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Design, Simulations and Optimization of a Tracked Mobile Robot Manipulator with Hybrid Locomotion and Manipulation Capabilities

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***Abstract*—This paper presents a new mobile robot design based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. The novel mechanical design is described in detail. To analyse the design, a virtual prototype tool was developed with ADAMS Software 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 proper components selection. Moreover, the simulations enabled us to define motor torque requirements and maximize end-effector payload capacity for different robot configurations.**

***Index Terms*—mobile robot manipulator, hybrid mechanism design, virtual prototyping, dynamic simulations.**

I. Introduction

The field of mobile robotics is growing very rapidly in numerous applications. In the past decade, new designs of mobile robots have been demonstrated by both academia and industry. A review of several existing mobile robot designs indicates that good performance was demonstrated in some applications based on their available functionality. However, there still exist challenges that need to be addressed in the context of small Mobile Robots for Unmanned Ground Vehicle (UGV) in field operations.

In the aftermath of September 11, 2001, mobile robots have been used for USAR (Urban Search and Rescue) activities [1] such as searching for victims, searching paths through the rubble that would be quicker than to excavate, structural inspection, detection of hazardous materials. Among the tracked robots that were used (such as Inuktun's Micro-Tracs and Foster-Miller's Talon), the capability was limited in terms of locomotion and mobility, and more so if one considers any 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 [1].

Increasingly, mobile robotic platforms are being proposed in rough terrain and 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 traction, leading to entrapment, and loss of stability, leading to flip-over, may occur, which may result in mission failure.

This work presents a new approach to mobile robot design for locomotion and manipulation purposes in a sufficiently 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. 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 [2] and Chaos [22] including the ability to return itself when flipped-over, but this may not be possible if the robot is equipped with a manipulator arm. We bridged this gap by providing a new approach of mobile robot design that provides locomotion and manipulation capabilities simultaneously and interchangeably.

The new design approach is based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. The approach is that the platform and manipulator are interchangeable in their roles in the sense that both can support locomotion *and* manipulation in several configuration modes as discussed in Section III B. Such a robot is expected to adapt very well to various ground conditions to achieve good performance for various missions for military, police and planetary exploration applications.

There are numerous good designs of tracked mobile robots such as PackBot [2], Remotec-Andros robots [3],[4], Wheelbarrow MK8 [5], AZIMUT [6], LMA [7], Matilda [8], MURV-100 [9], Helios robots [10]–[13], Variable configuration VCTV [14], Ratler [15], MR-5 and MR-7 [16], NUGV [17], and Talon by Foster Miller [18]. Some legged robots [19] 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 capability.

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II. Issues, Related Research Problems, and Solutions

A detailed literature review and discussions with users has assisted us in identifying major issues of design of mobile robots used in field operations. The issues that have led to the new design and the related research problems and solutions are briefly defined below:

1) Issue: In current designs the 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.

Research problem: Each module contributes separately to design complexity, weight, and cost.

Approach to solution: The manipulator arm and the mobile platform are designed as one entity rather than two separate modules. The mobile platform is part of the manipulator arm, and the arm is also part of the platform. As fewer components are required, this approach may result in a simpler and robust design, significant weight reduction and lower production cost.

2) *Issue*: In all cases where the mobile robot includes a manipulator arm, it is mounted on top.

Research problem: The arm is exposed to the surroundings and therefore is susceptible to breakage and damage especially when a flip-over occurs.

Approach to solution: The main feature of the design is that the arm and platform are designed as one entity, and the arm is part of the platform. This eliminates the exposure of the arm to the surroundings while the robot is heading to a target perhaps in close or narrow areas. As soon as the target is reached, the arm is deployed to execute desired tasks.

3) *Issue*: When operating over rough terrains, robots often reach positions from where they could not be righted /controlled further for a purpose. Some designs provide various active means to self-righting using the arm.

Research problem: To provide self-righting without special purpose active means.

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

III. Description of the Design Concept

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 modules. In other words, the mobile platform can be used as a manipulator arm and vice versa. Thus, the same joints (motors) that provide the manipulator's dof's also provide the platform's dof's.

2) Enhance the robot's mobility 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. When a flip-over takes place, it will only be required to command the robot to continue to its destination from the current position.

A. Concept Embodiment

To demonstrate the concept, Fig. 1 depicts a possible 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 (motion direction of the tracks needs to be changed). Also it is able to deploy/stow the manipulator arm from either side.

The platform includes two identical and parallel base link 1 tracks that are fixed to the ends of one common stationary shaft located in joint 1, link 2, link 3, end-effector and passive wheels. 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. 1(b)). 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 (Fig. 1(c)).

