecture eliminates the arm’s exposure to the surroundings, thereby minimizing the risk of damage. The fully symmetric structure eliminates the need of additional active means for self-righting when it falls or flips over.
  - Design of rounded and pliable side covers attached to the sides of the platform to prevent immobilization as well as to absorb some of the energy resulting from falling or flipping over of the robot.
  - A new design of embedded interchangeable track tension and suspension mechanism in the mobile robot base links that provides the locomotion
subsystem and the track tensioning system of the robot. The mechanism accounts for the symmetric nature of the design and operation of the mobile robot.

- Design of special flat antennas embedded in the side covers for data RF signals and audio/video RF signals. The flat shape of the antennas and their location in the side covers maintains the symmetric nature of the entire hybrid platform.

- A computer aided procedure to develop and analyse a virtual prototype with Adams for dynamic motion simulations of mobile robots. This development tool can be utilized to considerably reduce the physical prototype development time and cost while aiding with demonstrating the mobile robots’ expected functionality for design optimization purposes and derivation of optimal operating parameters.

- A new design of on-board wireless sensor/actuator control interfaces. This includes the development and implementation of a new control paradigm for on-board RF communication network among the robot’s links and subsystems. This approach eliminated the need for any wire, cable loop, and slip-ring mechanical connections between different parts of a given mechanical system. The module-specific RF communication and standalone power supply capabilities allow for an efficient modular mechanical as well as control architecture.

  - The standalone power supply in each link includes the design of modular high current discharge Li-Ion battery packs.
  - The implementation of the control paradigm includes the design of power and data signal distribution boards used in each of the base link tracks in the hybrid robot. The layered custom design of the distribution boards dramatically reduce
the footprint while providing sufficient input/output interfaces for a large number
of on-board devices as well as attachable devices for the mobile robot.

- Design of multi-DOF Operator Control Unit (OCU) that consists of two control
  sticks in order to simultaneously coordinate the robot degrees of freedom.
CHAPTER 2

BACKGROUND

Mobile robots were used for USAR activities in the aftermath of the World Trade Center (WTC) attack on September 11, 2001 [1],[2]. The mobile robots were used mainly for searching of victims, searching paths through the rubble that would be quicker than to excavate, structural inspection and detection of hazardous materials. In each case, small mobile robots were used because they could go deeper than traditional search equipment, could enter a void space that may be too small for a human or search dog, or could enter a place that posed great risk of structural collapse. Among the tracked robots that were used (such as Foster-Miller’s Solem and Inuktun’s Micro-Tracs and VGTV), the capability was limited in terms of locomotion and mobility, and more so if one considers requirements of manipulation with an arm mounted on the mobile robot, which were not used at all. Some of the major problems with some of the robots used on the rubble pile searches were the robot flipping over or getting blocked by rubbles into a position from where it could not be righted or moved at all.

Increasingly, mobile robotic platforms are being proposed for high-risk missions for law enforcement and military applications (e.g., Iraq for IEDs – Improvised Explosive Devices), hazardous site clean-ups, and planetary explorations (e.g., Mars Rover). These missions require mobile robots to perform difficult locomotion and dexterous manipulation tasks. During such operations loss of wheel traction, leading to
entrapment, and loss of stability, leading to flip-over, may occur, which results in mission failure.

Various robot designs with actively controlled traction [3],[4],[5],[6],[7], also called “articulated tracks”, were found to somewhat improve rough-terrain mobility. The mobility gains due to the articulated track mechanism yield a larger effective track radius for obstacle negotiation. Efforts are continuously made in designing robots that allow a wider control over COG (Center of Gravity) location [10] to produce robustness to effects attributed to terrain roughness. This was achieved by designing the robot with actively articulated suspensions to allow wider repositioning of the COG in real-time. However, the implementations of such solutions may result in complex designs that may reduce robot’s operational reliability, and also increase its cost.

Mobile robot mechanical design architectures can be classified into several major categories such as Tracked, Wheeled, Legged, Wheel-Legged, Leg-Wheeled, Segmented, Climbing and Hopping. The dozens of available mobile robots encompassing the aforementioned categories represent a fraction of the existing body of robotics research demonstrated by industry, research institutes, and universities. Therefore, due to the lack of consistent performance metrics reported by researchers, it would be very difficult to conduct performance comparisons between different robot architectures. A brief list of robots from each category is outlined as follows: (a) Tracked robots: iRobot “Packbot” [3],[4], Foster-Miller “TALON” [21], CMU “Gladiator” [25], Sandia “microcrawler” [26], ESI “MR-1 & MR-5” [19], Remotec’s Andros series [5],[6][7]; (b) Wheeled robots: National Robotics Engineering Consortium “Spinner” [27], University of Minnesota “SCOUT” [28],[29], Stanford “Stanley” [30], JPL
“Inflatable Rover” [31], Draper “Throwbot” [32], EPFL “Alice” [33], CMU “Millibot” [34]; (c) Legged robots: Stanford “Sprawlita” [35], Draper “Bug2” [36], Draper “Ratbot” [36], Boston Dynamics “Big Dog” [37], Frank Kirchner “Scorpion” [38]; (d) Wheel-Legged robots: Hirose Lab “Roller-Walker” [39], Lockheed Martin “Retarius” [40], JPL “ATHLETE” [41], EPFL “Octopus” [42], EPFL “Shrimp” [43]; (e) Leg-Wheeled robots: University of Minnesota “SCOUT” [28],[29], Draper “SpikeBall” [36], Boston Dynamics “RHex” [22], CWRU “Mini-Whegs” [44], (f) Segmented robots: CMU “Millibots” [34], Draper “Throwbot” [36], Draper “HISS” [36], Draper “Rubble Snake” [36], Draper “HMTM” [45]; (g) Climbing robots: Stanford/JPL “Lemur” [46], Boston Dynamics “RiSE” [47], Clarifying Technologies “Clarifying Climber Robot” [48], iRobot “Mecho-gecko” [49]; (h) Hopping robots: JPL “Frog” [50], JPL “hopping robot” [51], Sandia “Self-Reconfigurable Minefield” [26], Sandia “hopping robot” [26].

USAR and MOUT operations require high ground mobility capabilities for the mobile robot to operate in rough terrain such as in collapsed buildings, disaster areas, caves and other outdoor environments, as well as in man-made urbanized indoor and outdoor environments. In those missions, small UGVs are strictly limited by geometry since even the smallest obstacle can hinder mobility simply by physics. For instance, such a limitation occurs with wheeled mobile robots due to wheelbase and in legged robots due to leg step height and minimal contact area, etc. Another factor could be the result of actuator strength compared to the mobile robot mass.

Among the wide spectrum of mobile robot mechanisms available, wheeled architectures are the most common, and are universally accepted to be the most efficient means of locomotion over smooth terrain. The disadvantages of some wheeled robots are
their limited obstacle negotiation capability since their available degrees of freedom of forward/reverse and steering limit their ability to handle mobility failures such as high centering. The maximum speed of wheeled robots is limited by rollover instability that is a function of steering curvature and terrain roughness. To solve the mobility problems of wheels, tracks are often used.

2.1 Review of Tracked Mobile Robots

There are numerous designs of tracked mobile robots. A brief review is provided in Fig. 1. PackBot [3],[4] by iRobot Corporation and Remotec-Andros robots–Andros Mark V [5][6][7] use articulations to enhance their mobility (Fig. 1(a) and 1(b)). The Wheelbarrow MK8 Plus [8] (Fig. 1(c)) is equipped with a track system, which incorporates wheels and guides to ensure track retention. AZIMUT [9] (Fig. 1(d)) has four independent articulations that can be wheels, legs or tracks, or a combination of these. By changing the direction of its articulations, it is capable of moving sideways without changing its orientation. Linkage Mechanism Actuator (LMA) [10] (Fig. 1(e)) has an actuated linkage for reconfigurable tracks. This design approach provides the robotic platform the ability to adjust its track configuration and therefore enhance traction when traversing different types of terrains. Matilda [11] (Fig. 1(f)) has a fixed track configuration and limited arm capability. MURV-100’s [12] (Fig. 1(g)) modular design allows the operator to configure the system off-line manually for specific needs. The crawler tracks in Helios series robots [13][14],[15],[16] (Fig. 1(h)) are hinged to their body. Their characteristics include higher terrain adaptability than fixed crawlers. Variable Configuration Tracked Vehicle’s (VCTV) [17] (Fig. 1(i)) by Iamamoto use a
planetary wheel to create a variable geometry track. Ratler [18] (Fig. 1(j)) has a fixed track configuration; however, the chassis is pivoted to allow limited adjustability of the platform to the terrain. The MR-5 [19] (Fig. 1(k)) has an optional track that can be placed over its wheels while the MR-7 [19] (Fig. 1(l)) has a fixed configuration track design. NUGV’s [20] (Fig. 1(m)) mobility is achieved by using a combination of six-motion dof and various sensors. This design is limited due to the existence of a virtual rolling axis that may result in roll-over. Talon mobile robot [21] (Fig. 1(n)) by Foster Miller is equipped with a fixed track configuration.
Fig. 2.1: Review of tracked mobile robots.
As mentioned above, some legged robots [22],[23] are also part of the scenarios assumed herewith, but we do not cover this area in this work. Our focus is on tracked mobile robots that are capable of providing locomotion as well as manipulation capabilities. The goal is to present new design and control paradigms derived based on a function-oriented analysis in order to address major design and operational issues of existing tracked mobile robots that also provide manipulation capabilities. We dedicated ample resources in developing a virtual prototype of the entire robotic system using Adams Software to perform various dynamic simulations. The simulations were performed with the purpose to be used as a tool to study the robot, develop the design, optimize it and define suitable operating parameters at different stages of the design and integration of the hybrid mobile robot.

2.2 Analysis of Issues and Related Research Problems and Proposed Solutions

A thorough review of the literature and discussions with users has assisted us in identifying major issues of design of mobile robots used in field operations. These issues are focused on robot functionality, and they have led us to our new design paradigm. The issues constitute a common denominator in the design of existing mobile robotic platforms. The issues are defined below along with proposed approaches for addressing them.

1) Issue: In current design architectures of mobile robots equipped with manipulation capability, the mobile platform and manipulator arm are two separate modules that are attachable to and detachable from each other. The platform and the arm have
distinct functions that cannot be interchanged. Therefore, each module contributes separately to design complexity, weight, and cost. Also, the mass of the manipulator arm attached or folded on top of the mobile platform is limited by the payload capacity of the mobile platform.

*Approach to solution:* The manipulator arm and the mobile platform are designed and packaged as one entity rather than two separate modules. The mobile platform is part of the manipulator arm, and the arm is part of the platform. Yet, the modules are attachable and detachable. The robot links’ interchangeability to provide the functions of the mobile platform and manipulator arm requires fewer components (approximately 50% reduction in the number of motors) while at the same time the actuator strength capacity for manipulation purposes increases due to the hybrid nature of the mechanical structure. This approach may result in a simpler and more robust design, significant weight reduction, higher end-effector payload capability, and lower production cost.

2) *Issue:* In designs where the mobile robot includes a manipulator arm, it is mounted and folded on top. Therefore, the arm is exposed to the surroundings and hence is susceptible to breakage and damage especially when the mobile robot is flipped over.

*Approach to solution:* The arm and platform are designed as one entity, and the arm is part of the platform. The design architecture with the arm integrated in the platform eliminates the exposure to the surroundings when the arm is folded during motion of the mobile platform towards a target. As soon as the target is reached, the arm is deployed in order to execute desired tasks.
3) **Issue:** When operating over rough terrain, robots often reach positions from where they could not be righted or controlled further for a purpose. This requires special purpose or active means for self-righting in order to restart the robot’s operation.

*Approach to solution:* In the new design architecture the platform is *fully symmetric* even with the manipulator arm integrated, thus it can continue to the target from any situation with no need of additional active means for self-righting when it falls or flips over.

