Proceedings of the 2007 IEEE
International Conference on Mechatronics and Automation
August 5 - 8, 2007, Harbin, China

A Novel Control Architecture and Design of Hybrid Locomotion and Manipulation Tracked Mobile Robot

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***Abstract*—This paper presents a novel control architecture for a 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 concept of the mechanical design is described and analyzed with the aid of a virtual prototype that was developed with multi-body dynamic motion simulation software. The simulation results were used to demonstrate the robot's expected functionality and demonstrate its capability while utilizing them for design optimization and ongoing construction of the first physical prototype. Along with the novel design we focus on a novel concept for on-board RF communication among robot's joints. This paper also summarizes the qualitative and quantitative performance of the hybrid robot in terms of mobility, communication, power, sensors, and control.**

***Index Terms*—mobile robot, control architecture, RF communication, virtual prototype, simulations.**

I. INTRODUCTION

Mobile robots were used for USAR (Urban Search and Rescue) 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 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.

New designs of mobile robots have been demonstrated by both academia and industry in the past decade. An overview of several existing mobile robot designs indicates that good performance was demonstrated in some applications based on their available functionality. However, there still exist various challenges that need to be addressed in the framework of small tracked Mobile Robots for Unmanned Ground Vehicle (UGV) operations in rough terrain applications.

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]–[5], 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 [8] 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 and cumbersome designs that may significantly reduce robot's operational reliability, and also increase its cost.

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. The design approach was realized by identifying and quantifying the existing gap between the traditional structures of existing mobile robots and their range of applications. This gap is bridged in our approach by providing a new paradigm of mobile robot design that provides locomotion and manipulation capabilities simultaneously. The approach is also a new way of robot-surroundings interaction as it expects to increase the mobile robot's functionality while reducing its complexity.

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 in several modes as discussed in Section II 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 designs of mobile robots that are mainly based on wheel mechanisms, track mechanisms and the combination of both such as PackBot [3], Remotec-Andros robots [4],[5], Wheelbarrow MK8 [6], AZIMUT [7], LMA

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[8], Matilda [9], MURV-100 [10], Helios robots [11]–[13], Variable configuration VCTV [14],[15], Ratler [16], MR-1[17], MR-5 and MR-7 [18], NUGV [19], and Talon by Foster Miller [20]. Some legged robots [21],[22] are also part of the scenarios assumed herewith, but we do not cover this area in our work. Our focus is on tracked mobile robots that are capable of providing locomotion as well as manipulation. A review of several leading existing mobile robot designs based on their functionality and range of applications has indicated that the proposed paradigm is advantageous functionally, operationally, and in terms of cost.

This proposed design architecture of the hybrid robot requires that the electrical hardware and other modules such as power sources, power distribution, data communication, sensors, and control in each of the robot's links or segments constituting the mobile robot are connected wireless. This, along with independent power in each segment, eliminates the need for physical wiring and slip ring connections between the rotating segments.

The issues that have led to the new paradigm, and the related research problems and proposed solutions are briefly defined in Table I.

TABLE I
ISSUES, RELATED RESEARCH PROBLEMS, AND PROPOSED SOLUTIONS

Issue	Research problem	Proposed solution
Manipulator arm and mobile platform are separate modules	Each module contributes to design complexity, weight & cost	Manipulator arm and mobile platform are designed as one entity
Manipulator arm mounted on top	Arm susceptible to breakage and damage	Arm and platform as one entity in a symmetric design eliminates its exposure
A mobile platform without a manipulator arm has better mobility	Functionality is limited as it cannot provide manipulation capability	Arm as part of the platform eliminates its exposure to surroundings
Flip-over occurrence: invertibility vs. self-righting	To provide self-righting without special purpose active means	Symmetric platform to allow flip-over and enhance mobility
Designs with obstacle avoidance systems (e.g., avoiding falling or colliding with an object)	Issues of complexity of design, reliability and cost arise	Sometime it may be preferable to let the robot fall and roll, and continue its mission without self-righteousness in order to reach the target sooner

II. DESCRIPTION OF THE DESIGN PARADIGM

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. 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 (self-righteousness). When a flip-over takes place, it will only be required to command the robot to continue its task from the current position.