The passive wheels are used to support links 2 and 3 when used for various configuration modes of locomotion. Link 2, link 3 and the end-effector are connected through revolute joints and are able to provide continuous 360^{o} 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. 1(a).

B. Configuration Modes of Operation

The links can be used in three modes:

1) All links used for locomotion to provide added level of maneuverability and traction;
2) All links are used for manipulation to provide added level of manipulability. The base links can provide motion equivalent to a turret joint of the manipulator;
3) 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 design.

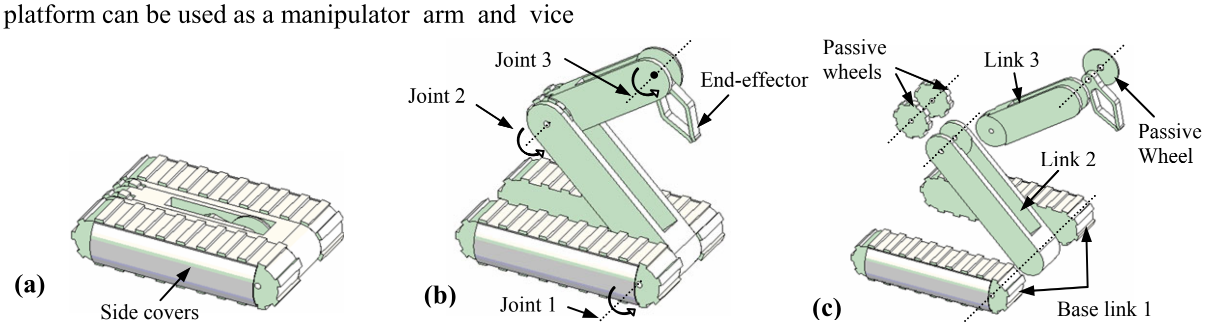

Fig. 1 (a) closed configuration; (b) open configuration; (c) exploded view.

All three modes of operation are illustrated in Figs. 2, 3 and 4. In the proposed design, the motor(s) used to drive the platform for mobility are also used for the manipulator arm due to the interchangeability of functions between the links.

C. Manoeuvrability

Fig. 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. 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. 2(c)).

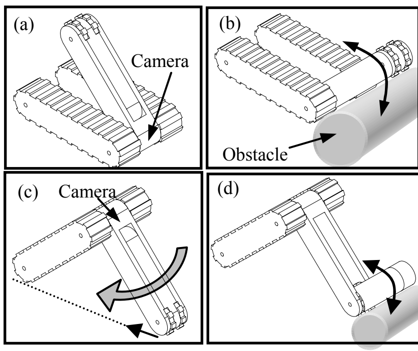

Fig. 2 Robot configurations for mobility/climbing purposes.

D. Traction

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

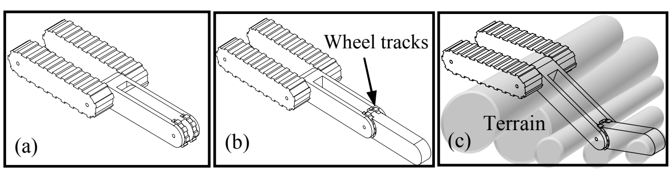

Fig. 3 Configurations for enhanced traction.

E. Manipulation

Fig. 4 depicts different configurations of the platform for manipulation purposes. While some links are used as platform others are used simultaneously for manipulation. Configuration (c) is similar to configuration (b) in terms of manipulation capabilities; however, configuration (b) is optimal for enhanced traction since the contact area between the platform and the ground is maximized. Configuration (c) is useful for increased manoeuvrability since the contact area between the platform and the ground is minimized.

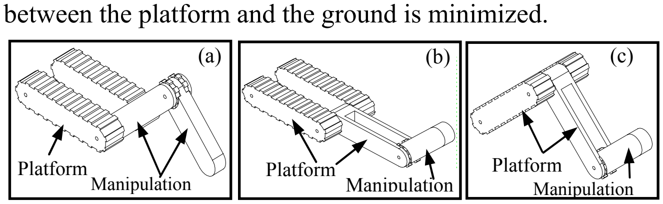

Fig. 4 Configurations for manipulation.

IV. Mechanical Design Architecture

The mechanical design architecture of the mobile robot shown in Fig. 5 embodies the conceptual design as described in Section III–A. 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 Subsection C. The closed configuration of the robot is fully symmetric.

