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Articulated hybrid mobile robot mechanism with compounded mobility and manipulation and on-board wireless sensor/actuator control interfaces

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ABSTRACT

This paper presents the development of a remotely operated mobile robot system with a hybrid mechanism whereby the locomotion platform and manipulator arm are designed as one entity to support both locomotion and manipulation interchangeably. The mechanical design is briefly described as well as the dynamic simulations used to analyze the robot mobility and functionality. As part of the development, this paper mainly focuses on a new generalized control hardware architecture based on embedded on-board wireless communication network between the robot's subsystems. This approach results in a modular control hardware architecture since no wire connections are used between the actuators and sensors in each of the mobile robot subsystems and also provides operational fault-tolerance. The effectiveness of this approach is experimentally demonstrated and validated by implementing it in the hybrid mobile robot system. The new control hardware architecture and mechanical design demonstrate the qualitative and quantitative performance improvements of the mobile robot in terms of the new locomotion and manipulation capabilities it provides. Experimental results are presented to demonstrate new operative tasks that the robot was able to accomplish, such as traversing challenging obstacles, and manipulating objects of various capacities; functions often required in various challenging applications, such as search and rescue missions, hazardous site inspections, and planetary explorations.

1. Introduction

Mobile robots have been used in the aftermath of September 11, 2001 for USAR (Urban Search and Rescue) activities such as: structural inspection, searching for victims, searching paths through the rubble that would be quicker than to excavate, and detection of hazardous materials. In each case, small mobile robots were used because they could go deeper than traditional search equipment and could enter void spaces too small for a human or search dog. Among the tracked robots that were used, the capability was limited in terms of locomotion and mobility, and more so if one considers requirements to perform manipulation tasks with an arm mounted on the mobile robot. One of the other problems with some of the robots used on the rubble pile searches were the robot flipping over into a position from where it could not be righted or moved [6].

Increasingly, mobile robotic platforms are being proposed for high-risk missions for law enforcement and military applications (e.g., to manipulate Improvised Explosive Devices – IEDs), hazardous site clean-ups, planetary explorations (e.g., Mars Rover), and rough terrain such as in collapsed buildings, disaster areas, caves and other outdoor environments. In those missions, small mobile robots 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 limited leg step height and minimal contact area, etc. Another factor could be the result of actuator strength compared to the mobile robot mass. To solve the mobility problems of wheeled and legged locomotion, tracks are often used.

There are various designs of tracked mobile robots that have optional feature in the design to attach a manipulator arm on top of the mobile platform as an add-on system or part of the platform. Some of the robots are: Talon [9], PackBot [24], Andros Mark V robots [23], Wheelbarrow MK8 [8], AZIMUT [18], LMA [11], Matilda [19], Helios VI and VII robots [13,12], Variable configuration VCTV [14], and Ratler [20]. Some legged robots [21,10,7,15] are also part of the scenarios assumed herewith, but they may not fall under the aforementioned category of applications due to their limited leg step height and minimal contact area (limited traction). Therefore, our focus is on tracked mobile robots that besides locomotion exhibit manipulation capabilities.

Typically, state-of-the-art tracked mobile robots have a separate manipulator arm platform attached on top of the locomotion platform. The platforms provide distinct functions. Namely, the locomotion platform provides mobility with a pair of tracks,

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wheels [1,22] or the combination of both, and the arm platform provides manipulation (manipulation of hazardous materials, neutralization of bombs or landmines, etc.). Furthermore, the presence of an arm limits the mobility, mainly because it is attached on top of the mobility platform and as such, platform flip-over may not be possible. On the other hand, there are several designs of mobile robots with enhanced mobility capability on the account that they are not equipped with a manipulator arm on top. We propose to bridge this gap in our approach by providing a new remotely operated mobile robot design that provides compounded manipulation and locomotion capabilities. The significance of the new mobile robot mechanism is that it has the ability to interchangeably provide locomotion and manipulation capability, both simultaneously. This was accomplished by integrating the locomotion and manipulator arm mechanisms as one entity resulting in a hybrid articulated mechanism rather than two separate and attached mechanisms. The manipulator arm can be used as part of the locomotion platform and vice versa. The platform and manipulator are interchangeable in their roles in the sense that both can support manipulation *and* locomotion in several configuration modes as discussed in Section 2.2.