As a useful comparison tool, Table 2.1 summarizes all the issues pertaining to mobile robots as were mentioned above. The table compares some of the robots from Fig. 1 with direct association to the aforementioned issues. Ideally, a robotic system that addresses all of the issues as analyzed and outlined above would potentially yield a system with greater mobility and manipulation capabilities. This table will aid in showing how the proposed idea as presented in Chapter 3 solves major problems with existing systems.
Table 2.1: Table of Comparison.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Andros</th>
<th>PackBot</th>
<th>Wheelbarrow</th>
<th>Matilda</th>
<th>MURV</th>
<th>Ratler</th>
<th>Helios</th>
<th>VCTV</th>
<th>MR-5and MR-7</th>
<th>NUGV</th>
<th>Proposed Idea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existence of manipulator arm</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Arm not susceptible to damage</td>
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<tr>
<td>Actively articulated suspension</td>
<td>√</td>
<td>√</td>
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<tr>
<td>Platform reconfigure-ability</td>
<td>√</td>
<td>√</td>
<td>√-</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Self-righting abilities</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A*</td>
<td></td>
<td></td>
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<tr>
<td>Backpack-ability (with arm!)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
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<tr>
<td>Multiple dof platform (&gt;2 articulations)</td>
<td>√</td>
<td>√</td>
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<tr>
<td>Rugged/robust design (with arm!)</td>
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<tr>
<td>Symmetric design (with arm!)</td>
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<tr>
<td>Obstacle negotiation capabilities</td>
<td>√</td>
<td>√</td>
<td>√-</td>
<td>√-</td>
<td>√-</td>
<td>√-</td>
<td>√-</td>
<td>√-</td>
<td>√-</td>
<td>√+</td>
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<tr>
<td>Negative obstacle avoidance/allowance</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A*</td>
<td></td>
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<tr>
<td>Traction vs. manoeuvrability adjustment</td>
<td>√</td>
<td>√</td>
<td></td>
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<tr>
<td>Invertability capability (with arm!)</td>
<td></td>
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<tr>
<td>Center of mass relocation for flip over prevention</td>
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<td></td>
<td></td>
<td></td>
<td>√-</td>
<td>N/A*</td>
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<tr>
<td>Structural stability</td>
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<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Low complexity</td>
<td>√-</td>
<td>√-</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Low cost (based on complexity )</td>
<td>√-</td>
<td>√-</td>
<td></td>
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</table>

* N/A indicates that the specified factor is not required due to the inherent design architecture.
3.1. Description of the Design Concept

A new design paradigm [52][53][54] is introduced in order to address the design problems mentioned above. The proposed approach is systematic and practical, and it addresses the overall system’s operational performance. The proposed idea is two-fold, and is described as follows:

1) The mobile platform and the manipulator arm are one entity rather than two separate and attached modules. And the mobile platform can be used as part of the manipulator arm and vice versa. Thus, some of the same joints (motors) that provide the manipulator’s dof’s also provide the platform’s dof’s, and vice versa.

2) The robot’s mobility is enhanced by “allowing” it to flip-over and continue to operate instead of trying to prevent the robot from flipping-over or attempting to return it (self-righteousness). When a flip-over occurs, due to a fully symmetric design with the arm integrated it is only required to command the robot to continue to its destination from the current position. Furthermore, the undesirable effects of flipping over or free falling are compensated by a built-in dual suspension and tension mechanism that also allows effective terrain adaptability.
3.1.1 Concept Embodiment

To demonstrate the concept, Fig. 3.1 depicts a possible embodiment of the proposed idea. If the platform is inverted due to flip-over, the symmetric nature of the design geometrical shape (Fig. 3.1(a)) allows the platform to continue to the destination from its new position with no need of self-righting. Also it is able to deploy/stow the manipulator arm from either side of the platform.

The platform includes two identical base links 1 with tracks (left and right), link 2, link 3, two wheel tracks, end-effector and passive wheel(s). To support the symmetric nature of the design, all the links are nested into one another. Link 2 is connected between the two base link tracks via joint 1 (Fig. 3.1(b)). Two wheel tracks are inserted between links 2 and 3 and connected via joint 2 and a passive wheel is inserted between link 3 and the end-effector via joint 3 (Fig. 3.1(c)). The wheel tracks and passive wheels are used to support links 2 and 3 when used for locomotion/traction. The wheel tracks may be used passively or actively for added mobility. Link 2, link 3 and the end-effector are nested into each other to allow complete symmetry of the platform’s geometrical shape. They are connected through revolute joints and are able to provide continuous 360° rotation and can be deployed separately or together from either side of the platform.

To prevent immobilization of the platform during a flip-over scenario, rounded and pliable covers are attached to the sides of the platform as shown in Fig. 3.1(a). The robot’s structure allows it to be scalable and can be customized according to various application needs.
3.1.2 Modes of Operation

The links can be used in three different modes:

1) Locomotion mode: all links are used for locomotion to provide added level of maneuverability and traction;

2) Manipulation mode: all links are used for manipulation to provide added level of manipulability. The pair of base links can provide motion equivalent to a turret joint.
of the manipulator arm;

3) Hybrid mode: combination of modes 1 and 2; while some links are used for locomotion, the rest could be used for manipulation at the same time, thus the hybrid nature of the design architecture.

All three modes of operation are illustrated in Figs. 3.2, 3.3 and 3.4. In the proposed design, the motor(s) used to drive the platform for mobility are also used for the manipulator arm to perform various tasks since the platform itself is the manipulator and vice versa. In other words, the platform can be used for mobility while at the same time it can be used as a manipulator arm to perform various tasks.

### 3.1.3 Maneuverability

Fig. 3.2 shows the use of link 2 to support the platform for enhanced mobility purposes as well as climbing purposes. Link 2 also helps to prevent the robot from being immobilized due to high-centering, also enables the robot to climb taller objects (Fig. 3.2(b)), and can help propel the robot forward through continuous rotation. Link 2 is also used to support the entire platform while moving in a tripod configuration (Fig. 3.2(c)). This can be achieved by maintaining a fixed angle between link 2 and link 1 while the tracks are propelling the platform. Configurations (a) and (c) in Fig. 3.2 show two different possibilities for camera use. Configuration (d) in Fig. 3.2 shows the use of link 3 to surmount an object while link 2 is used to support the platform in a tripod structure. The posture of the tripod configuration as shown in Fig. 3.2(c) can be switched by rotating link 2 in a clockwise direction while passing it between the base link 1 tracks.
This functionality is effective when it is necessary to rapidly switch the robot's direction of motion in a tripod configuration.

Fig. 3.2: Configurations of the mobile platform for mobility purposes.

3.1.4 Manipulation

Fig. 3.3 depicts different modes of configuration of the platform for manipulation purposes. While some links are used as platform for locomotion, others are used simultaneously for manipulation. Configuration (b) is similar to configuration (d) in terms of manipulation capabilities; however, configuration (d) is optimal for enhanced traction since the contact area between the platform and the ground is maximized. Configuration (b) is useful for increased maneuverability since the contact area between
the platform and the ground is minimized. In all configuration modes for manipulation, while links 2 and 3 are used for manipulation, the pair of base links can provide motion equivalent to a turret joint of the manipulator arm. Further analysis on the stability gains of each configuration for manipulation as well as end-effector load capacity analysis of each configuration is discussed in the simulation results presented in Section 4.2.

**Fig. 3.3:** Configuration modes for manipulation.
3.1.5 Traction

For enhanced traction, link 2, and if necessary link 3 can be lowered to the ground level as shown in Fig. 3.4(a) and 3.4(b). At the same time, as shown in configuration (c), the articulated nature of the mobile platform allows it to be adaptable to different terrain shapes and ground conditions.

Fig. 3.4: Configurations for enhanced traction

3.1.6 Additional Embodiments of the Concept

The main purpose of this section is to show that other possible embodiments of the concept may exist as well as to illustrate other locomotion means that could be used. Therefore, some of the design configurations shown in Fig.3.5 may not be realizable exactly as shown. Fig. 3.5 shows perspective schematic views of alternate embodiments.
of the hybrid mobile robot. Fig 3.5(a) shows the robot without tracks showing it with wheels. Fig. 3.5(b) shows perspective schematic view of an alternative hybrid mobile robot with the right and left base links aligned parallel to each other and joined at the front and the back and the second link folds by the side of the base links and the third link folds inside the second link. Fig. 3.5(c) shows perspective schematic view of a further alternative hybrid mobile robot similar to Fig. 3.5(b) except that the third link folds by the side of the second link; and Fig. 3.5(d) shows schematic view of a further alternative hybrid mobile robot with the right and left base links aligned parallel to each other and joined at the front and the back, the second link being attached to one of the right and left base links, and the third link attached to the other of base links. The various configuration modes of mobility, manipulation and traction as described in Figs 3.2, 3.3 and 3.4, respectively, can also be demonstrated by the alternative embodiments as described in Fig. 3.5.

**Fig. 3.5:** Additional possible embodiments of the design concept
3.2 Mechanical Design Architecture

This section presents one implementation of the design concept as a case study. The presented case aims at describing in detail the design structure as well as specific design issues and design novelties. The case study provides a design solution selected from a range of alternatives that are described in Subsections 3.1.1 and 3.1.6. These solutions, generated from the conceptual function-oriented analysis, could be readily used in the development of various types and configurations of robots.

Fig. 3.6 shows the complete mechanical design architecture of the mobile robot mechanism (with all covers removed). It embodies the conceptual design architecture described in Section 3.1.1, and includes the following design specifications and requirements:

(i) Design and package the manipulator arm and the mobile platform as one entity rather than two separate mechanisms;
(ii) Integrate the manipulator arm into the platform such that to eliminate its exposure to the surroundings;
(iii) Nest all robot links and the end-effector into each other to allow complete symmetry of the platform’s geometry;
(iv) Provide the ability to deploy/stow the manipulator arm from either side of the platform;
(v) Integrate passive wheels into the robot joints in order to support the robot links when used for locomotion/traction;
(vi) Integrate each link with a revolute joint and to be able to provide continuous 360° rotation;
(vii) Attach rounded and pliable covers to the sides of the platform to prevent immobilization as well as to absorb some of the energy resulting from falling or flipping over of the robot;

(viii) Embed interchangeable track tension and suspension mechanism in the mobile robot base links to form the locomotion subsystem of the robot.

The design includes two identical base link tracks (left and right), link 2, link 3 passive wheels, and end-effector mechanism (Fig. 3.6 detail A). The two base links have identical orientations and they move together. This is achieved by fixing each of the base links to the ends of one common shaft. The common shaft is stationary and is located in joint 1, as shown in Figs. 3.6 and 3.8. To support the symmetric nature of the design, all links are integrated into the platform such that they are nested into one another. Link 2 is connected between the left and right base link tracks via joint 1 and is rotating about the main common shaft. Passive wheels are inserted between links 2 and 3 and connected via joint 2 and another passive wheel is inserted between link 3 and the end-effector via joint 3. The design also includes a built-in dual-operation track tension and suspension mechanism situated in each of the base link tracks and is described in detail in Section 3.5 and analysed and simulated in Subsection 4.2.2. This section describes the platform drive system, arm joint design and integration of the arm into the platform as well as several specifications of the robot based on a CAD detail design assembly that was used for the manufacturing of the prototype.
Along with the challenge and effort to realize the concept into a feasible, simple and robust design, most of the components considered in this design are off-the-shelf. The assembly views show the platform/chassis design and the different internal driving mechanisms along with description of the components used and their function. The closed configuration of the robot (Fig. 3.7 - all links stowed) is symmetric in all directions x, y and z. This design characteristic is extremely important for significantly enhancing locomotion ability. As shown in Fig. 3.7, rounded and pliable side covers are attached on the sides of the mobile robot to prevent immobilization when flip-over occurs as well as to absorb some of the energy resulting from falling or flipping over.
events. Although the design is fully symmetric, for the purpose of explanation only, the location of joint 1 will be taken as the reference point, and it will be called the front of the robot.