A. Motors Layout

Excluding the end effector, the design includes four motors; 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. Both motors at the back together provide the mobile robot's translation and orientation in the plane of the platform. 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 (Figs. 5 and 6). All link motors are situated at the base to maintain the entire structure's COG close to the ground.

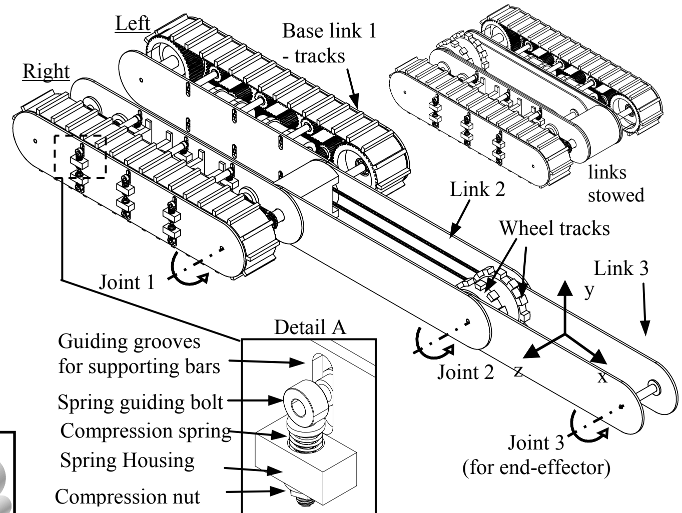

Fig. 5 Open configuration of the mobile robot.

B. Base link 1 - Tracks

The right and left base link tracks are identical in terms of the internal driving mechanisms although the mechanism situated at the front of each base link track drives a different link. All electrical hardware is situated in the left and right base link tracks. Motors and associated electrical hardware for the gripper mechanism are situated in link 3.

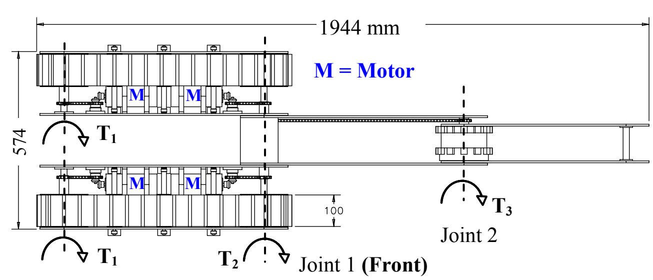

Fig. 6 Open configuration (top view – all dimensions in mm).

C. Built-in track tension and suspension mechanism

The arrangement of the supporting planetary pulleys is shown in Fig. 7. Each of the supporting pulleys is mounted on a supporting bar that is connected at each end to a compression spring (Fig. 5–Detail A). 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. 7. 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 suspension and tension role between the pulleys is switched.

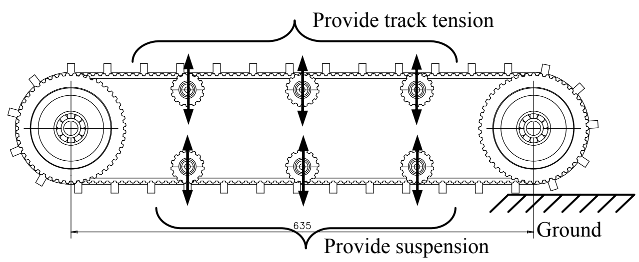

Fig. 7 Pulley arrangement and track tension and suspension mechanism.

The total estimated weight of the robot is 65 [Kg]. The height is 179 [mm] and some other general dimension are provided in fig. 6. A fully loaded depiction of the complete mobile robot system is shown in Fig. 8.

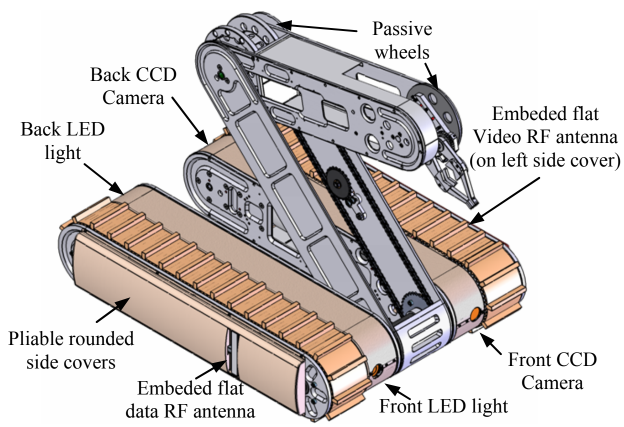

Fig. 8 Detail design assembly of the entire robotic system.