In order to provide a modular mechanical and control system architecture (to satisfy a set of requirements for better kinematic functionality, as discussed in Section 4 under 'requirements'), the links or subsystems constituting the mobile robot are connected wirelessly. This, along with an independent power source in each subsystem, eliminates the need for physical wiring between the rotating articulated mobile robot links. The developed novel onboard wireless sensor/actuator control paradigm and the related electrical hardware architecture are discussed in detail in Sections 4 and 5, respectively.

A thorough review of the literature assisted us in deriving a conceptual function-oriented analysis [3,5]) in order to qualitatively identify the major issues related to mobile robots functionality in field operations. This analysis has led to the design approach. A brief summary of the issues, related research problems and proposed solutions are summarized in Table 1.

This paper is organized as follows. Section 2 provides a brief description of the mobile robot design. In Section 3, relevant simulation results that assisted with the design development are presented, and then compared with the experimental results performed with the physical prototype, as presented in Section 6. Sections 4 and 5 present the new generalized systematic approach for modular control hardware architecture with on-board distributed wireless communication network between the robot's subsystems and modules. This approach is then implemented as part of the hybrid mobile robot (HMR) System development. Section 6 provides extensive experimental results and discussions. The experiments demonstrate the coincidence and hence the validity of the simulations described in Section 3. They also demonstrate how the embedded wireless control hardware architecture dramatically increases the locomotion and manipulation functionalities of the mobile robot.

Table 1
Summary of 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 and cost	Design the manipulator arm and mobile platform as one entity mechanism
Manipulator arm mounted or folded on top	Arm susceptible to breakage and damage when platform inverted	Integration of arm and platform as one entity in a geometrically *symmetric* design eliminates exposure
Flip-over occurrence: invertibility versus self-righting	To provide self-righting without special purpose or active means	Design a symmetric platform to allow flip-over without the need to return it, and as such greatly enhance mobility

2. Hybrid mobile robot (HMR) mechanism design

In this section, the mechanical design architecture of the remotely controlled HMR mechanism is briefly presented as part of the overall system development and as a case study for the implementation of the newly proposed control hardware architecture. In depth details of the mechanical design are available in Ben-Tzvi et al. [5].

The proposed design approach is twofold and is described as follows: (i) integrate the manipulator and the mobility platform as one entity resulting in a hybrid mechanism rather than two separate and attached mechanisms. Consequently, the same joints (motors) that provide the manipulator's dof's also provide the mobile platform's dof's. Therefore, the actuator strength capacity for manipulation purposes dramatically increases due to the hybrid mechanical structure and (ii) design the overall mobile robot platform in a geometrically symmetric manner in order to allow flip-over and invert-ability. Therefore, when a flip-over takes place, the robot can continue its task from the current position, with no need of self-righting or added active means to return it.

2.1. Description of the design

The design concept embodying the proposed idea is depicted in Fig. 1. If the platform is inverted due to flip-over, the fully *symmetric* design (Fig. 1a) allows the platform to continue to the destination from its new position with no need of active means for self-righting. Also it is able to deploy/stow the manipulator arm from either side of the platform.

The platform includes two identical and parallel base link 1 tracks (left and right), 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. 1b). 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. 1b). The passive wheels are used to support links 2 and 3 when used for various configuration modes of locomotion/traction. Link 2, link 3 and the end-effector 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.

The hybrid mobile robot system is remotely controlled by an operator using an Operator Control Unit (OCU) as described in detail in Section 5.4.

2.2. Configuration modes of operation

The links can be used in three modes: (a) locomotion mode: all links used for locomotion to provide added level of maneuverability and traction; (b) manipulation mode: all links are used for manipulation to provide added level of manipulation. The pair of base links can provide motion equivalent to a turret joint of the manipulator arm; (c) hybrid mode: combination of modes (a) and (b) – 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.