Fig. 3.7: Stowed-links configuration mode of the mobile robot (top/bottom covers removed).
3.3 Motor Layout and Driving Mechanisms

The design includes four motors situated in the base links and two more in the space available in link 3 for the gripper mechanism. Of the four motors located in the base links two are situated at the back of each of the base links and the other two at the front (Fig. 3.8). All four motors at the base link tracks are identical Brushless DC Motors (BN34-25EU-02, available from Moog Components Group) with a rated power of 363 Watts and a continuous stall torque of 0.7 Nm. The motor at the back of each base link provides propulsion to the track attached to that specific base link. The motion from each motor at the back is transmitted through a 1:32 ratio planetary servo gearhead (Series E60, available from Textron Fluid & Power) and a 1:2 ratio bevel gear in order to transfer the motion in a $90^\circ$ angle as well as to amplify the torque capacity required for propelling the pulleys that drive the tracks. Both motors at the back together provide the mobile robot translation and orientation in the plane of the platform. The motor at the front of each base link provides propulsion to one additional link. The motion is transmitted through a 1:120 ratio harmonic drive (CSF-20-120-2UH, available from Harmonic Drive Systems Inc.) and two additional transmission stages – namely, a 1:2 ratio bevel transmission followed by a 1:2.5 ratio chain and sprocket transmission in order to achieve greater torque capacities as required for each link 2 and 3 (Fig. 3.8). The motor at the front of the right base link propels link 2 and the motor at the front of the left base link propels link 3 (Figs. 3.6 and 3.8). The required torque capacities were derived with the aid of the dynamic simulations as described in detail in Section 4.2, which helped in selecting appropriate combination of components such as motors and gearheads. Each of the motors is equipped with a spring applied break (FSBR007,
available from Inertia Dynamics) as well as a miniature optical encoder (E4 series, available from US Digital) for position and velocity control purposes. The overall location of the platform’s COG is an important characteristic that affects the robot’s tip-over stability. Therefore, the mechanical structure was derived such that motors and driving mechanisms for the tracks and all links are situated at the base to maintain the entire structure’s COG closer to the ground.

The gripper mechanism along with its associated electronics and independent power sources are situated in the space available in link 3. For the existing design, the gripper has two dof’s and hence two additional motors and gear systems. As for links 2 and 3, the gripper sub-mechanism is integrated such that it can provide continuous rotations about joint 3 (Fig. 3.6 – Detail A) and hence can be deployed from either side of link 3. Rotation about joint 3 is generated with a DC Micromotor (Series 3557-012C, available from Faulhaber Group) with an output power of 14.5 Watts and a continuous stall torque of 115 mNm, connected to a 1:246 ratio planetary gearhead (Series 38/2, available from Faulhaber Group) and a 1:3 ratio bevel gear. The open/close motion of the gripper is implemented with a flat brushless DC motor (EC45, available from Maxon Motor) with an output power of 12 Watts and a nominal torque of 22.8 mNm connected to a miniature 1:100 ratio Harmonic Drive (CSF-Mini Series Type 2XH–J, available from Harmonic Drive Systems Inc.) and a 1:30 ratio worm gear (Fig. 3.8).
3.4 Base link 1 - Tracks

The right and left base link tracks are each symmetric in all directions (x, y & z) and identical in terms of the internal driving mechanisms although the mechanisms situated at the front each drives a different link.

In the center of each track, there is a solid self-tracking rib that fits into a guide located at the center of the main pulleys outer rim, as well as on all six planetary supporting pulleys, as shown in Fig. 3.9. This feature prevents the track from sliding off laterally, thus preventing the tracks from coming off the pulleys. In addition to the motors, all electrical hardware (such as batteries, controllers, drivers, electrical boxes, sensor boxes, Audio/Video and Data RF cards, gear-heads etc) are situated in the left
and right base link tracks. Other motors and associated electrical hardware for the gripper mechanism are situated in the space available in link 3.

Other accessories typically found in mobile robots such as cameras, lights and antennas are imbedded in the platform. In other designs of mobile robots, these items typically stick-out or protrude from the platform. In order to prevent their exposure to the surrounding and thereby eliminate risk of damage in cases were the robot flips over or falls, the CCD cameras and LED lights were imbedded in the front and the back of the left and right base link tracks, respectively, as shown in Fig. 3.7 and the top view in Fig. 3.8. Two special flat antennas are embedded in the right and left side covers for Data RF signals and Audio/Video RF signals, respectively (Fig. 3.7). The flat shape of the antennas and their location in the side covers maintains the symmetric nature of the entire hybrid platform and minimizes the chance for loss of data or breakage of the antenna if it were to protrude vertically up.

![Isometric view of base link track showing internal pulley arrangement](image)

**Fig. 3.9:** Isometric view of base link track showing internal pulley arrangement
3.5 Built-in Dual-operation Track Tension and Suspension Mechanism

The arrangement of the supporting planetary pulleys is shown in Fig. 3.9. Each of the supporting pulleys is mounted on a supporting bar (Fig. 3.9) that is connected at each end to a compression spring (Fig. 3.6 – Detail B). The ends of each supporting bar are guided through a groove on either side of the base link as shown in Detail B of Fig. 3.6. Therefore, each set of three planetary pulleys in the top and bottom of the left and right base link track is suspended by a 2x3 spring array. The purpose of the supporting pulleys is dual and provides two very important functions. While the bottom three supporting pulleys in each base link are in contact with the ground, they act as a suspension system. At the same time, the upper three supporting pulleys will provide a predetermined tension in the tracking system as shown in Fig. 3.10. This dual operation track suspension and tension mechanism accounts for the symmetric nature of the design and operation of the mobile robot. In other words, if the platform is inverted, the three supporting pulleys that were used as suspension will act to maintain the tension in the tracks, while the other three pulleys that were used to provide tension in the tracks will act as a suspension system. The required tension in the track belt and the suspension stroke can be preset by fastening or loosening the compression nuts (Fig. 3.6 – Detail B). Another usage of the spring array is to absorb some energy resulting from falling or flipping, thus providing compliance to impact forces. Further discussion and analysis of this mechanism is provided in Subsection 4.2.2.
Fig. 3.10: Side view of base link track showing general pulley arrangement and track tension/suspension mechanism.

General design specifications of the robot are provided in Table 3.1. Photos of the hybrid mobile robot physical prototype are shown in Fig. 3.11.

Table 3.1: Robot Design Specifications.

<table>
<thead>
<tr>
<th>Spec</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total estimated weight (including batteries and electronics)</td>
<td>65 [Kg]</td>
</tr>
<tr>
<td>Length (arm stowed)</td>
<td>814 [mm]</td>
</tr>
<tr>
<td>Length (arm deployed)</td>
<td>2034 [mm]</td>
</tr>
<tr>
<td>Width (with pliable side covers)</td>
<td>626 [mm]</td>
</tr>
<tr>
<td>Height (arm stowed)</td>
<td>179 [mm]</td>
</tr>
</tbody>
</table>
Fig. 3.11: A picture of the physical prototype: (a) stowed-links configuration mode; (b) open configuration mode.
CHAPTER 4

MODELLING AND DYNAMIC SIMULATIONS

Dynamic simulations of the complete robotic system were performed in order to study its functionality and demonstrate its expected capability for design optimization purposes[53][54][55]. The 3D mechanical design assembly that was developed with a CAD Software was exported to and modelled in ADAMS software to perform motion simulations. The simulation experiments are accounting for the mass distribution of the robot (including batteries, motors, electronics, etc.), inertia properties and acceleration of the links as well as contact and friction forces between the links and tracks and the ground.

4.1 Robotic System Modelling and Postprocessing

4.1.1 Virtual Prototyping and Simulations Using ADAMS Software

When designing a mechanical system such as this hybrid robot, it was required to understand how various components interact as well as what forces those components generate during operation. We used ADAMS, commercial motion simulation software, to analyze the behavior of the entire robotic mechanical system. It allowed us to test virtual prototypes and optimize designs for performance, without having to build and test several physical prototypes. This dramatically reduced our prototype development time and cost.
The process of virtual product development is described in the diagram of Fig. 4.1. Once the design parts are generated with a CAD Software, they can be either imported to ADAMS directly or used to create first a digital mock-up (fitting the parts by assembling), and then import the design assembly to create the virtual prototype for functional tests.

The benefits of the robotic system simulations are listed as follows:

1) Visualize and validate different robot mobility cases (ground scenarios) to study its functionality and hence optimize the design. The design optimization process involved optimal weight distribution optimization, proper component selection (e.g., springs for track tension/suspension mechanism; motor torque requirements for different mobility tasks), proper gear ratios selection, etc.

2) Vary the type of analyses being performed without having to modify physical instrumentation, test fixtures, and test procedures.

3) Used as concept validation tool to determine whether or not the mechanism works and check whether or not the design parts fit properly and function as intended, such as clearance checks during motion under different working conditions.

4) Analyze design changes faster and at a lower cost than physical prototype testing.

5) Improve product quality by exploring design variations to optimize full-system performance.

Weight distribution optimization was performed by identifying the optimal weight of each robot link (base links, link 2, and link 3) such that the robot’s posture remained stable (tip-over stability) during the motion of the robot links while performing various locomotion and manipulation tasks. This was done by visualizing each task with
the aid of the animations, as described in detail in Subsection 4.2.1, and changing the weight of each link as necessary until a stable posture was observed during the entire range of the links motion for a particular task. This procedure was repeated for several locomotion and manipulations tasks, as described in Subsections 4.2.1 and 4.2.4 respectively, until a common optimal combination of link weights was identified.

![Virtual Product Development Diagram](image)

**Fig. 4.1:** Virtual product development diagram.

### 4.1.2 Model Structure

In addition to modelling all the rigid body parts of the robot, one of the major challenges faced was to capture the flexible behaviour of the track system and its interaction with the pulleys and the ground. In other words, this system involves both flexible and rigid body dynamics. The requisite for a flexible dynamics capability for the track system was addressed with ADAMS Tracked Vehicle (ATV) Toolkit [56][57],[58]. A modus operandi using ADAMS along with its ATV Toolkit has been
used to build the tracks [59],[60]. It describes the steps required in the software to build a track made of a series of discrete rigid segments connected together.

The various parts and subassemblies were imported from the CAD software into ADAMS Software in Parasolid format. This format retains all the inertia and mass properties of the solid parts, which enables accurate representation of the parts in the ADAMS model created for simulations.

The ADAMS Virtual Prototype Model Structure is described in Fig. 4.2. The prototype assembly of the robot in ADAMS is made up of several subsystems. Subsystems can be duplicated by using the same template such that \( M \leq N \). Each template includes the definition of the various parts, joint between the parts, joint motion functions and external forces. The communicator is a mean by which templates communicate in order to define the connections between the different parts of the system. In the case of the hybrid robot, 6 templates were created to establish 10 subsystems (track template, front main pulley template, back main pulley template, bottom planetary pulley template, upper planetary pulley template and body template). Each of the bottom and upper planetary pulley templates constitute 3 subsystems, while the rest of each of the templates creates each of the remaining subsystems (10 subsystems in total).

The templates were created to include parts appearing symmetrically on either side of the robot. For instance, the same front main pulley appears in each of the base links; therefore, they constitute a single template. After the final assembly is created, the terrain geometry and properties are incorporated to create the full simulation model.
The virtual model includes 178 parts, 888 dof’s, 41 joints and joint motions, and 1579 force and contact elements. The large number of parts, dof’s and contact elements is due to the segmented nature of the tracks.

**Fig. 4.2:** ADAMS virtual prototype model structure.
4.1.3 Simulations and Postprocessing

The data pertaining to each simulation performed was processed for the following specific major purposes that will be discussed in detail in subsequent subsections:

(i) Study the robot’s mobility characteristics through animations of different possible tasks that require various locomotion and manipulation capabilities;

(ii) Analyze the suspension and track tension retention by examining the spring array force distributions;

(iii) Define each joint’s torque requirements for different mobility tasks and select proper gear ratios and motors;

(iv) Define maximum end-effector payload capacity for different robot configurations.

Different types of terrains such as flat roads, obstacles, stairs, ditches, and ramps, were created in a manner such that they could be easily changed according to different size and shape requirements.