Each idea has its own advantages and each one is an idea by itself. Also, the two parts of the idea complement each other.

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. Also it is able to deploy/stow the manipulator arm from either side.

The platform includes two identical base link 1 tracks (left and right), 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(c)). The wheel tracks 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. Links 2 and 3 are connected through revolute joint and are able to provide continuous 360^{o} rotation. The robot's structure allows it to be scalable and can be customized according to various application needs.

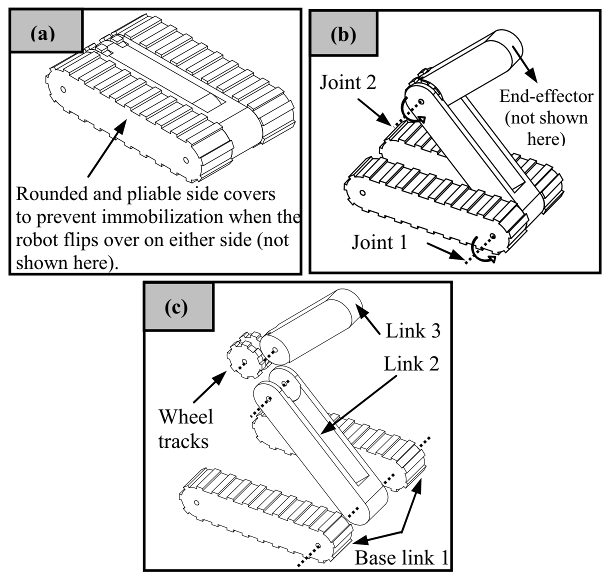

Fig. 1 (a) closed configuration; (b) open configuration; (c) exploded view.

B. 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 used for manipulation to perform various tasks;
3) 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.

All three modes of operation are illustrated in Figs. 2 – 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.

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 is a tripod configuration (Fig. 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. 2 show two different possibilities for camera use. Configuration (d) in Fig. 2 shows the use of link 3 to surmount an object while link 2 is used to support the platform in a tripod structure.

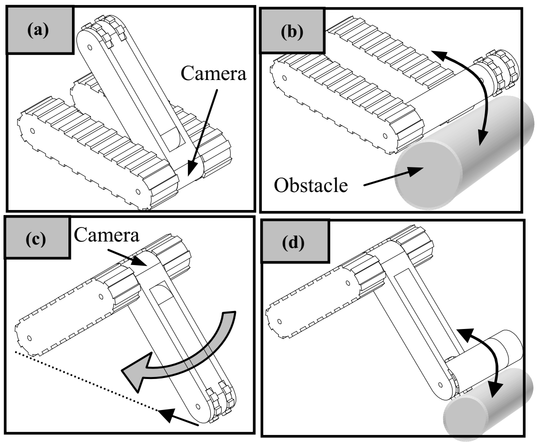

Fig. 2 Configurations of the mobile platform for mobility purposes.

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.

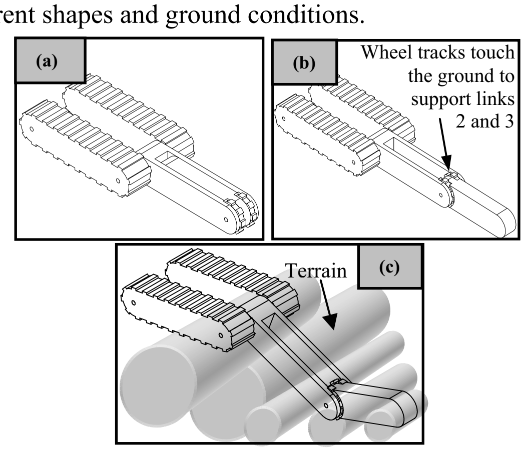

Fig. 3 Configurations for enhanced traction.

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 (d) 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 (d) is useful for increased maneuverability since the contact area between the platform and the ground is minimized.