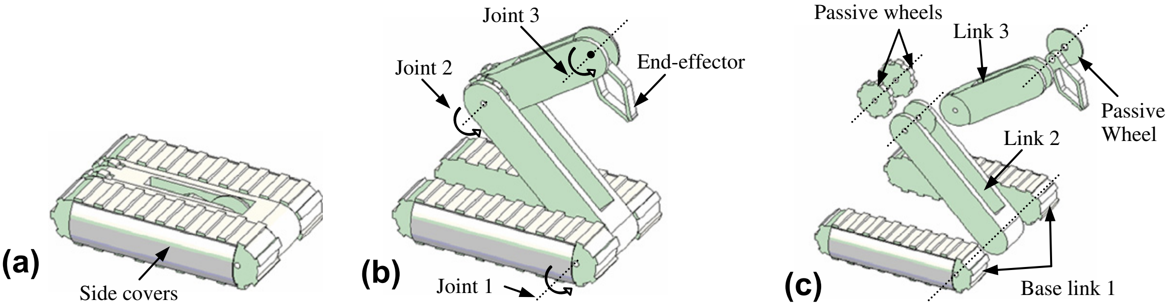


Fig. 1. (a) Closed configuration; (b) open configuration; and (c) exploded view.

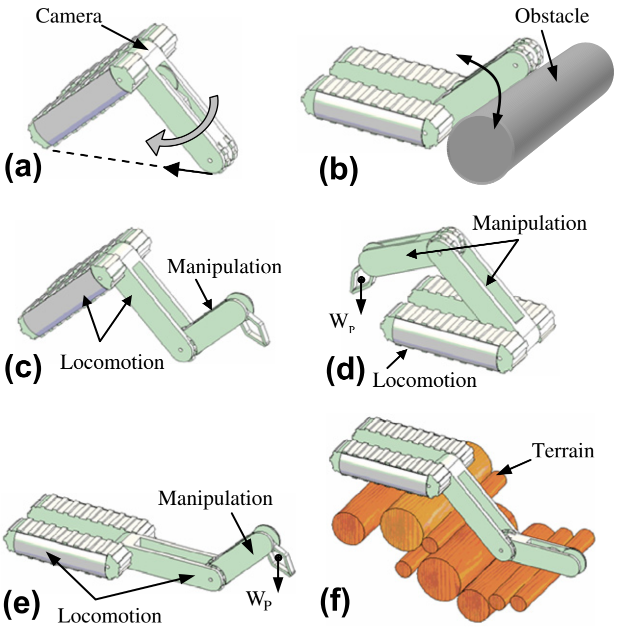


Fig. 2. (a and b) sample mobility configurations; (c and d) sample manipulation configurations; (e and f) configurations for enhanced traction.

2.3. Maneuverability, traction and manipulation

To qualitatively illustrate the configuration modes, some are depicted in Fig. 2. More detailed information on the various configuration modes is available in Ben-Tzvi [3] and Ben-Tzvi et al. [5]. Fig. 2a 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 it also enables the robot to climb taller objects (Fig. 2b). Link 2 is also used to support the entire platform when moving in a tripod configuration while using the other links for manipulation (Fig. 2c). For enhanced traction, the articulated structure of the mobile platform allows it to be adaptable to different terrain shapes and ground conditions (Fig. 2f). Fig. 2c–e depict a few of the various configurations for manipulation purposes. While some links are used for locomotion, the others are used simultaneously for manipulation.

A complete depiction of the mobile robot is shown in Fig. 3. Other accessories typically found in mobile robots such as cameras, lights and antennas, 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, LED lights and antennas were embedded inside the base link tracks, as shown in Fig. 3.

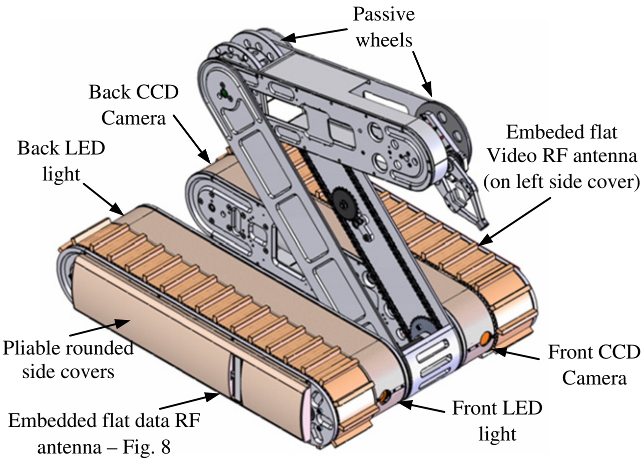


Fig. 3. Complete depiction of the hybrid mobile robot.