V. MODELLING AND SIMULATIONS OF THE ROBOTIC SYSTEM

Dynamic simulations of the complete robotic system were performed in order to study its functionality and optimize the design. The 3D mechanical design that was developed with the CAD Software was exported to ADAMS software to perform 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.

A. Virtual Prototype and Simulations Using ADAMS

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 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 simulations enabled us to visualize and validate various robot mobility cases to study its functionality and hence develop the design. The design process involved identification of optimal link weights, proper component selection (e.g., springs for track tension/suspension; motors, gear ratios), etc. The requisite for a flexible dynamics capability for the track system was addressed with ADAMS Tracked Vehicle (ATV) Toolkit. A tool using ADAMS and ATV Toolkit was developed and used to model the tracks [20],[21].

B. Simulations and Postprocessing

The data pertaining to each simulation performed was processed for the following specific major purposes that will be discussed 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 gears and motors; and (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.

VI. SIMULATION RESULTS AND DISCUSSION

A. Animation Results

The following simulations were performed for the purpose of studying the robot's functionality: various manipulation scenarios, 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, several of the above mentioned simulations are presented in Fig. 9. Each of the subfigures (a)–(d) represents several configuration steps (1)–(4) that the different links along with the tracks need to undergo in order to accomplish each task.

B. 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 done by visualizing the spring compression and expansion (different stiffness values) to verify that it meets the allowable displacements for track tension/suspension.

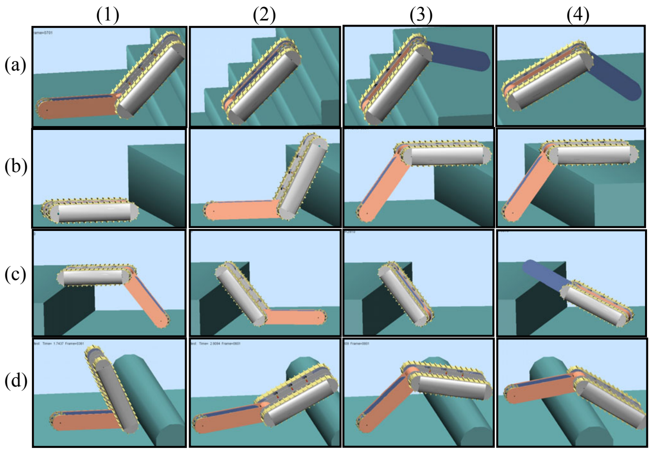

Fig. 9 Animation results: (a) stair climbing; (b) step climbing with tracks; (c) step descending; (d) surmounting tall circular obstacles.

The graphs in Fig. 10 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 face up to maintain a predetermined tension in the track system. To illustrate this, Fig. 10 shows simulation results of the robot surmounting a small obstacle to observe how the springs react to obstacles situated between the planetary pulleys.

From the top spring array force distribution (Fig. 10(a)) we observe that the average force in each spring is constant 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. 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 (Figure 10(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.

C. Analysis of Motors Torque Requirements

This section outlines the results of additional dynamic simulations performed in order to calculate the torque required in joints T_1, T_2 and T_3 (Fig. 6) 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 can be 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 are identified. The peak torque values define the maximum torque capacity necessary for each joint.

Fig. 11 shows a series of motions the different links and 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.

According to the torque plot, the torque peak value for this case occurs at the beginning of the motion ($T_2 = 141.2 N \cdot m$ at $t = 0$). A torque value of $T_2 = 141.7 N \cdot m$ was required when the climbing was performed with link 2.

Similar analysis was performed to obtain link 3 motor torque requirement (joint 2) for different scenarios and was found to be $T_3 = 157 N \cdot m$. For symmetry reasons, we defined $T_2 = T_3$ when selecting the motors.