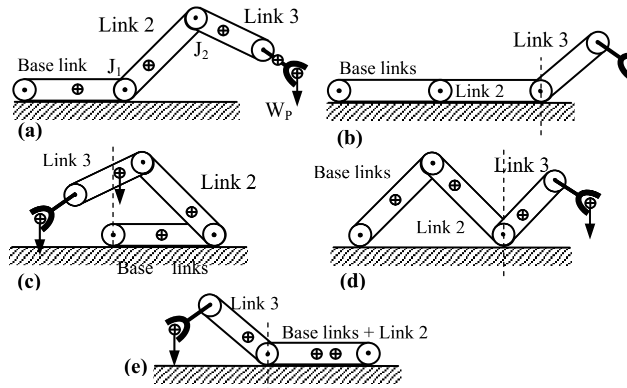

Fig. 4 Configurations for manipulation.

III. Mechanical Design Architecture

The mechanical architecture of the mobile robot shown in Fig. 5 embodies the conceptual design paradigm as described in Section IIA. 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. This section describes the platform drive system, arm joint design and integration of the arm into the platform as well as some specifications of the robot based on a CAD detail design assembly that is used for manufacturing of the first prototype. The closed configuration of the robot (Fig. 1(a)-all links stowed) is symmetric in all directions.

A. Motors

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). It was important to ensure that all link motors are situated at the base since it keeps the entire structure's COG closer to the ground.

B. 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 of each base link track drive 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 This feature prevents the track from sliding off laterally, thus preventing the tracks from coming off the pulleys. All electrical hardware (such as batteries, controllers, drivers, gear-heads etc) is 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.

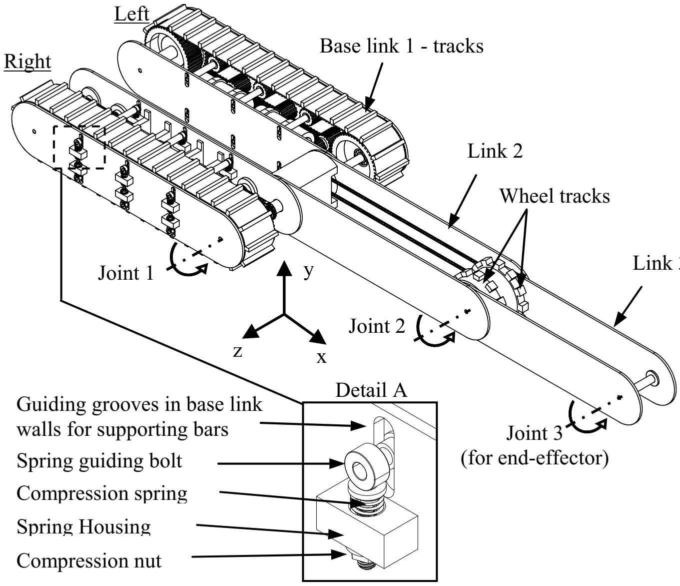

Fig. 5 Open configuration of the mobile robot.

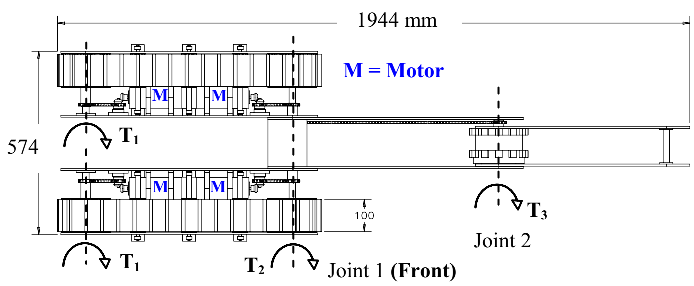

Fig. 6 Open configuration (top view – all dimensions in mm).

C. Built-in track tension and suspension mechanism

Fig. 7 shows the arrangement of the supporting planetary pulleys. 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). The ends of each supporting bar are guided through a groove on either side of the base link as shown in Detail A of Fig. 5. 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 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 to a required value by fastening or loosening the compression nuts. Another usage of the spring array is to absorb some of the energy resulting from falling or flipping, thus providing some degree of compliance to impact forces.

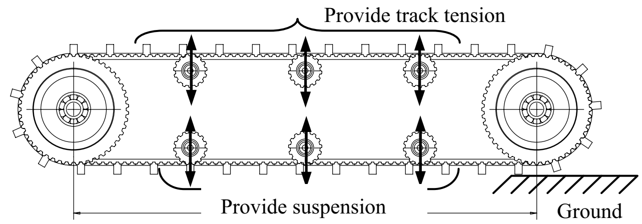

Fig. 7 Side view of base link track showing general pulley arrangement and track tension and suspension mechanism.