General specifications of the robot are provided in Table 2.

The design also includes a built-in dual-operation track tension and suspension mechanism situated in each of the base link tracks [2]a). The suspension mechanism is also used to absorb some of the energy resulting from falling or flipping, thus providing some compliance to impact forces.

3. Modelling and simulations of the hybrid robot

A detailed 3D mechanical design assembly was developed with ADAMS software to perform dynamic simulations of the complete robotic system in order to study its functionality and improve the design [4]. The simulation experiments are accounting for the mass

Table 2
Robot design specifications.

Total mass	65 (kg)	Max. Torque in Joint 1 – T_1	32 (Nm)
Length (arm stowed)	814 (mm)	Max. Torque in Joint 2 – T_2	157 (Nm)
Length (arm deployed)	2034 (mm)	Max. Torque in Joint 3 – T_3	157 (Nm)
Width (with pliable side covers)	626 (mm)	Link 1 rotation speed about joint 1	30 (deg/s)
Height (arm stowed)	179 (mm)	Link 2 rotation speed about joint 1	52 (deg/s)
On-board battery power	~2.5 h	Link 3 rotation speed about joint 2	52 (deg/s)
Speed of platform	up to 1 (m/s)	Gripper wrist rotation speed about joint 3	15 (deg/s)

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.

ADAMS, motion simulation software, was used to analyze the behavior of the robotic system. It allowed us to test virtual prototypes and enhance designs for performance, without having to build and test several physical prototypes. This noticeably reduced our prototype development time and cost.

The design enhancement process involved proper links' weight selection, 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 [16,17].

The simulations were performed for the following major purposes: (i) visualize and validate robot mobility characteristics through animations of different possible tasks that require various locomotion and manipulation capabilities; (ii) define each joint's torque requirements for different mobility tasks and select proper gear ratios and motors; (iii) analyze the suspension and track tension retention by examining the spring array force distributions; 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 such that they could be easily changed according to different size and shape requirements.

In this section we focus on some of the animation results in order to eventually compare them to the experimental results presented in Section 6. This validates the mobility analysis performed for the purpose of enhancing the design at the early design stages. The simulation results described in items (ii)–(iv) above can be found in Ben-Tzvi et al. [2].

3.1. Mobility analysis – animation results

To study the mobile robot's functionality enabled by the hybrid approach for mechanism design, various simulations were performed as follows: executing a variety of manipulation scenarios, traversing cylindrical obstacles of different diameters, climbing and descending step obstacles with different link configurations, crossing ditches with different gap dimensions, climbing and descending stair, flipping over events, lifting tasks and more. These animation results demonstrate the advantages of the proposed hybrid mechanism and its ability to overcome challenging obstacles by interchanging locomotion and manipulation function modes between the articulated links.

To illustrate, several of the above mentioned simulations are presented in:

3.1.1. Stair climbing (Fig. 4a)

The base link tracks are first deployed until they touch the stairs (a)(1); link 2 is closed and the robot starts climbing with the tracks (a)(2); at the end of the stairs link 3 opens (a)(3) to support the platform while the robot is in motion until position (a)(4); link 3 lowers the robot until the tracks are in full contact with the ground.

3.1.2. Step climbing (0.5 m step) with Tracks (Fig. 4b)

The base link tracks are first deployed on the step (b)(2); link 2 continues to rotate until the base link tracks adjust with the profile of the terrain (b)(3); the platform advances to accomplish the climbing process (b)(4) and link 2 closes.