4.2 Simulation Results and Discussion

4.2.1 Mobility Characteristics Analysis - Animation Results

To study the robot’s functionality, the following simulations were performed: various manipulation scenarios (all 3 modes of operation as described in Subsection 3.1.2), random rotations of all links, traversing pipes of different diameters, climbing and descending rectangular obstacles with different link configurations, crossing ditches with
different gap dimensions, climbing and descending stairs, flipping over due to a ramp obstacle, lifting tasks and more.

To illustrate, several of the above mentioned simulations are presented in Figs. 4.3 – 4.12. Fig. 4.3 shows several possible configuration modes for manipulation purposes as was shown in Fig. 3.3.

The segmented nature of the robot’s structure allows it to be able to surmount cylindrical obstacles such as pipes and tree logs. Fig. 4.4 depicts several configuration steps to accomplish such tasks as follows: the base link tracks are deployed until they touch the obstacle (a) – (c); at that point, the tracks start to propel the platform while at the same time they continue their rotation about joint 1. Only the combination of these simultaneous motions allows the robot to surmount such obstacles.
Fig. 4.4: Surmounting circular obstacles.

Fig. 4.5 shows a series of motions that different links along with the tracks need to undergo in order to climb the stairs. The steps are as follows: the base link tracks are first deployed until they touch the stairs (b); link 2 is closed and the robot starts climbing with tracks (c); at the end of the stairs link 3 opens (d) to support the platform while the robot is in motion until position (e); link 3 rotates (until closed) to lower the robot until the tracks are in full contact with the ground (f).
The steps the robot needs to undergo in order to descend stairs as shown in Fig. 4.6 are as follows: link 2 is deployed until it touches the stairs (a); the robot advances until the entire platform is on the stairs (b); link 2 closes (c); and the platform descends the stairs (d).

Fig. 4.7 shows series of motions in order to climb a 0.5 m step obstacle with the base link tracks. The steps are as follows: the base link tracks are first deployed on the step (b); link 2 continues to rotate until the base link tracks adjust with the profile of the terrain (c); the platform advances to accomplish the climbing process (d) and link 2
closes. This climbing can also be accomplished with link 3 by interchanging the roles of links 2 and 3 (in this case, the back of the robot will be facing the step obstacle).

**Fig. 4.6:** Stair descending.

**Fig. 4.7:** Step obstacle climbing with tracks.
Similarly, Fig. 4.8 shows a series of configurations the robot needs to undergo in order to climb the step obstacle with link 2 while link 3 is deployed from the back to support the entire platform to complete the climbing process. This climbing can also be achieved with link 3 by interchanging the roles of links 2 and 3 (in this case, the back of the robot will be facing the step obstacle).

**Fig. 4.8:** Step obstacle climbing with links 2 and 3.
Fig. 4.9 shows series of motions in order to descend the step obstacle. The steps are as follows: link 2 is deployed until it touches the ground to support the robot when advancing (b), link 2 rotates to lower the front of the platform (c); link 2 fully closes (d); link 3 opens and the robot moves forward (e); link 3 rotates (until closed) to lower the robot until the tracks are in full contact with the ground (f).

Fig. 4.9: Step descending.
Since the robot can deploy link 2 from the front and link 3 from the back (when all links are stowed), ditches up to 0.635 m in width can be easily traversed as shown in Fig. 4.10. The steps involved are as follows: from the back edge of the ditch, link 2 is deployed (b); the robot advanced until the front and back pulleys are supported by the ditch edges (c); link 2 closes and link 3 opens from the back (d); the robot continues its forward motion until the COG passes the front edge of the ditch while link 3 prevent from the robot from falling into the ditch when the COG is before the front edge (e) – (f).

**Fig. 4.10:** Ditch crossing.
In cases where it is required to remove objects or lift heavy objects from underneath, the compact and symmetric structure of the robot and yet increased actuator strength due to the hybrid structure allows is to go under such objects and lift as shown in Fig. 4.11.

![Fig. 4.11: Lifting tasks.](image)

The fully symmetric structure of the mobile robot along with its ability to sustain some forces resulting from falling or flipping over (due to its track suspension system and pliable rounded sides) can allow it to accomplish a mission requiring manipulation capabilities in spite of the fact that the robot flips over or falls due to an obstacle the robot could not avoid. Fig. 4.12 shows several snapshots of a simulation showing a robot stowing its links before flipping over occurs and deploying them again from the other side of the platform after the robot flipped over.
4.2.2 Analysis of Track Tension and Suspension Mechanism

These analyses aided in finding the optimal spring stiffness value for the dual tension-suspension mechanism. This was performed by visualizing the spring compression/expansion (with different stiffness values) to verify that it meets the allowable displacements for track tension and suspension purposes.

The graphs in Fig. 4.13 represent the force in each spring in the top and bottom spring array on each side of the platform (due to symmetry, each graph represents the force of the right and left spring in each base link). While the bottom supporting springs
in each track contact the ground, they act as a suspension system for the platform. At the same time, the upper supporting springs exert forces upwards to maintain a predetermined tension in the track system. To illustrate this, Fig. 4.13 represents simulation results of the robot surmounting a small obstacle (3x4 cm) to observe how the springs react to obstacles situated between the planetary pulleys.

From the top spring array force distribution (Fig. 4.13(a)), we observe that the average force in each spring is constant as expected since they support only the part of the track that doesn’t touch the ground. In this case the springs act to retain tension in the track. Also, the forces in the springs supporting the middle planetary pulley are generally smaller than those located off center, which is in agreement with the track shape characteristics due to its bending. Namely, the springs in the center are less compressed than those off center and hence generate less force. The forces are in the range of 0–40 N as the installation compression of each spring was 8 mm and the optimal spring constant was found to be 5.19 N/mm.

From the bottom spring array force distribution (Fig. 4.13(b)), the force in each spring is fluctuating as expected since it supports the part of the track that touches the ground and hence in direct contact with the obstacle. The forces in all bottom springs are generally of equal range of magnitude since none of these springs are free to expand according only with the tracks pliability. In this case, the forces are greater than 40 N since the springs are compressed more then the installation compression value due to the ground’s shape irregularities, which exert additional external forces on the tracks.
4.2.3 Analysis of Motors Torque Requirements

This section outlines the results of additional dynamic simulations performed in order to assess and predict the torque required in joints T_1, T_2 and T_3 (Fig. 4.14) to propel the tracks (base link 1), link 2 and link 3, respectively. Once the maximum torque requirement for each joint is defined, proper gear ratios and motors can be selected. The simulations account for weights, inertia properties and acceleration of the links as well as contact and friction forces between the links and tracks and the ground.
The torque requirement of each joint can be predicted for different mobility scenarios in order to properly select a motor. Practically, the harshest operating conditions for each motor will dictate the motor’s selection criteria. An analysis is performed for each motor in the system.

To demonstrate this capability, torque plots for several mobility scenarios requiring the largest torque capacity are shown. Based on these torque plots, the maximum peak torque and its occurrence in a given range of motion can be identified. These peak torque values define the maximum torque capacity necessary for each joint.

1) Step obstacle climbing with tracks (Fig. 4.7): Fig. 4.14 shows a series of motions the different links along with the tracks need to undergo in order to climb a 0.5m height step with the base link tracks and the torque required at every step of the motion. The angular velocity of link 2 (30 deg/sec) can be used to identify the torque at every step of the motion with respect to the angle travelled by the link. The torque value is changing its direction when the base link tracks and link 2 are perpendicular (at \( t = 3 \text{ sec} \), the base link tracks travelled 90° relative to link 2) since at this point the COG of the base link tracks is vertically above the joint connecting link 2 and the base link tracks (joint 1). Beyond that point, when the base link tracks touch the step, larger torque value is required to accomplish the climbing task. According to the torque plot, the torque peak value for this case occurs at the beginning of the motion \( (T_2 = 141.2 \text{ N} \cdot \text{m} \text{ at } t = 0) \).

2) Step obstacle climbing with link 2 (Fig. 4.8): Fig. 4.15 shows a series of motions the different links along with the tracks need to undergo in order to climb a 0.5m height step with link 2. When link 2 touches the step (3.7 sec), a torque peak value of
\( T_2 = 141.7 \text{N} \cdot \text{m} \) is required in order to start lifting the base link tracks above the ground. The instantaneous jump in the torque requirement at 3.7 sec indicates the touching point with the step.

**Fig. 4.14:** Link 2 motor torque requirement – step obstacle climbing with tracks (via joint 1).
Since step obstacle climbing as described in Figs. 4.7 and 4.8, can also be achieved with link 3, similar analyses were performed to obtain link 3 motor torque requirements (joint 2). The results are shown in Fig. 4.16. The angular velocity of link 3 is 30 deg/sec. If climbing is performed with the base link tracks (via joint 2), instantaneous jump in the torque value occurs when the tracks touch the step (at $t = 4.2 \text{ sec}$) according to torque plot (a) in Fig. 4.16. As predicted, the torque peak value ($T_3 = 189 N \cdot m$) occurs at the beginning of the motion.

If climbing is performed with link 3, the torque peak value ($T_3 = 157 N \cdot m$) occurs when it touches the step (at $t = 3.4 \text{ sec}$). This torque is required in order to start lifting the base link tracks above the ground (as in the case when climbing the step with link 2).
The maximum torque required to drive link 3 occurs when climbing is performed with the base link tracks. This case yields a torque peak value of $T_3 = 189 N \cdot m$. However, the configurations resulting from this case in order to climb the step can be fulfilled with link 2 (as shown in Fig 4.7), in which case the torque requirement is less ($T_2 = 141.2 N \cdot m$). Therefore, lifting of the tracks above the ground to climb stairs or steps will be performed with link 2 rather than with link 3. Link 3 is mostly used as a support (other than manipulation purposes) when climbing or descending steps. For symmetry reasons, we shall define $T_2 = T_3$ when selecting the motors.

Fig. 4.16: Link 3 motor torque requirement – (a) Step obstacle climbing with tracks (via joint 2); (b) Step obstacle climbing with link 3.
When the robot moves on a flat ground or a slope, the driving torque $T_1$ (Fig. 4.17) for a single track is determined based on the condition that slipping does not occur. Therefore, static friction coefficients were used to estimate the required driving force.

Equation (4.1) is used in order to estimate the driving force for a single track. Practically, vibrations and impacts occur in the driving system and there are random noises in real-time values of $F_D$.

$$F_D \geq \mu_s N + \frac{W}{2} \sin(\alpha) = \frac{W}{2} (\mu_s \cos \alpha + \sin \alpha)$$ (4.1)

To ensure incline motion conditions, the expression to estimate the torque can be written as follows:

$$T_1 \geq \frac{W R}{2} \cdot (\mu_s \cos \alpha + \sin \alpha) \cdot \left( \frac{1}{\eta_{gear} \cdot k_{gear} \cdot \eta_{track}} \right)$$ (4.2)
where:

\( F_D \) – Driving force of a single track (friction force)

\( R \) – Outer radii of track

\( W \) – Total weight

\( \mu_s \) – Coefficient of static friction

\( \eta_{\text{gear}} \) – Gear efficiency

\( k_{\text{gear}} \) – Gear ratio (input to output rotational speeds)

\( \eta_{\text{track}} \) – Track efficiency

### 4.2.4 End–Effector Payload Capacity Analysis

The purpose of this simulation was to identify the maximum allowable end-effector payload capacity of the platform with respect to various configurations by examining the COG vertical movement with respect to the ground, which indicates tip-over stability. The graphs shown in Fig. 4.18 describe the change in the robot’s COG position (in the vertical direction) with respect to linearly increasing load applied at the end-effector. The change of the COG position implies on the robot’s structural stability for a given end-effector load. Clearly, configuration (b) as shown in Fig. 4.18 is optimal for this purpose. The maximum load capacity is found from the graph in Fig. 4.18(b) at the instant when the COG position is greater than zero (dashed line). This indicates that the COG of the robot starts to move vertically. According to the graph, the static load capacity with configuration (b) is approx. 77 kg. Practically, the maximum allowable torque capacity of joints 1 and 2 will restrict the actual payload capacity as explained in the following paragraph.
Some possible configurations for manipulation (or combined manipulation and locomotion) purposes are presented schematically in Fig. 4.19. Among the configurations shown in this figure, some other configurations can be generated in the range of the configurations shown, such as vertical or horizontal reach. It is clear from configurations (a) and (c) that link 2 joint (J₁) will be the weakest in its ability to sustain a given payload compared to link 3 joint (J₂). In some of the cases, the limiting factor in analyzing end-effector payload capacity would be the robot’s ability to sustain structural stability (tilt due to the payload at the end-effector) for a given end-effector payload rather than verifying whether joint torques T₂ and T₃ meet the torque requirements to support a given payload at the end-effector for a given configuration for manipulation purposes.