The final detailed design assembly was performed with SolidWorks CAD Software for manufacturing the first prototype of the hybrid robot is shown in Fig. 8. General specifications of the robot are provided in Table II.

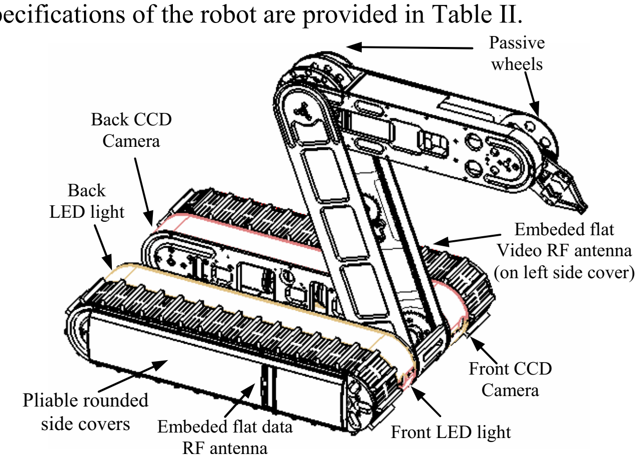

Fig. 8 Detail design assembly of the entire robot.

TABLE II – ROBOT DESIGN SPECIFICATIONS

Total estimated weight (including batteries and electronics)	65 [Kg]
Length (arm stowed)	814 [mm]
Length (arm deployed)	2034 [mm]
Width (with pliable side covers)	626 [mm]
Height	179 [mm]

IV. MODELLING AND SIMULATIONS OF THE ROBOTIC SYSTEM

The 3D mechanical design assembly that was developed with the CAD Software was exported to ADAMS software to perform dynamic simulations of the complete robotic system in order to study its functionality and demonstrate its expected capability. The simulation experiments are accounting for the mass distribution of the robot (including batteries, motors, electronics, etc.), inertia properties of the links and contact and friction forces between the links and tracks and the ground.

We used ADAMS, commercial motion simulation software, to analyze the behavior of the robotic system. It allowed us to test virtual prototypes and optimize designs for performance, without having to build and test physical prototypes. This noticeably 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 optimize the design. The design optimization process involved optimal weight optimization, 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 modus operandi using ADAMS and ATV Toolkit was used to build the tracks [23],[24].

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 gear ratios 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.

A. 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 IIB), random rotations of all links, traversing pipes of different diameters, climbing and descending rectangular obstacle with different link configurations, crossing ditches with different gap dimensions, climbing and descending stair, flipping over due to a ramp obstacle, lifting tasks and more. To illustrate, only few of the above mentioned simulations are presented in Figs. 11-14. The segmented nature of the robot's structure allows it to surmount circular obstacles such as pipes and tree logs. Fig. 11 depicts several configuration steps to accomplish such tasks. The base link tracks are deployed until they touch the obstacle (a)–(b); at that point, the tracks propel the platform (c) while at the same time they continue to rotate about joint 1.

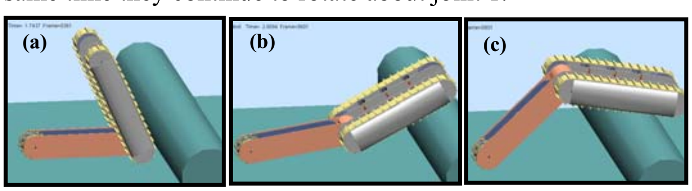

Fig. 11 Surmounting circular obstacles.

Fig. 12 shows a series of motions that different links need to undergo in order to climb stairs. 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 to finish climbing and closes to lower the robot back to the ground.

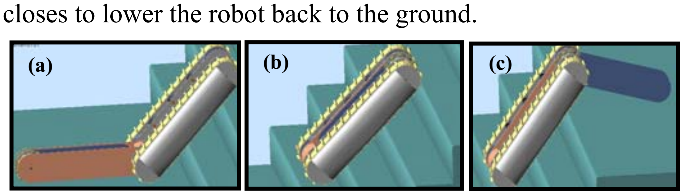

Fig. 12 Stair climbing.