3.1.3. Step descending (Fig. 4c)

Link 2 is deployed until it touches the ground to support the robot when advancing (c)(1), link 2 rotates to lower the front of the

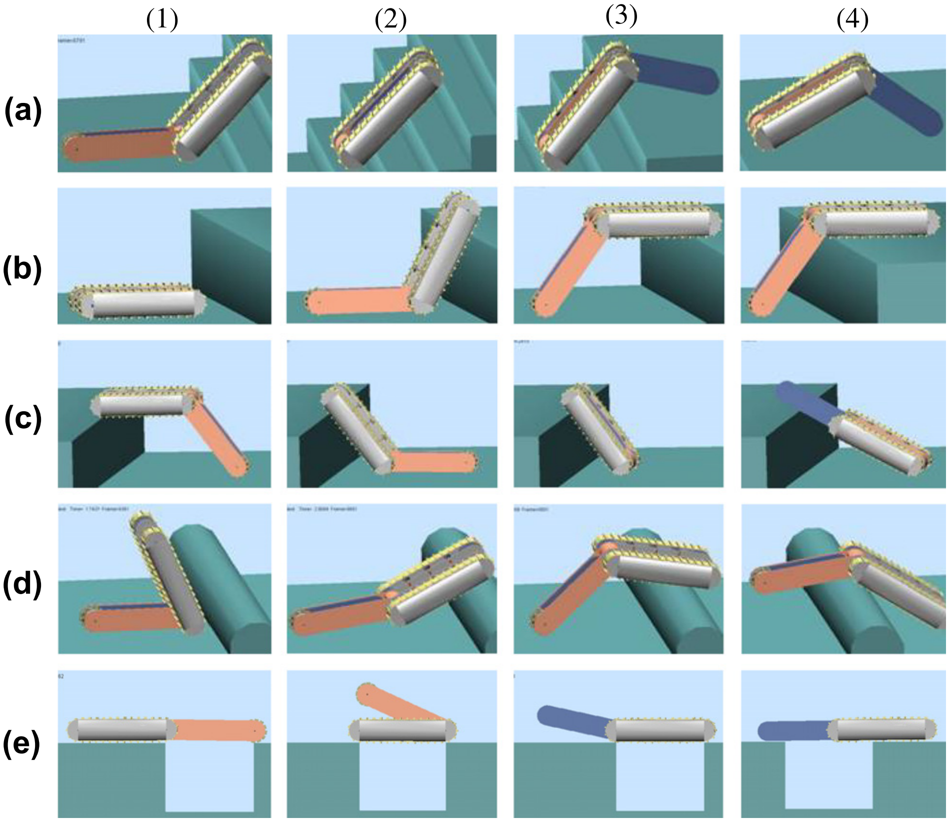
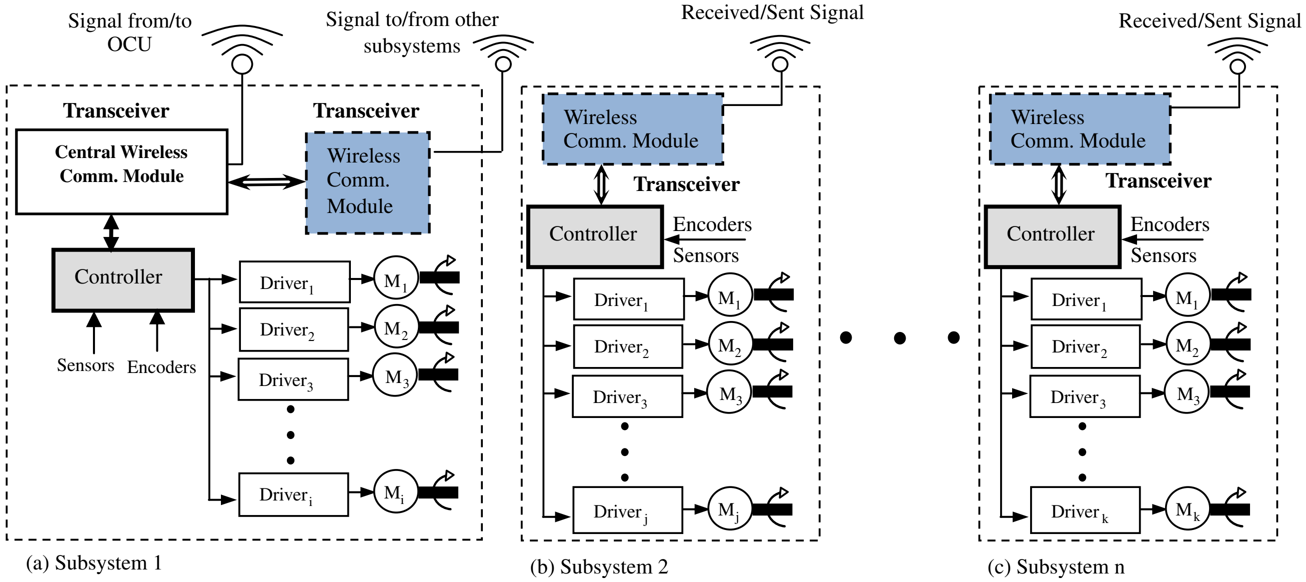


