Virtual Prototype Development and Simulations of a Tracked Hybrid Mobile Robot

Pinhas Ben-Tzvi [a], Cyrus Raoufi [a], Andrew A. Goldenberg [a], and Jean W. Zu [b]

[a] Robotics and Automation Laboratory, [b] Vibration and Computational Dynamics Laboratory
Department of Mechanical and Industrial Engineering, University of Toronto
5 King's College Rd., Toronto, ON, Canada M5S 3G8

Abstract— **This paper presents the process of virtual prototype development and simulation results for a novel tracked hybrid mobile robot that was designed based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. The novel mechanical design paradigm is analyzed with the aid of a virtual prototype that was developed with Adams Software along with Adams Tracked Vehicle (ATV) Toolkit for multi-body dynamic motion simulations of the complete robotic system. The simulation results were used to study the robot's mobility characteristics through animations of different possible tasks that require various locomotion and manipulation capabilities. The ability to visualize and validate various robot mobility cases and to study its functionality in the early design stages aided in optimizing the design and hence dramatically reduce physical prototype development time and cost. The design optimization process also involved optimal weight optimization and proper component selection. Moreover, the simulations enabled us to define motor torque requirements and maximize end-effector payload capacity for different robot configurations. Visualization of the mobile robot on different types of virtual terrains such as flat roads, obstacles, stairs, ditches, and ramps, helped in determining the mobile robot's expected performance and specify optimal specifications in the early design stages and ongoing construction of the first physical prototype.**

Index Terms— **Mobile Robot, Virtual Prototype, Dynamic Simulations, Animations**

1. INTRODUCTION

Virtual prototyping is gaining popularity as an effective tool to reduce time to market and hence the cost to design and manufacture new products. Physical prototyping, although is more desirable because of its tangible nature, can often be time consuming and expensive. Companies, especially in the automotive and aerospace industries, are extensively depending on the virtual prototyping process in initial stages of the design and development of physical prototypes leading to a commercial product. In many cases, virtual prototyping has been able to significantly reduce the amount of physical testing required.

Nowadays, due to the wide use of Computer Aided Design (CAD) tools in the design process, sufficient product data is digitally available. This provides a good basis for evaluating the design in a virtual environment using various Computer Aided Engineering (CAE) tools. The CAD models can be transferred to various CAE tools for evaluation of different aspects of the design such as kinematics and dynamics, structural mechanics, system control, etc. While the CAD model will only represent the real product, the CAE model will also behave like it.

The virtual prototyping process can facilitate conceptual design [1] by helping the designer to visualize the functionality and study the quality of the design. The designers can tryout various design changes on the virtual prototype and see their effects on the dynamic behavior of the virtual prototype even before building the physical prototype. Although virtual prototyping cannot in general completely replace the physical prototyping process, it can greatly reduce the cost of physical prototyping and the physical testing that would be required later on.

In this paper, we present the application of virtual prototyping to the design, development and optimization of a novel design of a tracked mobile robot.

Tracked mobile robots equipped with a manipulator arm are used for various operations such as reconnaissance, search/rescue operations [2], handling of hazardous materials, manipulation of objects, etc. The mobile robot using its track system is generally capable of negotiating various types of terrains such as stairs, slopes, obstacles, ditches, rubble pile, pipelines, etc. Therefore, there is a need to extensively test the mobile robot to study its performance on various types of terrains.

Typically, a mobile robot's structure consist of a mobile platform to propel the robot with the aid of tracks, wheels or legs, and a manipulator arm attached on top of the mobile platform to provide manipulation capability (neutralize bombs or landmines, manipulate hazardous materials, etc). However, the presence of an arm limits the robot's mobility. On the other hand, there are several designs of mobile robots with enhanced mobility capability such as PackBot [3] and LMA [4] but not if equipped with a manipulator arm. This gap is bridged in our approach by providing a new mobile robot design that provides locomotion and manipulation capabilities simultaneously and interchangeably.

The new design paradigm is based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. The paradigm is that the platform and manipulator are interchangeable in their roles in the sense that both can support locomotion *and* manipulation.

With the aid of Adams Software, we developed a functional virtual prototype of the hybrid mobile robot design

presented in this paper without having to wait until the construction of a physical prototype. With the virtual prototype we were able to validate the functionality of the mobile robot in the conceptual design stage and improve the design based on the feedback from the simulation results to yield an optimized final design. The VP was tested on various virtual terrains to assess the robot's functionality, and make necessary design changes much earlier in the design process. By adopting this approach, fewer changes were required in the physical prototyping stage and hence saved valuable time and cost.