Fig. 13 shows series of motions in order to climb a 0.5 m step obstacle with the base link tracks. 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 and link 2 closes. This climbing as well as step descending can also be performed with other link motion combinations.

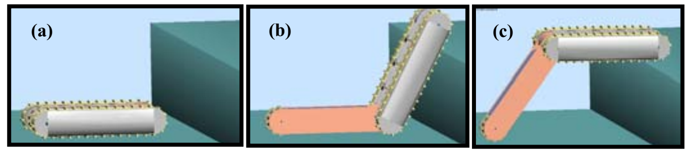

Fig. 13 Step obstacle climbing with tracks.

The symmetric nature 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) allows it to accomplish missions that require manipulation capabilities even if the robot flips over or falls due to an obstacle the robot could not avoid. Fig. 14 shows several snapshots of a simulation showing a robot stowing its links before flipping over occurs and deploying them again from the other side after the robot flipped over.

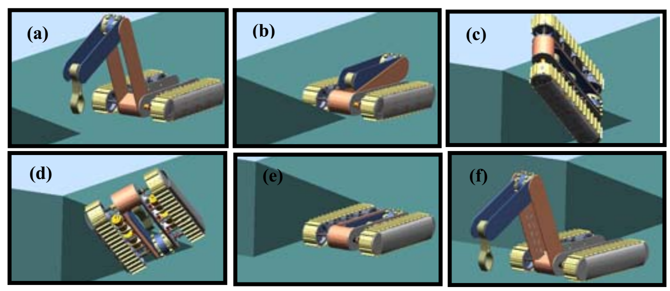

Fig. 14 Flip-over scenario.

According to additional simulation results (configurations not shown here), 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 traversed.

B. Analysis of Track Tension and Suspension Mechanism

The optimal spring stiffness value for the dual tension-suspension mechanism was analyzed and found by visualizing the spring compression/expansion (with different stiffness values) to verify that it meets the allowable displacements for track tension and suspension purposes (Fig. 7). Simulation results data obtained from graphs representing the force in each spring in the top and bottom spring array on each side of the platform corroborated the functionality of the dual operation of the track suspension/tension mechanism. This was done by simulating the robot when surmounting a small obstacle to observe how the springs react to obstacles situated between the planetary pulleys. From the top spring array force distribution, the average force in each spring was constant as expected since those springs 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 were 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 the force in each spring was 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

Additional dynamic simulations were 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 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. For symmetry reasons, we defined T_2=T_3=157[Nm] when selecting the motors. In order to be able to generate the required torques, Lithium-Ion batteries with high drain current capabilities as well as proper Harmonic Gear-head drives and brushless DC motors were incorporated in the design. The driving torque T_1 for each track was determined based on the condition that slipping does not occur when the robot moves on a flat ground or a slope. Therefore, static friction coefficients were used to estimate the required driving force.

D. End-Effector Payload Capacity Analysis

The end-effector load capacity of the platform with respect to various configurations was estimated by examining the COG vertical movement with respect to the ground, which indicates tip-over stability. The change of the robot's COG position (in the vertical direction) was examined 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. 4(b). The maximum end-effector load capacity was found at the instant when the COG location of the robot starts to move up vertically. According to the simulation results, 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.

Possible configurations for manipulation were presented schematically in Fig. 4. For a given torque capacity in joint 1, configuration (c) is optimal for maximum load capacity W_P due to its greater tip-over stability. In each of the configurations (b), (d) and (e) (depending on required level of mobility), an end-effector load of *18.3 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.