Fig. 4. Animation results: (a) stair climbing; (b) step climbing with tracks; (c) step descending; (d) surmounting tall cylindrical obstacles; and (e) Ditch crossing.



(a) Subsystem 1 (b) Subsystem 2 (c) Subsystem n

Fig. 5. Generalized on-board wireless communication layout.

platform (c)(2); link 2 fully closes (c)(3); link 3 opens and the robot moves forward (c)(4); link 3 rotates (until closed) to lower the robot.

3.1.4. Surmounting circular obstacles (Fig. 4d)

The segmented nature of the robot's structure allows it to surmount cylindrical obstacles such as pipes and tree logs. The base link tracks are deployed until they touch the obstacle (d)(1)–(2); at that point, the tracks start to propel the platform (d)(c) while at the same time they continue their rotation about joint 1.

3.1.5. Ditch crossing (Fig. 4e)

Since the robot can deploy link 2 from the front and link 3 from the back (when all links are stowed), ditches can be traversed according to the following steps: from the back edge of the ditch, link 2 is deployed (e)(1); the robot advanced until the front and back are supported by the ditch edges (e)(2); link 2 closes and link 3 opens from the back (e)(3); the robot continues its forward motion until the COG passes the front edge of the ditch while link 3 prevents from the robot from falling into the ditch as long as the COG is before the front edge (e)(4).

4. On-board wireless sensor/actuator control hardware architecture

Control architecture issues are the 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 section presents the development of a new systematic approach for a modular control hardware architecture that dramatically increases the functionality of the hybrid mobile robot and provides operational fault-tolerance. This is done by providing on-board distributed wireless communication between the robot's subsystems and modules such as the actuators and sensors.

The proposed generalized wireless and modular control hardware architecture is depicted in Fig. 5. This scheme provides on-board wireless hardware control interfaces between several subsystems constituting a given mechanical system and fulfils a list of general requirements as listed below. It also enables distribution of the electrical hardware independently (i.e., no wire connections) in a given robotic system's links/segments (subsystems). In the case of the hybrid mobile robot, the electrical hardware is situated in two base link tracks and link 3. The electrical hardware associated with the gripper mechanism is situated in link 3 (Fig. 3) and is not connected to any of the base link tracks via wires. This allows link 3 to provide continuous rotation inside link 2. Similarly, the wireless data communication between the left and right base link tracks allow continuous rotation for link 2 between the base link tracks. Based on the design architecture of the hybrid mobile robot and the required functionality and specifications, the requirements and the related solutions for the control architecture are analyzed as follows:

Requirements

(1) Provide modular mechanical and control system architecture: this provides operational fault-tolerance – namely, if one of the robot subsystems (links) fails during operation, others will continue to operate with no interruption.
(2) Enable continuous rotation between robot links without: (i) physical wiring or cable loops (which limit the robot links range of motion) and (ii) slip ring connections (which greatly complicated the system design).
(3) Avoid direct RF communication between each robot segment and the Operating Control Unit (OCU) in order to:

- Eliminate stand-alone protruding antennas from each subsystem and thereby maintain the overall structure's symmetry.
- Prevent inconsistent data loss between the OCU and each link that may lead to de-synchronization between the track and link motions. Therefore, it is required that the data pertaining to all robot links is received in one location on the robot (any of the links), and then transmitted and distributed to the other links wirelessly.