2. CONCEPTUAL DESIGN PARADIGM

In this section we present the novel design approach for a mobile robot where the mobile platform and the manipulator arm are one entity rather than two separate and attached modules. In other words, the mobile platform is used as a manipulator arm and vice versa. This way, the same joints (motors) that provide the manipulator's dof's, also provide the mobile platform's dof's.

2.1 Concept Embodiment

Fig. 1 depicts the embodiment of the proposed idea. If the platform is inverted due to flip-over, the symmetric nature of the design (Fig. 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 base link tracks, link 2, link 3 and two wheel tracks. Link 2 is connected between the two base link tracks via joint 1 (Fig. 1(b)). Two wheel tracks are inserted between links 2 and 3 and connected via joint 2 (Fig. 1(b)). The wheel tracks are used to support links 2 and 3 when used as part of the platform while touching the ground. Both links 2 and 3 are revolute joints and are able to provide continuous 360° rotation.
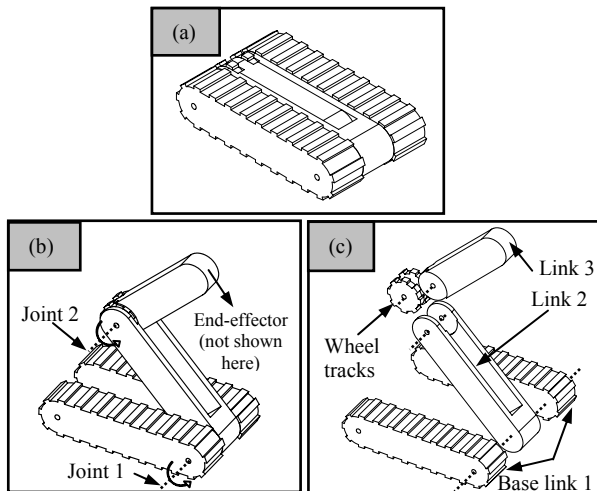

Fig. 1 (a) closed configuration; (b) open configuration; (c) exploded view.

The links can be used in three modes: (i) all links used for locomotion to provide added level of manoeuvrability and traction; (ii) all links used for manipulation to perform various tasks; (iii) combination of modes 2 and 3 – 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 paradigm.

2.2 Manoeuvrability, Traction and Manipulation

Fig. 2(a) 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, and also enables the robot to climb taller objects (Fig. 2(b)). Link 2 is also used to support the entire platform when moving is a tripod configuration while using the other links for manipulation (Fig. 2(c)). For enhanced traction, the articulated nature of the mobile platform allows it to be adaptable to different terrain shapes and ground conditions (Fig. 2(d)).
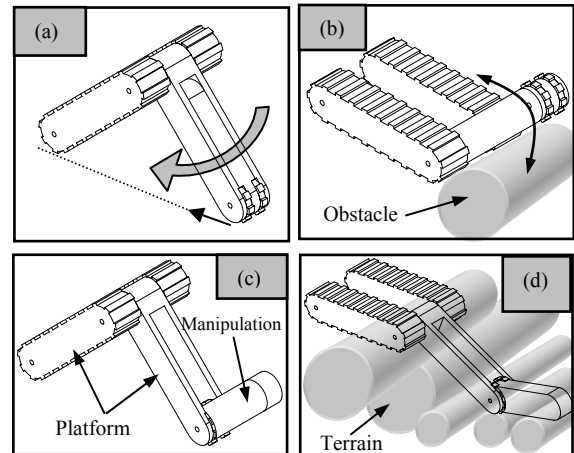

Fig. 2 (a),(b) mobility configurations; (c) manipulation configuration; (d) configuration for enhanced traction.

3. MECHANICAL DESIGN ARCHITECTURE

The mechanical architecture of the mobile robot shown in Fig. 3 embodies the conceptual design paradigm as described in Section 2. Excluding the end effector, the design includes four motors (including gearhead); two are situated at the back of each base link track and the other two at the front. The motor at the back of each base link track provides propulsion to the track attached to it. The motor at the front of the right base link propels link 2 and the motor at the front of the left base link track propels link 3.