V. CONTROL/COMPUTER HARDWARE ARCHITECTURE

A. On-Board Inter-segmental RF Communication Layout

The design architecture of the hybrid mobile robot requires that the electrical hardware, discussed in detail in Section VI, in each of the segments constituting the robot (two base links, link 2 and link 3) are 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 end-effector (gripper mechanism) is situated in link 3 and is not connected to any of the base link tracks via wires. Each of the segments contains individual power source (rechargeable batteries) and RF modules for *inter-segmental RF communication.*

The right base link track contains a central RF module (Fig. 17(a)) for communication with the OCU (Operator Control Unit), while each of the remaining segments contain 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 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 assists in eliminating the following major problems:

1. It eliminates the need to have a stand-alone vertically sticking out antenna for each of the robot's segments. Sticking out antennas is not desirable due to the robot's structural symmetry, which allows the robot to flip-over when necessary and continue to operate with no need of self-righting. For that reason, special flat antennas [25] were designed (Fig. 15) and embedded into the side covers of the robot for RF video communication and RF data communication as shown in Fig. 8.
2. 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 de-synchronization between the track motions. On the other hand, if all the data pertaining to all segments of the robot is received in one location in 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.

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.

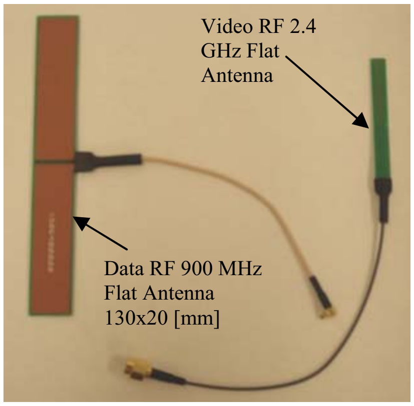

Fig.15 Flat antennas for video and data RF communication.

B. RF Hardware for the Hybrid Robot

As shown in Fig. 16, the OCU includes MaxStream [26] 9XCite or 9XTend 900 MHz RF Modem. The data transmitted by the stand alone RF modem at the OCU is received by a 9XCite or 9XTend OEM RF Module (depending on the required range) that is situated in the right base link track as shown in Fig. 17(a). The 9XCite 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. This dada 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 (Fig. 17(b) and (c)).

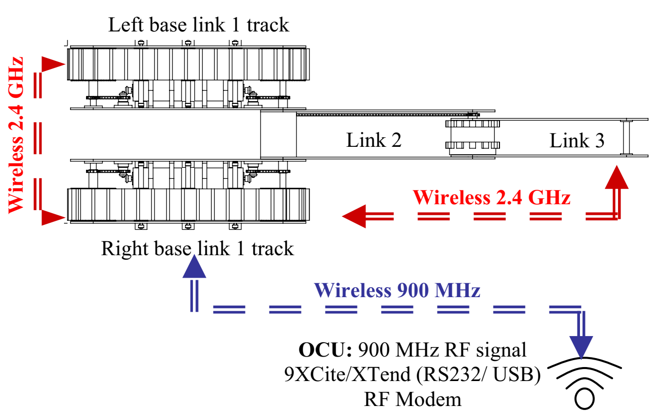

Fig. 16 RF communication layout.

The major advantages of the XBee OEM RF module are: (i) it is available with a PCB chip antenna (Fig. 18), which eliminates the need for a vertically sticking out antenna for each link segment of the robotic platform; (ii) its operating frequency is 2.4 GHz – namely, different operating frequency than the primary 9Xtend/9Xcite RF module; (iii) fast RF data rate of 250 kbps; and (iv) its small form factor (2.5x3[cm]) saved valuable board space in the compact design of the robot.

The chip antenna is suited for any application, but is especially useful in embedded applications. 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 up to 24 [m] range. 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].