For a given torque capacity in joint 1, configuration (c) is optimal for maximum payload capacity $W_p$ due to its dramatically greater structural stability. This payload capacity can be increased if joint 1 torque capacity is increased.

For greater payload requirements, depending on the required level of mobility, either of configurations (b), (d) and (e) can be employed. In each of these configurations (with 157 $N\cdot m$ torque capacity in joints 1 and 2 for instance), a payload of ~20 kg can be manipulated by the robot. For this robot size, this load capacity and configuration cannot be achieved with any of the existing mobile robots. This result is a direct consequence of the novel design paradigm – namely, the hybrid nature of the platform and manipulator arm and their ability to be interchangeable in their roles.
Fig. 4.18: Platform COG vs. load capacity.
Fig. 4.19: Possible configurations for manipulation.
CHAPTER 5

CONTROL SYSTEM DESIGN PARADIGM

Control architecture issues are key to the design and construction of mobile robots, just as they are for any computer–controlled complex system that is subject to hard time constraints. Mobile robots need to constantly process large amounts of sensory data in order to execute required controlled motions based on the operator’s commands, or in autonomous operations, to build a representation of its environment and to determine meaningful actions. The extent to which control architecture can support this enormous processing task in a timely manner is affected significantly by the organization of information pathways within the architecture. The flow of information from sensing to action should be maximized to provide minimal delay in responding to the dynamically changing environment.

A distributed processing architecture offers a number of advantages for coping with the significant design and implementation complexity inherent in sophisticated robot systems. First, it is often cheaper and more resilient than alternative uniprocessor designs. More significantly, multiple processors offer the opportunity to take advantage of parallelism for improved throughput and for fault tolerance.

This chapter presents the development of a new systematic approach for a modular control architecture that dramatically increases the functionality of the hybrid mobile robot and provides operational fault tolerance. This is done by providing on–
board distributed RF communication between the robot’s subsystems and modules such as the actuators and sensors.

5.1 On-Board Wireless Sensor/Actuator Control Paradigm

All electrical hardware (such as motors, batteries, controllers, drivers, electrical boxes, sensor boxes, audio/video and data RF cards, gear-heads, etc.) is situated in the left and right base link tracks. Other motors and associated electrical hardware for the gripper mechanism (end-effector) are situated in the space available in link 3 (Fig. 3.7 and 3.8).

5.1.1 On-Board Inter-segmental RF Communication Layout

The design architecture of the hybrid mobile robot requires that the electrical hardware in each of the segments constituting the robot (two base links, link 2 and link 3) is not connected via wires for data communication purposes. The electrical hardware is situated in three of the robot’s segments – namely, two base link tracks and link 3. The electrical hardware associated with the gripper mechanism that is situated in link 3 is not connected to any of the base link tracks via wires. Each of the segments contains individual power source (Lithium-Ion rechargeable batteries) and RF modules for inter-segmental on-board RF communication network [61][62][63].

The right base link track contains a central RF module (Fig. 8(a)) for communication with the OCU (Operator Control Unit), while each of the remaining segments contains an RF module for inter-segmental on-board RF communication. This, along with independent power source in each segment, eliminates the need for physical
wiring and slip ring connections between the rotating segments. This enables each of the links 2 and 3 and the gripper mechanism to provide continuous rotation about their respective joints without the use of slip rings, cable loops and other mechanical means of connection that may restrict the range of motion of each link.

The requirement to avoid direct RF communication between each of the three segments of the robot and the OCU also assisted in eliminating the following major problems:

(i) It eliminates the need to have a stand-alone vertically sticking out antenna for each of the robot’s segments. Sticking out antennas are not desirable due to the robot’s structural symmetry, which would allow the robot to flip-over when necessary and continue to operate with no need of self-righting. For that reason, special flat antennas [64] were designed (Fig. 5.1) and embedded into the side covers of the robot for RF video communication and data communication as shown in Figs. 3.7 and 5.1. The flat shape antennas and their location in the side covers maintains the symmetric nature of the entire hybrid platform and minimizes the chance for loss of data or breakage of the antenna if it were protruding vertically up;

(ii) If each of the base links receives data from the OCU directly, loss of data due to physical obstructions (walls, trees, buildings, etc.) between transmitter and receiver can result in inconsistent data acquisition by each base link that may lead to desynchronization between the track motions. On the other hand, if all the data pertaining to all segments of the robot is received in one location on the robot, and then transmitted and distributed to the other segments (the segments are separated by fixed distances from one another with no external physical obstructions), then
the data received by each of the base link tracks will be virtually identical, and any
data loss that occurred between the OCU and the robot will be consistent.

![Embeddable flat antennas for video and data RF communication.](image)

**Fig. 5.1:** Embeddable flat antennas for video and data RF communication.

Due to the short and fixed distances between the robot’s segments/links, the
above mentioned problems can be solved by using a low-power on-board RF
communication between the left and right base link 1 tracks and link 3.

**5.1.2 RF Hardware for the Hybrid Mobile Robot**

As shown in Fig. 5.2, the OCU includes MaxStream [65] 9XTend 900 MHz RF
Modem. The data transmitted by the stand alone RF modem on the OCU is received by a
9XTend OEM RF Module that is situated in the right base link track as shown in Fig.
5.3(a). The 9XTend module communicates with the controller that controls the
electronics (motors and associated drivers, sensors, etc.) in the right base link track while at the same time sends data pertaining to the other segments (left base link track and link 3) to a MaxStream XBee OEM 2.4 GHz RF Module in a wire connection (through the distribution board). This data is then transmitted in a wireless manner to two other XBee OEM 2.4 GHz RF modules – one for the left base link track and the other for link 3 (Figs. 5.3(b) and (c)), thus providing on-board wireless (RF) data communication among robot joints.

**Fig. 5.2:** On-board wireless communication layout and design details (all covers removed).
900 MHz from OCU

2.4 GHz to left base link track & link 3

(a) Right base link track.

(b) Left base link track.
The use of the XBee OEM RF module (Fig. 5.4) is advantageous in several ways:

(i) The need for a vertically sticking out antenna for each link segment of the mobile manipulator is eliminated since the RF module is available with a PCB chip antenna or miniature whip antenna (Fig. 5.4);

(ii) Its operating frequency is 2.4 GHz – namely, different operating frequency than the primary 9Xtend RF module;

(iii) Fast RF data rate of 250 kbps;

(iv) Its small form factor (2.5x3[cm]) saves valuable board space in the compact design of the robot.
Since the radios do not have any issue radiating through plastic cases or housings, the antennas can be completely enclosed in our application. The XBee RF module with a chip antenna has an *indoor* wireless link performance of 24 [m] range approx. In the case of the hybrid robot design, the maximum fixed distance between the base link tracks and link 3 is less than 0.5 [m].

This hardware architecture provides a simple and cheap solution for on-board inter-segmental wireless communication, and avoids any wire and slip-ring mechanical connections between different parts of a given mechanical system.

Preliminary experiments were performed in order to test the RF communication between the distributed RF XBee modules in the system. Using the joystick, we sent motor rotation commands through the OCU 9XTend RF Module to an on-board 9XTend RF Module that distributed the data to a local XBee RF module in a wire connection. The wireless data transmitted by the local XBee module was successfully received by the on-board XBee modules in the other links in a wireless manner with no data loss even when the XBee modules were partially/fully enclosed and apart from one another.
in the robotic system. Specifically, the track motions were consistently synchronized (both stopped and started precisely at the same time) despite the fact that the communication between the tracks is wireless.

5.2 Electrical Hardware Architecture

5.2.1 Controllers, Drivers, Sensors and Cameras Layout

The microcontroller in each link is a Rabbit based core module. There are several analog input channels on the module through which the microcontroller receives signals from the sensors. Each motor in the base link tracks is driven by a Logosol driver (LS-173s), which acts as a motor controller to provide position and speed control. Signals from encoders attached to the rear shaft of each motor are sent to the drivers as feedback. The sensors which the robot is equipped with are: a tilt sensor; thermometer, GPS, three-axis compass (inclinometer) and battery-voltage monitor (Fig. 5.5). As shown in Fig. 3.7, there are two embedded cameras located in the front and back of the left base link track, which provide visual information to the OCU operator on the robot’s surroundings. A transmitter is used to transmit the video signals to the OCU. A switch controlled by the sensor processor (described in more detail in Subsection 5.2.3) decides the image of which camera is being transmitted.
5.2.2 Power System and Signal Flow Design and Implementation

One of the constraining factors for small mobile robot design is generally the power system design. In order to generate the required high torques for each joint, rechargeable Lithium-Ion battery units in a special construction, as discussed later on, were developed and used. This power source along with a proper selection of brushless DC motors and harmonic gear–head drives were integrated (Section 3.3) to generate the high torques required.

A modular and expandable power system design was developed and implemented for the hybrid robot. It has two major key elements that allow for easy reconfiguration and expansion: Li-Ion battery packs and power/signal distribution boards as discussed as follows.

Fig. 5.5: Sensors and cameras layout.
**Li-Ion Battery Packs**

Each tracked link of the hybrid robot carries four 9-cell Panasonic CGR18650D Li-Ion battery packs in a series connection as shown in Fig. 5.6. Each Li-Ion battery cell nominally provides 3.7V at 2.4Ah. We used smaller Li-Ion cells such as Panasonic CGR18650D with the benefit of being able to increase capacity and continuous current discharge due to the increased number of cells used in a given volume. A combination of number of cells and protection circuits was designed in order to achieve a specified current discharge of up to 15 Amps. This was implemented by constructing a 9-cell assembly of Panasonic CGR18650D Li-Ion battery cells in 3S3P construction (three of three-cell connected in Parallel were connected in Series) resulting in 11.1V pack at 7.2 Ah. A 5 Amp max PCM (Protection Circuit Module) was embedded in each paralleled branch, which provides a total of 15 Amp maximum current discharge. Four 9-cell packs, in a 4S construction (Fig. 5.6), constitute the battery pack for each traction link (45V nominal), which provide power to local motors and other electrical hardware. One 9-cell pack (12V) is used as an independent power source for the gripper mechanism.

According to the tests performed, this special construction provides a battery unit with nominal voltage of ~45V and continuous current discharge of 13.2 Amp with a max current discharge of 15 Amp due to the PCM. This electrical performance is advantageous considering the very compact size of the battery pack (110x110x70 mm) and overall weight of only 1.6 Kg.
The power and data signal distribution board is an in-house [19] designed circuit board used in each of the base link tracks in the hybrid robot (Fig. 5.7). The distribution boards for the right and left base links are identical. In order to dramatically reduce the footprint of the distribution board, it was custom designed and manufactured in a layered manner, while providing sufficient input/output interfaces for a large number of on-board devices as well as attachable devices for the mobile robot, such as LED lights (front and back), cameras (front and back), various sensors, etc. One of the board’s purposes was to take the power provided by the battery charging boards and distribute it to the various on-board instruments. There are two 48V inputs from the battery to the distribution board in order to provide two independent 48V outputs to power the back
and front motor drivers in each base link track. Flexibility is achieved through the use of commercial DC-DC converters. Power from the battery charging boards is funnelled through several DC-DC converters which regulate the voltage up or down as necessary before being distributed to the on-board instruments, such as 3.3V for the XBee 2.4GHz RF Module, and several DC voltage output levels, such as 5V output for LED lights and video quad, 12V for cameras and motor Logosol controller, 48V for motor drivers, and 5V for motor hall–effect sensor terminal voltage. The distribution board also includes switch circuits that switches between the four cameras and the video quad. Since these units are available in many different output voltages, it was easy to mix and match converters as needed. Each power distribution board can be extended by stacking boards as necessary to provide additional output voltages or more power per voltage source.