The design also includes a built-in dual-operation track tension and suspension mechanism situated in each of the base link tracks. It includes spring suspended supporting planetary pulleys; three situated at the bottom of each track and another three at the top. While the bottom three

supporting pulleys 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. This dual operation track suspension and tension system accounts for the symmetric 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.
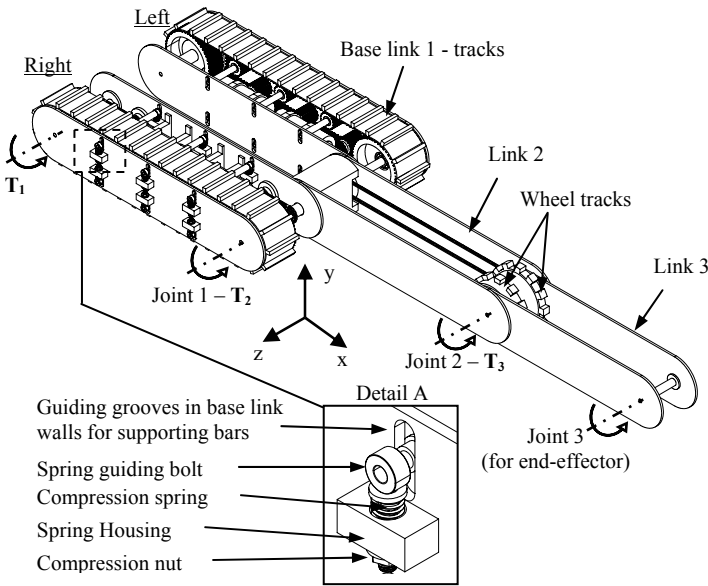

Fig. 3 Open configuration of the mobile robot.

4. MODELING AND DYNAMIC SIMULATIONS OF THE ROBOTIC SYSTEM

Dynamic simulations of the complete robotic system were performed in order to study its functionality and demonstrate its capability. The 3D mechanical design assembly of the concept that was developed with I-DEAS CAD Software was exported to ADAMS software [5] in order to perform motion simulations. The process of setting up a virtual prototype in ADAMS and the details and results of the simulations performed are thoroughly described in the following subsections.

4.1 Virtual Prototyping and Simulations Using ADAMS Software

When designing a mechanical system such as this hybrid robot, it is required to understand how various components interact as well as what forces those components generate during operation. ADAMS is commercial motion simulation software for analyzing the behavior of complex mechanical systems. It allows testing virtual prototypes and optimizing

designs for performance, without having to build and test physical prototypes. This dramatically reduced our product development time and cost. The process of virtual product development is described in the diagram of Fig. 4. 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 optimization, proper component selection (springs for belt tension and suspension system; motor torque requirements for different mobility tasks), proper gear ratios selection and 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.
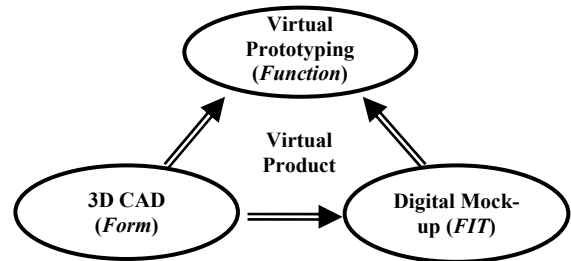5) Improve product quality by exploring design variations to optimize full-system performance.

Fig. 4 Virtual product development diagram.

4.2 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 [6],[7],[8]. A modus operandi using ADAMS along with its ATV Toolkit has been used to build the tracks [9],[10]. 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. 5. 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.

4.3 Simulations and Postprocessing

The data pertaining to each simulation performed was processed for the following specific major purposes, which will be discussed in detail in subsequent subsections: (i) show animations of different possible tasks requiring various locomotion and manipulation capabilities in order to study the robot's mobility characteristics; (ii) define each joint's torque requirements for different mobility tasks given constant angular velocity and then select proper gear ratios and motors; and (iii) define maximum end-effector payload capacity for different robot configurations by examining the COG vertical location with respect to the ground.