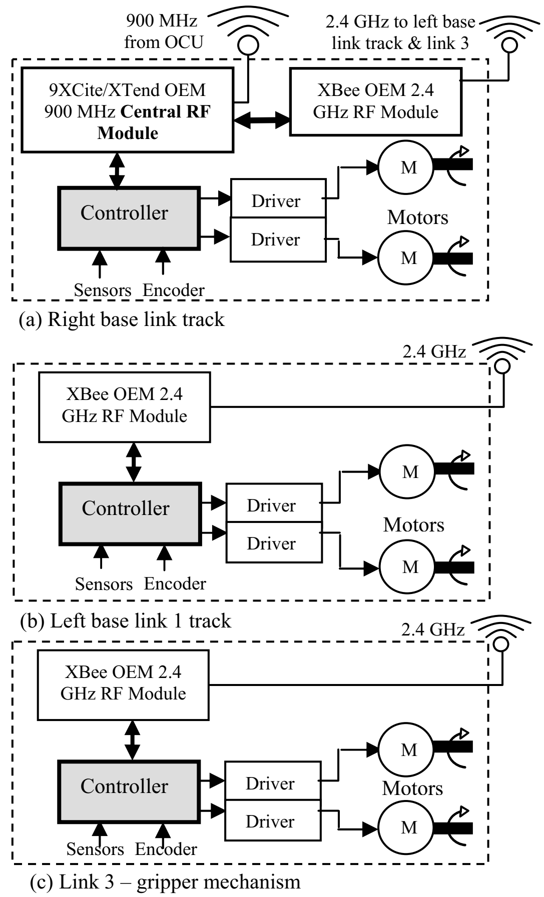

Fig. 17 Hardware architecture: (a) right base link track; (b) left base link track; (c) link 3 – gripper mechanism.

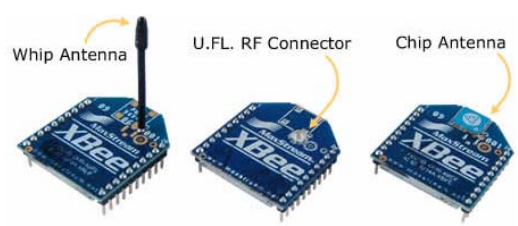

Fig. 18 XBee OEM 2.4GHz RF module [26].

This concept provides a simple and cheap solution when on-board inter-segmental wireless communication is required to avoid any wire and slip-ring mechanical connections between different parts of a given mechanical system.

VI. Electrical Hardware Architecture

A. Controllers, Drivers and 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, 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. A socket to the microcontroller is reserved for other signals, which may be added in the future. As shown in Figs. 8 and 19, 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 microcontroller decides the image of which camera is being transmitted.

B. Power Sources

Power is generally one of the constraining factors for small robot design. In order to generate the required torques for each link including the gripper mechanism, we used rechargeable Lithium-Ion battery units in a special construction with the inclusion of Protection Circuit Modules (PCMs) in order to safely generate high current discharge based on the motors demands. With the combination of this power source along with a proper selection of brushless DC motors and harmonic gear-head drives, we can generate the high torques that were estimated based on the simulation results. Each of the left and right base link track and the gripper mechanism situated in the space provided in link 3 has a standalone power source.

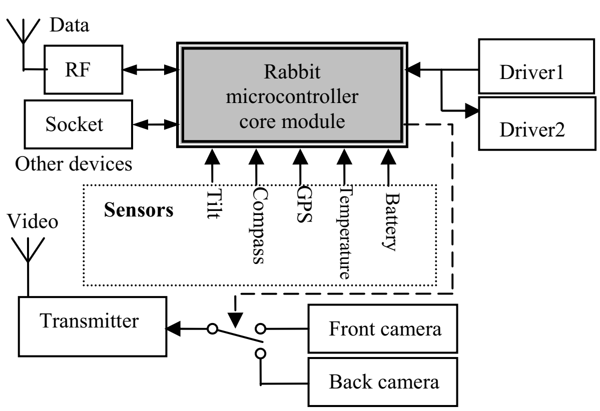

Fig. 19 Sensors and cameras layout.

VII. CONCLUSION

The new mobile robot design presented in this paper was based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. It is expected that this design approach along with other design characteristics inherent to the robot presented will provide solutions to various issues related to design of mobile robots operating on rough terrain and in hazardous environments. 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. The derived parameters are used in the design and ongoing construction of a physical prototype. Furthermore, a novel concept was presented for on-board inter-segmental RF communication among the robot's links and the associated electrical hardware architecture for the entire robotic platform. This control architecture has the potential to be used in various other applications where similar design characteristics are exhibited.

ACKNOWLEDGMENT

This work was partially supported by Natural Sciences and Engineering Research Council of Canada (NSERC), grants held by Professors Andrew A. Goldenberg and Jean W. Zu.