The RS485 input terminal (Fig. 5.7) is used to interface with the 9XTend Central RF Module or Sensor Processor Board, depending on which base link track the distribution board is used for (Fig. 5.3(a) & (b)). The RS485 output terminal provides interface with the local Logosol controller in each base link track as well as a 12V output in order to power the controller. With this type of electrical connection, the data pertaining to the other base link track and the gripper mechanism is transferred to the XBee RF Module for on-board wireless data communication.
RS485 Input for 9XTend Central RF Module or Sensor Box Interface

RS485 Output to Logosol Controller

48V and 12V Outputs for Front Motor and Driver

48V and 12V Outputs for Back Motor and Driver

RS485 Input

Signal Relay Switch

Four video inputs + video quad

Quad 1 2 3 4

Front & Back LED Lights

12V DC Power for Video Transmitter

Fig. 5.7: Power/signal distribution board for base link tracks.
Gripper Mechanism Power/Signal Distribution Board and Hardware Architecture

As shown in Fig. 5.8, the RCM3400 analog RabbitCore provides a processor and analog input subsystem for OEMs to quickly integrate into the custom design [19] power/signal distribution board for the gripper mechanism. The RCM3400 features a low-EMI Rabbit 3000-based CPU subsystem running at 29.4 MHz, with 512K Flash / 512K SRAM, 5 serial ports, and 8 channels of programmable gain analog input in an extremely small footprint (34×29 mm). The development board features 10/100Base-T Ethernet and can be used as a reference design in conjunction with Dynamic C's TCP/IP software libraries.

As for the base link tracks, Link 3 distribution board is also equipped with integrated DC-DC modules in order to provide the required DC voltage levels for on-board modules, such as 3.3V for RCM3400 Rabbit Core µ Processor and XBee 2.4GHz RF Module, and 5V DC output for the logics of the motor drivers.
As shown in Fig. 5.3(c), the gripper wrist is driven by an external motion controller (MCDC 3006S) that is designed for the entire range of Faulhaber DC micromotors. The motion controller is based on a high performance digital signal processor (DSP), which enables a high control quality, precise positioning and very low speeds. The following tasks can be performed with this controller: velocity control with high requirements on synchronous operation and minimal torque fluctuations. A PI controller ensures observance of the target velocities; velocity profiles such as ramp, triangular or trapezoidal movements can be realized; and positioning mode.
The gripper motor is driven by a 1-Quadrant amplifier (DEC 24/1 1-Q-EC), which is used for controlling EC motors with Hall sensors with a maximum output of 24 watts.

### 5.2.3 Sensor Processor Board

The sensor processor (Fig. 5.9) board is equipped with Honeywell HMR3300 digital compass used for precision robot inclination measurements. This compass solution is designed for precision compass integration into our system using a 5-voltage logic level serial data interface with commands in ASCII format. The HMR3300 includes a MEMS accelerometer for a horizontal three-axis, tilt compensated precision compass for performance up to a ±60° tilt range.

The RCM3400 Rabbit Core µ Processor is the same as the one embedded in link 3 distribution board and is used to process the data received from the various sensors in the mobile robot. Each of the DC-DC modules regulates the 12V input into the board to generate 3.3V and 5V DC voltage levels for the microprocessor and the inclinometer, respectively. Additional RS485 inputs are available in order to interface supplementary sensors or devices.
5.3 Robot DOF Coordination and Operator Control Unit (OCU)

The custom made OCU [19] unit as shown in Fig. 5.10 consists of two control sticks (LS-731, from Logosol), controller LS991 with text monitor, 900 MHz RF data transceiver (XTend modem, from Maxtream), and 12V battery and battery charger. The OCU also includes sockets for optional video monitor and video/audio RF receiver. The
OCU controller (Fig. 5.10) includes several control buttons that perform the following functions (from left to right):

(1) Switch modes between track motions and gripper mechanism motions for control stick #1;

(2) Switch between front and back videos;

(3) Power save mode to switch off different devices such as video, drivers, sensors, etc. (excluding data RF transceiver and controllers, otherwise the robot global positioning will be lost);

(4) Change track direction to preserve consistent control stick motions when the robot is flipped over;

(5) Read sensors;

(6) Turn on/off front and back lights;

(7) Reserved control button for additional functionality.

The remote OCU includes two control sticks in order to coordinate the robot degrees of freedom when generating the motions required for a given task. The forward, backward, right turn and left turn motions of the base link tracks are controlled by an up, down, right and left movement of the first control sticks (C1). The second control stick (C2) is used to control links 2 and 3 degrees of freedom. A right movement of C2 control stick will generate a clockwise (CW) independent motion of link 2 while a left movement of the control stick will generate a counterclockwise (CCW) independent motion of link 2. Similarly, an up and down movement of the second control stick will generate an independent clockwise and counterclockwise motion of link 3, respectively. Furthermore, four diagonal movements of the second control stick (i.e., +x’, -x’, +y’, -y’
directions as shown in Fig 5.10) will generate simultaneous motions of links 2 and 3 as follows:

(i) Movement of C2 in the +x’ direction will move links 2 and 3 simultaneously both in the CW direction.

(ii) Movement of C2 in the -x’ direction will move links 2 and 3 simultaneously both in the CCW direction.

(iii) Movement of C2 in the +y’ direction will move links 2 and 3 simultaneously in the CW and CCW directions, respectively.

(iv) Movement of C2 in the -y’ direction will move links 2 and 3 simultaneously in the CCW and CW directions, respectively.

The CW and CCW wrist motions of the gripper mechanism as well as the open and close motions of the gripper jaws are generated with a separate mode of the first control stick.

The first and second control sticks can be operated simultaneously by the operator in order to provide simultaneous motions of the tracks along with different motion combinations of links 2 and 3, as explained above.

The above motion procedures are summarized in Fig. 5.10 and Table 5.1. Fig. 5.10 shows the top view of Control Stick # 1 (C1) with two switch–able modes as follows: (i) track motions – Mode 1 (M1); and (ii) gripper mechanism motions – Mode 2 (M2). Control Stick # 2 (C2) has two coordinate systems x–y and x’–y’ for link 2 and 3 motions as specified in Table 5.1. The control angle $\theta$ in C2 provides speed variability to each of links 2 and 3 when operated simultaneously.
Table 5.1: Robot Motion Specifications.

<table>
<thead>
<tr>
<th></th>
<th>FWD</th>
<th>BWD</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracks motions</td>
<td>C1 + M1 (+y) H/L</td>
<td>C1 + M1 (-y) H/L</td>
<td>C1 + M1 (+x) H/L</td>
<td>C1 + M1 (-x) H/L</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Wrist CW</th>
<th>Wrist CCW</th>
<th>Gripper Jaws Open</th>
<th>Gripper Jaws Close</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gripper</td>
<td>C1 + M2 (+y)</td>
<td>C1 + M2 (-y)</td>
<td>C1 + M2 (+z)</td>
<td>C1 + M2 (-z)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CW</th>
<th>CCW</th>
<th>CW/CCW</th>
<th>CCW/CCW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link 2 alone</td>
<td>C2 (+x)</td>
<td>C2 (-x)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Link 3 alone</td>
<td>C2 (+y)</td>
<td>C2 (+y)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Links 2+3</td>
<td>C2 (+x')</td>
<td>C2 (-x')</td>
<td>C2 (+y')</td>
<td>C2 (-y')</td>
</tr>
</tbody>
</table>

Fig. 5.10: Operator control unit (OCU) architecture and robot degrees of freedom.
6.1 Research Hypothesis Validation

Extensive experiments were performed in order to prove and validate the hypothesis of this work. The proposed novel design paradigm of the hybrid mobile robot was thoroughly tested in simulations in Chapter 4. The simulations demonstrated a compact and unique hybrid mechanism that is able to exhibit various novel mobility, manipulation, and combined locomotion and manipulation capabilities. The experimental results in this chapter demonstrate the validity of the proposed design paradigm hypothesis as well as the validity of the simulations. The simulations are claimed to be valid by showing that the functionalities of the virtual prototype robot shown through simulations and testing in computer generated virtual environments can be replicated with the actual physical prototype in real-world environments. The experiments were also performed for the following major purposes that will be discussed in greater detail in subsequent subsections:

(i) Test and demonstrate the robot’s superior mobility characteristics through experimentation of different possible tasks that require various locomotion and manipulation capabilities;

(ii) Demonstrate and define the end-effector’s superior payload capacity for various robot configurations.
Different types of terrains such as flat roads, obstacles, stairs, ditches, ruble piles and ramps, were tested with different shapes and sizes.

**6.2 Performance Metrics as Design Targets**

The evolution of the concept leading to a significantly improved design of a UGV for missions in rough terrain and hazardous environments required the early consideration of suitable performance metrics that were used as design targets in order to effectively define the specifications of the system’s capability and functionality.

The derived performance metrics that were used as design targets were mobility, simultaneous and interchangeable locomotion and manipulation capability, durability, communications, power system design, control system design, situational awareness, overall system modularity and endurance.

The metrics also aided with testing, measuring and understanding the performance of the hybrid robot and to show its capabilities in terms of locomotion and manipulation in comparison with other existing mobile robotic systems. Therefore the set of experimental tests also aided with corroborating and validating the objective and motivation of this work.

Following the completion of the physical prototype, a series of tests were performed to assess the robot’s mobility and durability characteristics. The obstacle course consisted of various test rigs including man-made and natural obstructions as a representative subset of the robot possible hindrances to cross country movement. The following list describes a set of obstacles and types of tests that were used in order to test the hybrid robot:
(a) Ditch crossing: different widths of ditches were tested. According to the experimental results, the hybrid robot could cross at least a 0.635 m (25 inch) ditch width;

(b) Step obstacle climbing and descending: different heights of step obstacles were tested. According to the experimental results, the hybrid robot could climb and descend steps up to 0.7 m (28 inch) height;

(c) Manipulation before and after flipping over;

(d) Traversing pipes of different diameters. The experiments prove that the hybrid robot is able to traverse up to 0.6 m (24 inch) pipe diameter;

(e) Climb and descend stairs with different materials (wood, metal, concrete, plastic plastered, etc.), different stair riser and run sizes, and inclinations;

(f) Lift and carry loads including testing pushing capacity from underneath objects up to 61 Kg (~135 lbs);

(g) Railroad ties;

(h) Inclined ramp adjustable from 0 to 60 degrees with and without payloads;

(i) Negotiation of rock channels and beds using rocks of different sizes;

(j) Various vegetation obstacles;

(k) Flat sand pits and sand furrow;

(l) Speed runs.

A summary of the hybrid mobile robot additional derived specifications are outlined in appendix A.
6.3 Robot Configurations for Manipulation

Fig. 6.1 depicts different modes of configuration of the platform for manipulation purposes as claimed in Fig.3.3. While some links are used as platform for locomotion, others are used simultaneously for manipulation. In all configuration modes for manipulation, while links 2 and 3 are used for manipulation, the pair of base links can provide motion equivalent to a turret joint of the manipulator arm.

Fig. 6.1: Configurations for manipulation.
6.4 Mobility/ Maneuverability Characteristics Testing and Validation

Fig. 6.2 shows a series of configurations that demonstrate a number of basic functions the robot structure can provide in order to perform advanced mobility tasks as claimed in Fig. 3.2. In subsequent sections it will be demonstrated how these basic set of configurations were utilized during the different stages of performing climbing of various obstacles as well as performing a variety of manipulation tasks. In these configurations link 2 is effectively used to support the platform for enhanced mobility purposes as well as climbing purposes. Link 2 also helps to prevent the robot from being immobilized due to high-centering, and also enables the robot to climb taller objects (Fig. 6.2(b)). Link 2 is also used to support the entire platform while moving in a tripod configuration (Fig. 6.2(c)). The posture of the tripod configuration can be switched by rotating link 2 and passing it between the base link 1 tracks as shown in Fig 6.2 (d). This functionality is effective when it is necessary to rapidly switch the robot’s direction of motion in a tripod configuration. The configuration in Fig. 6.2(e) demonstrates a very important and effective functionality whereby the entire platform (base link tracks) is lifted above the ground and rotated continuously about joint 1. This functionality is used to climb tall objects and cylindrical obstacles as will be demonstrated in subsequent subsections. Fig 6.2 (g) shows how the passive wheels attached at the end of link 3 can be used to mobilize the entire platform while in motion.
Fig. 6.2: Configurations of the hybrid robot for mobility purposes.
6.5 Traction Configurations

Fig. 6.3 shows several configurations for enhanced traction. The articulated structure of the mobile platform allows it to be adaptable to different terrain shapes and ground conditions. The passive wheels located at joints 2 and 3 provide additional support to the entire platform for different traction configuration modes.