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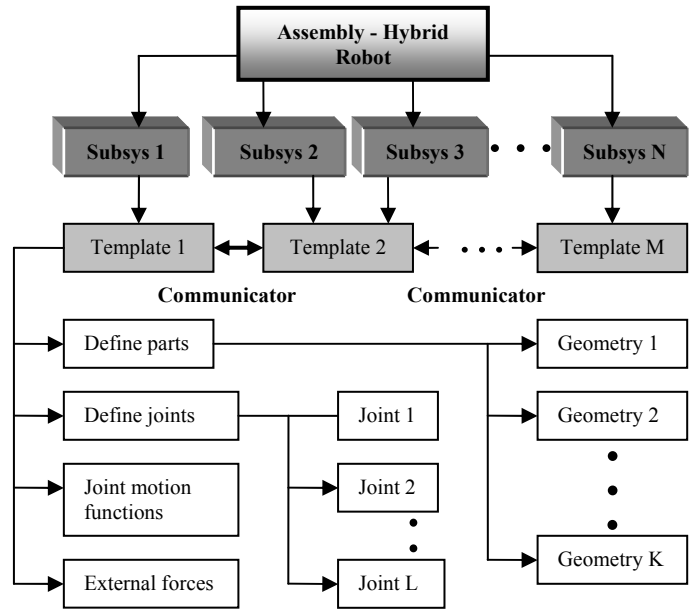

Fig. 5 ADAMS virtual prototype model structure.

5. SIMULATION RESULTS AND DISCUSSION

5.1 Animation Results

The following simulations have been performed for the purpose of studying robot's functionality: various manipulation scenarios, flipping over due to a ramp obstacle, traversing pipes of different diameters, rectangular obstacle climbing and descending with different configurations, ditch crossing with different gap dimensions, stair climbing and descending, lifting tasks and more. To illustrate the robot's functionality, several of the above mentioned simulations are presented in Figs. 6-10. Fig. 6 shows several possible configuration modes for manipulation purposes.
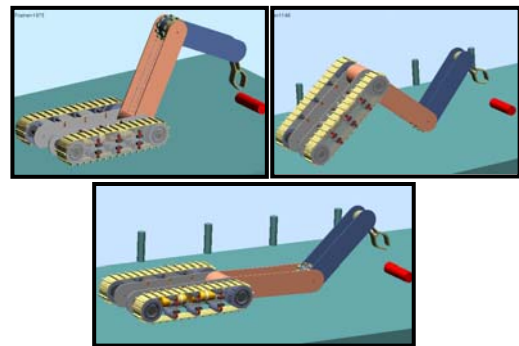

Fig. 6 Configurations for manipulation.

Fig. 7 shows a series of motions that different links along with the tracks need to undergo in order to climb stairs. The steps are as follows: the base link tracks are first deployed until they touch the stairs (a); link 2 is closed and the robot starts climbing with tracks (b); at the end of the stairs link 3 opens (c) to support the platform while the robot is in motion until position (d); link 3 rotates (until closed) to lower the robot until the tracks are in full contact with the ground.
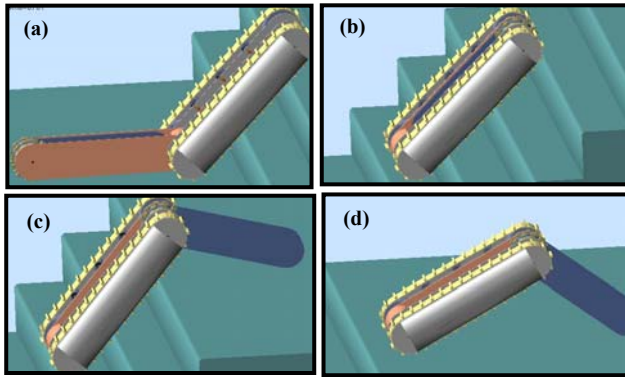

Fig. 7 Stair climbing.

Fig. 8 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.
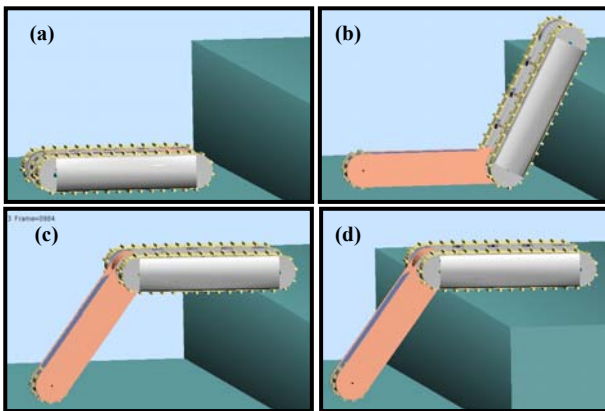

Fig. 8 Step obstacle climbing with tracks.