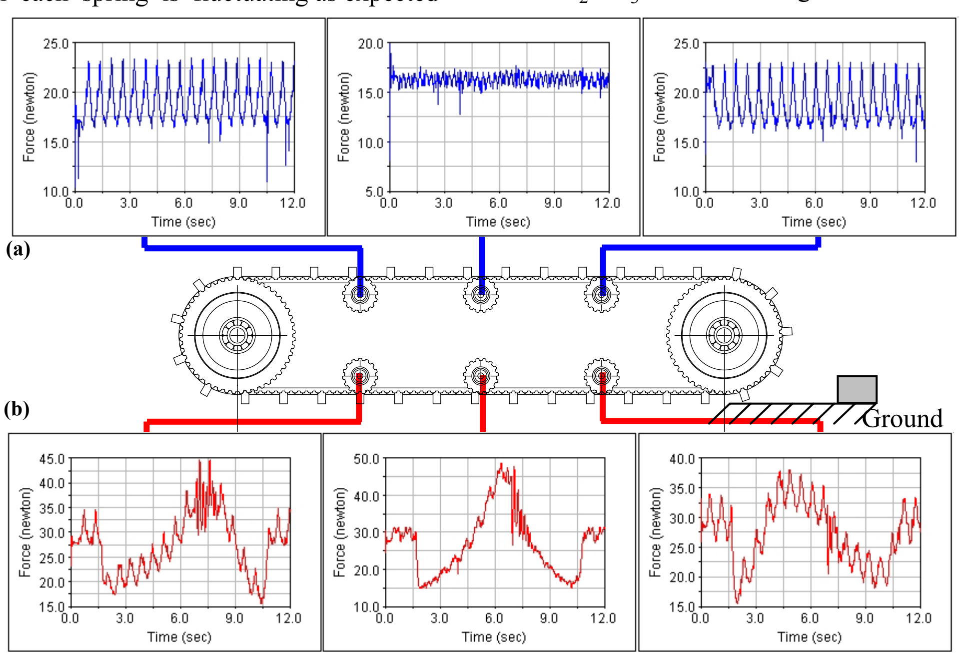

Fig. 10 Top ((a) - track tension) and bottom ((b) – suspension) spring array force distribution.

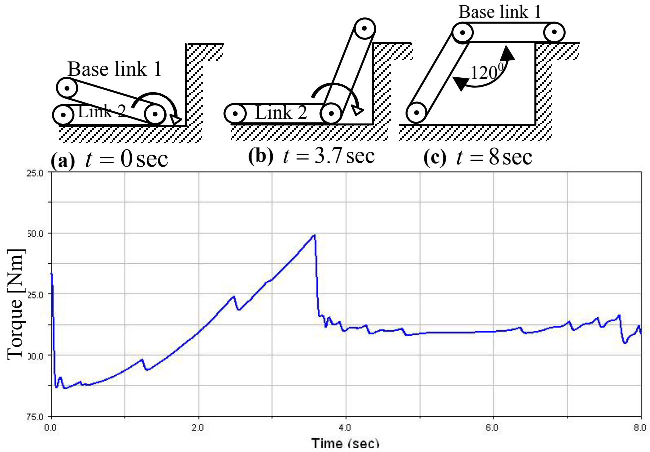

Fig.11 Link 2 motor torque requirement –obstacle climbing with tracks.

D. End-Effector Payload Capacity Analysis

The purpose of this simulation was to estimate the end-effector load 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 graph shown in Fig. 12 describes the change in the robot's COG position with respect to linearly increasing load applied at the end-effector. Among several simulation results based on various configurations, one possible optimal configuration for this purpose is shown in Fig. 12. According to the graph, the static load capacity with this configuration is approx. 77 kg. Practically, the maximum allowable torque capacity of joints 1 and 2 will restrict the actual load capacity.

Some possible configurations for manipulation are presented in Fig. 4. Additional configurations were analyzed and it was found that an end-effector load of *~20 kg* is expected with configuration (b) for instance. This result is a direct consequence of the novel design– namely, the hybrid nature of the platform and manipulator arm and their ability to be interchangeable in their roles.

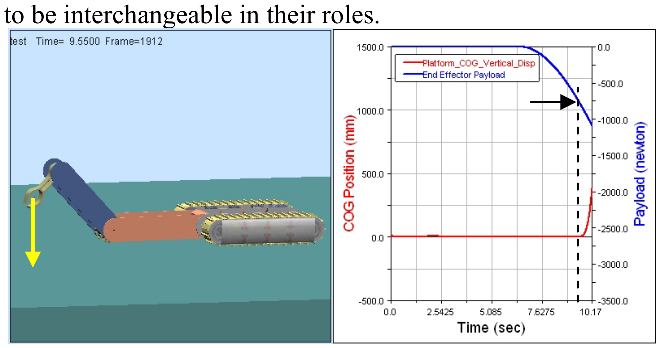

Fig. 12 Platform COG vs. load capacity.

VII. Conclusion

This paper presented a new mobile robot design was based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. To model and analyze the robotic system, a virtual prototype was developed in Adams Software for multi-body dynamic motion simulations of the complete robotic system. This has considerably reduced the prototype development time and cost and aided with derivation of optimal operating parameters. The derived parameters were used in the construction of a physical prototype.

Acknowledgment

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