![Fig. 6.3: Configurations for enhanced traction.](image)

6.6 Traversing Cylindrical Obstacles

The segmented nature of the robot’s structure allows it to be able to surmount cylindrical obstacles such as pipes and tree logs up to 0.6 m in diameter. Fig. 6.4 depicts several configuration steps to accomplish such tasks as follows: the base link tracks are
deployed until they touch the obstacle (a) – (c); at that point, the tracks start to propel the platform while at the same time they continue their rotation about joint 1 (d) – (f). Only the combination of these simultaneous motions allows the robot to surmount such obstacles.

6.7 Stair Climbing and Descending

6.7.1 Stair Climbing

Fig. 6.5 shows a series of motions that different links along with the tracks need to undergo in order to climb the stairs. The steps are as follows: the base link tracks are first deployed until they touch the stairs (a)–(c); link 2 is closed and the robot starts climbing with tracks (d)–(e); at the end of the stairs link 3 opens (f) to support the platform while the robot is in motion until position (g); link 3 rotates (until closed) to lower the robot until the tracks are in full contact with the ground (h).

6.7.2 Stair Descending

The steps the robot needs to undergo in order to descend stairs as shown in Fig. 6.6 are as follows: link 2 is deployed until it touches the stairs (a)–(b); the robot advances until the entire platform is on the stairs (c); link 2 closes (d); and the platform descends the stairs. Link 3 can be deployed from the back in cases where smooth landing from the stair edge is required (e)–(f).
Fig. 6.4: Surmounting circular obstacles (photos taken at ESI premises).
Fig. 6.5: Stair climbing.
6.7.3 Stair Descending – Other Configurations

Fig. 6.7 depicts other configurations for stair descending. In both cases the descending stage is performed by deploying links 2 and 3 together in order to support the entire platform while descending. The difference between the steps shown in each case is the platform’s initial orientation with respect to the stairs. These configurations are in
particular useful in cases when the last step edge is much taller than the preceding steps. In this case the motion sequence of the robot links is as shown for the case when descending a step obstacle (steps (f)–(i) in Fig. 6.11).

Fig. 6.7: Stair descending – other configurations (right column photos taken at ESI premises).
6.8 Step Obstacle Climbing

Climbing step obstacles can be performed in several ways with the hybrid robot. These include: (i) climbing with the base link tracks; (ii) climbing with link 2; and (iii) climbing with link 3. The climbing process with the first two options is described in detail in the following subsections. The only difference between climbing with link 2 or 3 is the maximum step height since link 3 is shorter than link 2.

6.8.1 Climbing with Tracks

Fig. 6.8 shows series of motions in order to climb a 0.7 m step obstacle with the base link tracks. The steps are as follows: the base link tracks are first deployed on the step (b)-(c); link 2 continues to rotate until the base link tracks adjust with the profile of the terrain (d); the platform advances to accomplish the climbing process (e) and link 2 closes (f). This climbing can also be accomplished with link 3 by interchanging the roles of links 2 and 3 (in this case, the back of the robot will be facing the step obstacle).

6.8.2 Climbing with Link 2

Similarly, Fig. 6.9 shows a series of configurations the robot needs to undergo in order to climb the step obstacle with link 2 while link 3 is deployed from the back to support the entire platform to complete the climbing process. The configurations required in this case are: (a)–(f), (j), (k). This climbing can also be achieved with link 3 by interchanging the roles of links 2 and 3 (in this case, the back of the robot will be facing the step obstacle).
The climbing process can also be accomplished with the tracks by including configuration (g)–(i) immediately after configuration (f) instead of skipping to configuration (j).

Fig. 6.8: Step obstacle climbing with tracks (photos taken at ESI premises).
6.9 Step Obstacle Descending

Descending step obstacles can be performed in several ways with the hybrid robot. Some of the possible ways are: (i) descending with links 2 and 3; and (ii) descending with the base links. These descending options are described in detail in the following subsections.

Fig. 6.9: Step obstacle climbing with links 2 and 3.
6.9.1 Descending with Links 2 and 3

Fig. 6.10 shows series of motions in order to descend a step obstacle with links 2 and 3. The steps are as follows: link 2 is deployed until it touches the ground to support the robot when advancing (b),(d) (link 3 can also be deployed, as shown in configuration (c), in cases when the step to be descended is taller than the length of link 2); link 2 rotates to lower the front of the platform (e); link 2 fully closes (f); link 3 opens and the robot moves forward (g),(h); link 3 rotates (until closed) to lower the robot until the tracks are in full contact with the ground (i)–(k).

Fig. 6.10: Step descending with links 2 and 3.
6.9.2 Descending with Base link Tracks

Figs. 6.11 and 6.12 show a series of motions in order to descend a step obstacle with the base links. The difference between the motion sequences in each case depends on whether the front end or the back end of the robot is facing the step to be descended. If climbing was performed with the base link tracks (Fig. 6.8) than the back end of the robot will be facing the step edge. In this case the platform will need to reconfigure itself such that descending is performed with the robot front end in order to be able to deploy and use both links 2 and 3 in the descending process as shown in Figs. 6.11 and 6.12.

The reconfiguration can be done in two ways.

![Fig. 6.11: Step descending with base link tracks – tracks flip on the table (photos taken at ESI premises).](image)

(a) (b) (c)  
(d) (e) (f)  
(g) (h) (i)  

Fig. 6.11: Step descending with base link tracks – tracks flip on the table (photos taken at ESI premises).
In the first way, the base link track will be rotated 180° about joint 1 until the tracks flip on the obstacle as shown in configurations (b)–(d) in Fig. 6.11. The rest of the steps are as follows: link 2 and 3 are deployed until they touch the ground to support the robot when advancing (e),(f), link 2 rotates to lower the front of the platform (g); the base link tracks continue to rotate until the tracks are in full contact with the ground (h),(i).

In the second way, the entire platform will be rotated 180° on the obstacle such that the front end of the platform will be facing the edge of the step to be descended Fig. 6.12(a). The rest of the steps are similar to the ones shown in Fig. 6.11.

Fig. 6.12: Step descending with base link tracks – tracks rotate on the table (photos taken at ESI premises).
6.10 Ditch Crossing

Ditches up to 0.635 m in width can be easily traversed since the robot can deploy link 2 from the front and link 3 from the back (when all links are stowed), as shown in Fig. 6.13. The steps involved are as follows: from the back edge of the ditch, link 2 is deployed with or without link 3 (b); the robot advanced until the front and back pulleys are supported by the ditch edges (c); link 2 closes and link 3 opens from the back (d); the robot continues its forward motion until the COG passes the front edge of the ditch while link 3 prevent from the robot from falling into the ditch when the COG is before the front edge (e)–(f); and link 3 closes (g)–(h).

Fig. 6.13: Ditch crossing.
6.11 Platform Lifting and Carrying Capacity Testing

In cases where it is required to remove objects or lift heavy objects from underneath, the compact and symmetric structure of the robot and yet increased actuator strength due to the hybrid structure allows is to go under objects and lift as shown in Fig. 6.14. According to the lifting experiments performed, the hybrid robot was able to lift objects of up to 61 Kg (~135 lbs). Various other experiments were also performed in order to test the load capacity the platform can carry. In one occasion the robot was able to carry two people standing on the robot with the OCU on top, which accounted for an overall weight of 187 Kg (411 lbs).

Fig. 6.14: Lifting capacity testing (photos taken at ESI premises).
6.12 Simultaneous Locomotion and Manipulation

The various climbing and descending tasks presented thus far can be incorporated simultaneously with manipulation of objects. Various experiments were performed in order to demonstrate this unique capability, which is a direct outcome of the hybrid nature of the platform and manipulator arm and their ability to be interchangeable in their roles and provide both functionalities simultaneously.

The following locomotion tasks were successfully experimented while simultaneously manipulating an object:

1. Ascending and descending of stairs;
2. Traversing tall cylindrical obstacles;
3. Crossing ditches,
4. Climbing and descending step obstacles with various motion configurations.

In order to demonstrate this capability, Subsections 6.12.1 and 6.12.2 present two cases where the robot climbed and descended a 0.7 m step obstacle while holding an object.

6.12.1 Simultaneous Climbing and Manipulation

Fig. 6.15 demonstrated the hybrid mobile robot’s capability to pick up an object, and climb a step obstacle with the base link tracks while holding the object with the gripper mechanism. The step climbing sequence in this case is similar to the one shown in Fig. 6.8 except that link 3 remains deployed in order to manipulate the object at the same time.
6.12.2 Simultaneous Descending and Manipulation

Fig. 6.16 shows the hybrid mobile robot’s configuration steps in order to descend the step obstacle with the base link tracks while holding the object with the gripper mechanism. The motion sequence of the robot links required to descend the obstacle is similar to the one presented in Fig. 6.12 with the exception that link 3 remains deployed in order to manipulate the object at the same time.
6.13 Mobility Configurations for Rubble Pile Climbing

Fig. 6.17 shows the hybrid robot’s capability to easily climb over a rubble pile and return by using a combination of the various mobility capabilities presented thus far. These mainly include climbing and descending with the aid of the base link tracks, link 2.
and link 3. Some of the configuration steps in Fig. 6.17 also show how the platform effectively utilizes its ability to adjust the level of traction to effectively traverse the rubble pile.

**Fig. 6.17:** Combined mobility configurations for rubble pile climbing (cont’d next page).
6.14 Robot Configurations for Manipulation

Fig. 6.18 depicts different modes of configuration of the platform for manipulation purposes as claimed in Fig.3.3. While some links are used as platform for locomotion, others are used simultaneously for manipulation. In all configuration modes for manipulation, while links 2 and 3 are used for manipulation, the pair of base links can provide motion equivalent to a turret joint of the manipulator arm.


Experiments were performed in order to demonstrate the claim that the actuator strength capacity for manipulation purposes dramatically increases due to the hybrid nature of the mechanical structure. The end-effector load capacity for different manipulation configurations was also evaluated. The graph shown in Fig. 6.18 describes the load capacity of the end-effector for each manipulation configuration. Among the
configurations shown in this figure, other configurations can be generated in the range of
the configurations shown, such as vertical or horizontal reach. In some of the cases, the
limiting factor in testing the end-effector payload capacity was the robot’s ability to
sustain structural stability (tilt due to the heavy payload at the end-effector). In other
cases, joint torques T₂ and T₃ of links 2 and 3, respectively were the limiting factor to
sustain a given payload at the end-effector for a given configuration for manipulation
purposes.

As seen from the graph in Fig. 6.18, for a given torque capacity in joint 1,
configuration (d) is optimal with a maximum payload capacity of ~61 Kg (~135 lbs) due
to its dramatically greater resistance to tip–over instability. This payload capacity can be
increased if joint 1 torque capacity is increased. The end-effector load capacity with
configuration (a) is the least due to the robot’s tendency to tip forward (tip–over
instability) beyond a load of ~14 Kg (~31 lbs).

For greater payload requirements, depending on the required level of mobility,
either of configurations (b), (c) and (e) can be employed. In each of these configurations
a payload of ~30 kg (66 lbs) can be manipulated by the robot. These load capacities are
limited by the joints capacity rather than the robot’s tip–over stability, but they can be
increased if joint 1 and joint 2 torque capacities are increased. It is also observed that this
actual load capacity measurement exceeds the capacity evaluated from the simulations
performed in Subsection 4.2.4 (~20 kg).