The segmented nature of the robot's structure allows it to surmount circular obstacles such as pipes and tree logs. Fig. 9 depicts several configuration steps to accomplish such tasks as follows: the base link tracks are deployed until they touch the obstacle (a) – (b); at that point, the tracks start to propel the platform (c) while at the same time they continue their rotation about joint 1.
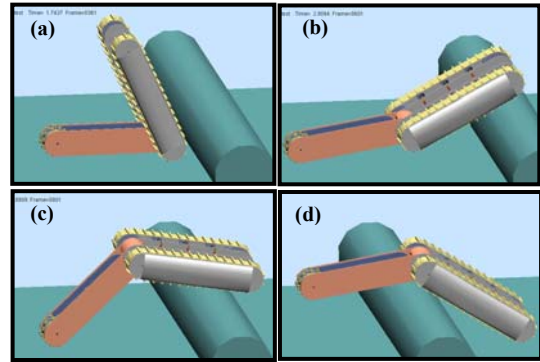

Fig. 9 Surmounting circular obstacles.

The symmetric nature of the mobile robot allows 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. 10 shows several snapshots of a simulation showing a robot stowing its links before flipping over occurs and deploying them again from the other direction after the robot flipped over.
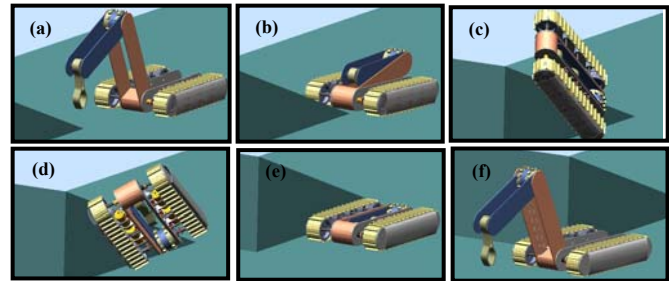

Fig. 10 Flip over scenario.

5.2 Analysis of Motors Torque Requirements

Additional dynamic simulations were performed in order to calculate the torque required in joints T_1, T_2 and T_3 (Fig. 3) to propel the tracks, link 2 and link 3 respectively for various mobility scenarios. Once the maximum torque requirement for each joint is evaluated, proper gear ratios and motors were selected. 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 by generating torque plots for several mobility scenarios that require the largest torque capacity. Based on those torque plots, the maximum peak torque and its occurrence in a given range of motion were identified. The peak torque values define the maximum torque capacity necessary for each joint. Maximum torque values of T_2=141.7[Nm] and T_3=157[Nm] were required for link 2 and link 3, respectively.

5.3 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. The graphs shown in Fig. 11 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 tip-over stability for a given end-effector load.
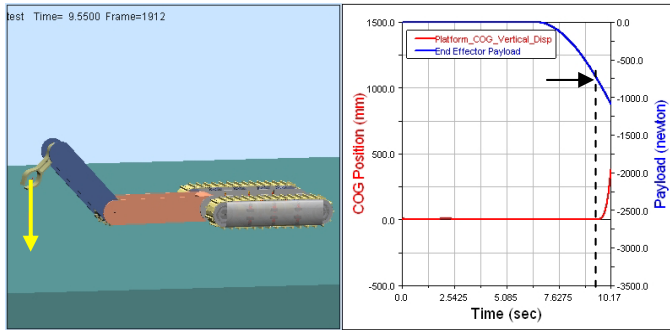

Fig. 11 Platform COG vs. load capacity.

The maximum load capacity is found from the graph in Fig. 11 at the instant when the COG position is greater than zero (dashed line). This indicates that the robot's COG starts to move vertically. According to the graph, the static load capacity with this configuration is approx. 77 kg. Practically, the maximum available torque of joints 1 and 2 will restrict the actual payload capacity.

All possible robot configurations for manipulation purposes were analyzed (such as those shown in Fig. 6). In some of the configurations, an end-effector load of ~20 kg is expected. 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.

6. CONCLUSION

This paper presented a new mobile robot design that was based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. A virtual prototype that was developed in Adams for dynamic motion simulations of the complete robotic system has considerably reduced the prototype development time and cost while aiding with demonstrating the robot's expected functionality for design optimization purposes and derivation of optimal operating parameters. The derived parameters are used in the design and construction of a physical prototype. The robotic system simulations enabled us to vary the type of analyses being performed without having to modify physical instrumentation, test fixtures, and test procedures. This way, design variations and changes were analyzed faster and at a much lower cost than physical prototype testing in order to improve product quality.

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