REFERENCES

[1] J. Carlson and R.R. Murphy, "How UGVs Physically Fail in the Field", IEEE Transactions on Robotics, Vol. 21, No. 3, pp. 423-437, June 2005.
[2] R.R. Murphy, "Activities of the Rescue Robots at the World Trade Center from 11-21 September 2001", IEEE Robotics and Automation Magazine, pp. 50-61, September 2004.
[3] T. Frost, C. Norman, S. Pratt, et al, "Derived Performance Metrics and Measurements Compared to field experience of the PackBot", iRobot Corporation. Available: http://www.isd.mel.nist.gov
[4] J.B. Coughlan, et al, "Small all terrain mobile robot", U.S. Patent 5,022,812, June 11, 1991.
[5] J.R. White, et al "All terrain mobile robot", US Patent 4,932,831, June, 1990.
[6] Remotec Wheelbarrow MK8 Plus. Available: http://www.remotec.co.uk
[7] F. Michaud, et al, "Co-Design of AZIMUT, A Multi-Modal Robotic Platform", ASME 2003 Design Eng. Tech. Conferences and Computers and Info. in Eng. Conference, Chicago, Illinois USA, Sep. 2-6, 2003.
[8] A.A. Goldenberg, J. Lin, "Variable Configuration Articulated Tracked Vehicle", US Patent Application # 11/196,486, August 4, 2005.
[9] MATILDA Robotic Platform. Available: http://www.mesa-robotics.com
[10] MURV-100. Available: http://www.hdemfg.com
[11] S. Hirose, E.F. Fukushima, R. Damoto, and H. Nakamoto, "Design of terrain adaptive versatile crawler vehicle HELIOS-VI", Proc. IEEE/RSJ Int.Conf. on Intelligent Robots and Sys., Hawaii, pp. 1540-1545, 2001.
[12] S. Hirose, T. Sensu, and S. Aoki, "The TAQT Carrier: A Pratical Terrain-Adaptive Quadru-Track Carrier Robot", Proc. IEEE/RSJ Int.Conf. on Intelligent Robots and Sys., Tokyo, pp.2068-2073, 1992.
[13] S. Hirose, S. Aoki, and J. Miyake, "Design and Control of Quadru-Truck Crawler Vehicle HELIOS-II", Proc. 8th RoManSy Symp.,Cracow, Poland, pp.1-10, 1990.
[14] T. Iwamoto and H. Yamamoto, "Mechanical design of variable configuration tracked vehicle", Transactions of the ASME - Journal of Mechanical Design, Vol. 112, pp. 289-294, 1990.
[15] T. Iwamoto and H. Yamamoto, "Variable configuration track laying vehicle", U.S. Patent No. 4483407, November 20, 1984.
[16] Sandia National Laboratories, Intelligent Systems and Robotics Center (ISRC). Available at: http://www.sandia.gov
[17] A.A. Goldenberg, N. Kircanski, S.K. Dickie, G.D. Scott, L. Gryniewski, "Explosive disposal robot", U.S. Patent 6,113,343, September 5, 2000.
[18] MR-5 and MR-7. Available at: www.esit.com
[19] M.R. Blackburn, R. Bailey, and B. Lytle, "Improved Mobility in a Multidegree-of-Freedom Unmanned Ground Vehicle (UGV)," SPIE Proc. 5422: UGV Technology VI, Orlando, FL, April 13-15, 2004.
[20] http://www.foster-miller.com/lemming.htm
[21] U. Saranli, M. Buehler, D.E. Koditschek, "RHex: a Simple and Highly Mobile Hexapod Robot", Int. J. Rob. Res, 20(7): pp. 616-631, 2001.
[22] R.J. Full, D.E. Koditschek, "Neuromechanical hypotheses of legged locomotion on land" J. of Experimental Biology, Vol. 202, pp. 3325-3332, 1999.
[23] S.M. Malik, J. Lin, and A.A. Goldenberg, "Virtual prototyping for conceptual design of a tracked mobile robot", Canadian Conference on Electrical and Computer Eng., Ottawa, Ontario, Canada, May 2006.
[24] S.M. Malik, "Virtual prototyping for conceptual design of tracked mobile robots," M.S. thesis, Univ. of Toronto, Ontario, Canada, 2006.
[25] Nearson Global Antenna Solutions. Available: http://www.nearson.com
[26] MaxStream Wireless Radios. Available: http://www.maxstream.net