For this robot compact size and weight, these load capacities and configurations
cannot be achieved with any of the existing mobile robots. This result is a direct
consequence of the novel design paradigm – namely, the hybrid nature of the platform and manipulator arm and their ability to be interchangeable in their roles.

**Fig. 6.18:** Configurations for manipulation.
6.14.2 Adaptive Manipulation

As discussed in the previous section, the end-effector load capacity with configuration (a) shown in Fig. 6.18 is the lowest due to the robot’s tendency to tip forward beyond a load of 14 Kg (~31 lbs). Tip-over instability becomes even more dominant for a given load when links 2 and 3 further extend forward without touching the ground (Fig. 6.19(a)). In such cases, the hybrid robot structure will readjust its configuration automatically. Namely, when the system feels that it loses the balance, the platform re-locates its COG to provide or compensate for the required counter moment.

This adaptive manipulation process is depicted in Fig. 6.19, and the steps involved are as follows:

(i) The robot tries to lift a load with the gripper mechanism (a);
(ii) The base link tracks rotate $180^\circ$ to provide the counter-torque until they touch the ground (b)–(e);
(iii) The robot lifts the object with its new configuration (f).

It is interesting to observe that the robot’s motion steps from configuration (a) to configuration (f) shown in Fig. 6.19, are equivalent to the robot automatically changing its configuration from its “weakest” (easily loses the balance) as shown in Fig. 6.18(a) to its “strongest” (structurally more robust to tip-over instability) as shown in Fig. 6.18(d). Consequently, according to the graph shown in Fig. 6.18, the robot is automatically increasing its end-effector capacity from 14 Kg (~31 lbs) to 61 Kg (~135 lbs).

This adaptive manipulation capability is a direct outcome of the novel design paradigm – namely, the hybrid nature of the platform and manipulator arm and their ability to be interchangeable in their roles.
Fig. 6.19: Adaptive manipulation configuration steps.
6.15 Robot DOF Speed Runs Testing and Measurement

Various speed run tests were performed in order to measure the speed capacity of each of the mobile robot’s degrees of freedom with and without loads. The results are summarized and tabulated in Table 6.1. These speed capacities can be further increased with adjustments to the motor’s pulse width modulation (PWM) control.

Table 6.1: Robot DOF Speed Measurements.

<table>
<thead>
<tr>
<th>Degree of Freedom</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform FWD/BKWD motion</td>
<td>up to 1m/sec</td>
</tr>
<tr>
<td>Platform rotation</td>
<td>36 deg/sec</td>
</tr>
<tr>
<td>Link 1 rotation about joint 1</td>
<td>30 deg/sec</td>
</tr>
<tr>
<td>Link 2 rotation about joint 1</td>
<td>52 deg/sec</td>
</tr>
<tr>
<td>Link 3 rotation about joint 2</td>
<td>52 deg/sec</td>
</tr>
<tr>
<td>Gripper wrist rotation about joint 3</td>
<td>15 deg/sec</td>
</tr>
<tr>
<td>Gripper open/close</td>
<td>8 deg/sec</td>
</tr>
</tbody>
</table>
CHAPTER 7

CONCLUSIONS

7.1 Summary

This research has primarily contributed to the field of mobile robotics for field operations and rough terrain applications. The research results provide major contributions in terms of utility and functionality for applications such as planetary explorations, defense, security, search and rescue, reconnaissance, etc.

The new mobile robot design paradigm presented in this dissertation is based on physical hybridization of the mobile platform and manipulator arm as one entity to provide functionality of locomotion as well as manipulation. The novel design was derived from a function-oriented analysis of the state-of-the-art in design of mobile robots for field operations. The new approach along with other design characteristics inherent in mobile robots, provide solutions to a series of mobility and manipulation issues related to operation of mobile robots over rough terrain and in hazardous environments as well as in urban indoor and outdoor environments. Hence, the proposed design approach provided a systematic and practical development method that addressed the overall system’s field operation performance requirements. The mobile robot development outlined in this thesis does not only improve the designers’ view of the design approach, but also allow novel design concepts with potentially better configurations.
To analyze the overall robotic system, a virtual prototype of the complete robotic system was developed in ADAMS for multi-body dynamic motion simulations. The simulations have been used to study the mobility characteristics through animations of tasks performed in various virtual environments (e.g., stairs, ditches, obstacles, etc.); to analyze various subsystems and derive their optimal operating parameters; to define joint torque requirements for different mobility tasks; and to define maximum end-effector payload capacity for different robot manipulation configurations. The modelling and analysis that helped to derived optimal design parameters, were found to considerably reduce the physical prototype development time and cost.

This dissertation also presented new control architecture and its hardware implementation in Chapter 5. The architecture is for an on-board inter-segmental wireless communication network among the robot’s actuators and sensors. This architecture provides a simple yet very effective solution to avoid cables and slip-ring mechanical connections between different parts of the mechanical system. This approach, along with independent power source for each subsystem (link), results in modular control architecture that also provides operational fault tolerance. The modularity also increases the functionality of the mobile robot by providing continuous rotation of each link constituting the hybrid mobile robot. Furthermore, design of high current discharge Li-Ion battery packs that provide an independent power source subsystem for each of the hybrid robot links was developed and successfully tested. The designed power source exhibits extensibility and modularity characteristics. These design characteristics enables easy expansion and reconfiguration of the power system to easily suite the power needs of mobile systems in terms of size, load capacity and
electrical performance. According to the tests performed, the electrical performance of the designed power subsystem is advantageous considering the very compact size of the battery pack.

Extensive tests were performed to assess the robot’s overall mobility and durability characteristics as thoroughly presented in Chapter 6. The tests were performed on an obstacle course that consisted of various test rigs including man–made and natural obstructions as a representative subset of the robot possible hindrances to cross country movement. The entire range of the hybrid mobile robot’s locomotion and manipulation modes, such as those shown in Figs. 3.2 – 3.4 and Figs. 4.3 – 4.12 and more, were successfully experimented and validated in Chapter 6.

Figs. 6.1 and 6.2 show how the different links constituting the hybrid mobile robot system can be used for both locomotion and manipulation purposes in several modes of operation (as discussed in Subsection 3.1.2). These functions of locomotion, manipulation and hybrid locomotion and manipulation have been utilized to demonstrate a large variety of unique and very challenging practical tasks the mobile robot was able to perform, unlike the state-of-the-art. Some tasks (Figs. 6.4 – 6.16) include: traversing tall cylindrical obstacles (up to 0.6 m); climbing and descending stairs (variety of slopes, materials, and sizes); climbing and descending tall obstacles (up to 0.75 m); crossing ditches (up to 0.7 m); lifting (up to 61 Kg or 135 lbs) and carrying (at least 187 Kg or 410 lbs) tasks; and tasks that require simultaneous manipulation and climbing/descending of obstacle. The hybrid mobile robot’s versatile and agile functionality has also shown the ability to traverse rubble piles (Fig. 6.17), which also demonstrate the durability characteristics of the new design paradigm. The robot’s
articulated structure had also demonstrated a unique ability to provide adaptive manipulation autonomously. Namely, to automatically change its links configuration (COG location) and thereby increasing its resistance for tip–over instability as shown in Fig. 6.19.

The proposed research provided solutions to a series of major issues related to design and operation of mobile robots operating on rough terrain. The proposed paradigm for mobile robot system design leads to locomotion and manipulation functionalities and capabilities that far exceed those of state-of-the-art existing systems, through the following major contributions:

- New mobile robot design paradigm based on hybridization of the mobile platform and manipulator arm:
  - Results in a hybrid mechanism that provides locomotion and manipulation capability interchangeably, both simultaneously;
  - Simpler, compact and robust structure; significant weight reduction; and significantly higher end-effector payload capability compared to any of the existing mobile robotic systems.

- New design specifications that significantly enhance the mobile robot’s overall locomotion and manipulation functionalities and operation on rough terrain:
  - Deploy/stow the manipulator from either side of the platform;
  - Links that provide continuous rotation;
  - Joints with passive wheels for enhanced locomotion/traction;
  - Robot accessories embedded without protruding;
- Fully symmetric structure that eliminates the need for active means for self-righting;
- Embedded interchangeable track tension & suspension mechanism;
- Rounded & pliable side covers that prevent immobilization and absorb energy.

Novel control hardware architecture with on-board wireless sensor/actuator interfaces that includes designs of:
- Flat antennas embedded in the side covers for data & A/V RF;
- Extensible and modular signal/power distribution PCB’s;
- High current discharge Li-Ion battery packs;
- Multi-DOF OCU to simultaneously control robot DOF;

7.2 Future Research

The following directions could be pursued for the future enhancement of the present research in terms of fully or partial (function specific) autonomous operation and redesign features related to the implementation of the new design paradigm:

- Develop control algorithms and sensing techniques that allow the hybrid mobile robot system to operate autonomously in unstructured environments. The control algorithm may be based on a library of the basic locomotion and manipulation functions of the hybrid mobile robot (Figs. 6.1 – 6.2) that could be automatically executed in a certain sequence to autonomously perform various rough terrain operational tasks.
- Improve some of the design features related to the implementation of the new design paradigm, such as:
- Redesign the data RF flat antennas to allow omnidirectional power radiation;
- Redesign the gripper mechanism by adding a roll degree of freedom in addition to the existing degrees of freedom;
- Redesign the system for overall weight and size reduction such that the mobile robot will be carryable by one person (i.e., backpackable).
REFERENCES


[19] Engineering Services Inc., Toronto, ON, Canada. Website: www.esit.com


## Appendix A

### Hybrid Mobile Robot Specifications

<table>
<thead>
<tr>
<th>Platform</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Height</strong></td>
<td>1</td>
<td>17.9 cm (Arm stowed); 190.2 cm (Arm vertical)</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>2</td>
<td>62.6 cm</td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>3</td>
<td>81.4 cm (Arm stowed); 207.2 cm (Arm horizontal)</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>4</td>
<td>65 kg</td>
</tr>
</tbody>
</table>
| **Speed** | 5 | On a flat ground: 1 m/sec max  
On a slope: 1 m/sec max  
On a stairway: 1 m/sec max |
| **Environment** | 6 | All-weather, All-terrain; Stair climbing 45 deg;  
Obstacles 70+ cm; Manoeuvres over gravel, snow, mud, sand, high grass |
| **Number of tracks** | 7 | Two tracks (width 100mm each) |
| **Number of motors** | 8 | 6 – 2 for tracks (link 1); 2 for arm (links 2 & 3); 2 for wrist-gripper |
| **Electronics** | 9 | Micro-processor control; abundant in RAM |
| **Standard sensors** | 10 | Temperature, inclinometer, compass, battery |
| **Payload** | 11 | 200+Kg |
| **Battery** | 12 | 2 – 4 hours |
| **Communication** | 13 | RF – 200m LOS; Video 2-way 2.4GHz video (1.7, 1.4 available); Data 1-way 900MHz;  
Computer and sensor communication ports |
| **Cameras** | 14 | 2 wide angle cameras |
| **Lights** | 15 | 2 high-light LEDs |
| **Transportation** | 16 | Portable by two people |

<table>
<thead>
<tr>
<th>Manipulator</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reach</strong></td>
<td>18</td>
<td>190.2cm vertically; 207.2cm horizontally</td>
</tr>
<tr>
<td><strong>Payload full-ext</strong></td>
<td>19</td>
<td>10Kg</td>
</tr>
<tr>
<td><strong>Joints/Links</strong></td>
<td>20</td>
<td>6 – 2 for link 1 (tracks); 2 for links 2 &amp; 3; 2 for wrist and gripper</td>
</tr>
<tr>
<td><strong>Dexterity</strong></td>
<td>21</td>
<td>Can be extended to 3-DOF wrist + gripper</td>
</tr>
<tr>
<td>OCU</td>
<td>Size</td>
<td>22</td>
</tr>
<tr>
<td>-----</td>
<td>------</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Monitor</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Panel</td>
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</tr>
<tr>
<td></td>
<td>Duration</td>
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</tr>
<tr>
<td></td>
<td>Software</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Communication</td>
<td>28</td>
</tr>
</tbody>
</table>