Solutions

(1) Provide independent power source for each robot link/subsystem (using Li-Ion battery packs).
(2) Enable on-board wireless communication between robot links/subsystems:
    - Ensures that data pertaining to the robot segments is received in one location and then distributed to other subsystems.

4.1. Generalized on-board wireless communication layout

Fig. 5 shows a mechanical system with *n* subsystems. A central wireless communication module is embedded in any of the *n* subsystems (e.g., Fig. 5a shows the central communication module in subsystem 1) for communication with the OCU, while each of the remaining subsystems contains a wireless communication module for inter-segmental on-board wireless communication. This, along with independent power source in each subsystem, eliminates the need for physical wiring between the rotating or translating subsystems. This enables the subsystems to provide continuous rotation or translation about their respective joints and prevent any restriction to their range of motion. In the case of the HMR, this enables links 1, 2 and 3 and the gripper mechanism to provide continuous rotation about their respective joints.

The data transmitted by the OCU is received by a central wireless communication transceiver module that can be situated in any of the *n* subsystems as shown in Fig. 5a. This wireless communication module communicates with the local controller that controls the electronics (motors and associated drivers, sensors, etc.) in that subsystem while at the same time sends data pertaining to the other subsystems to a separate wireless transceiver module in a wire connection. This data is then transmitted wirelessly to the remaining (*n-1*) wireless transceiver modules (subsystem 2-subsystem *n*), thus providing on-board wireless data communication among robot subsystems.

This hardware architecture provides extendibility in terms of the number of subsystems that can be added or removed in order to constitute a given robotic system. It also provides expandability in the subsystem level – namely, the number of components (e.g., drivers and motors) in each subsystem can be expanded depending on the required number of dof's. It should be taken into consideration however that both types of expandability may be limited by the number of available wireless communication ports in the central wireless module as well as the number of drivers that could be interfaced in each subsystem's on-board controller.

Based on this hardware architecture, fault-tolerance is achieved since each subsystem is independent of the other. For instance, if subsystem 2 fails, the others can continue to operate. This may not work if the subsystem that contained the central wireless communication module fails. In order to solve this problem, a central wireless module can be embedded in each of the subsystems and triggered in a predetermined sequence in case their neighboring subsystem failed.

4.2. Case study – wireless hardware architecture for the hybrid mobile robot using RF communication

To experimentally demonstrate the validity of the control hardware architecture provided in Fig. 5, it was implemented as a case study on the hybrid mobile robot using RF communication in the manner shown in Fig. 6. In this case, the OCU includes a 900 MHz RF transceiver. The data transmitted by the stand alone RF transceiver on the OCU is received by an RF transceiver that is situated in the right base link track as shown in Fig. 7a. This RF transceiver communicates with the local 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 2.4 GHz RF transceiver in a wire connection. This data is then transmitted wirelessly to two other 2.4 GHz RF transceiver – one for the left base link track and the other for link 3 (Figs. 7b and c), thus providing on-board wireless RF data communication among robot joints.

The RF modules for on-board wireless communication are advantageous in several ways: (i) they eliminate the need for a protruding antenna for each link segment of the robot since it is available with a PCB chip antenna (Fig. 8a) and (ii) they have different operating frequency (2.4 GHz) than the primary RF module. Due to the short and fixed distances between the robot's links/subsystems, low-power on-board RF modules between the left and right base link 1 tracks and link 3 were used without any communication interferences between the subsystems.

Protruding antennas are avoided by using custom designed flat antennas (Nearson Global Antenna Solutions) and embedding them into the robot side covers for wireless video communication and wireless data communication as shown in Figs. 3 and 8.

5. Electrical hardware architecture

5.1. Controllers, drivers, sensors and cameras layout

Each motor in the base link tracks is driven by a 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. The sensors which the robot is equipped with are: a tilt sensor; thermometer, GPS, three-axis compass (inclinometer) and battery-voltage monitor (Fig. 9). As shown in Fig. 3, 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

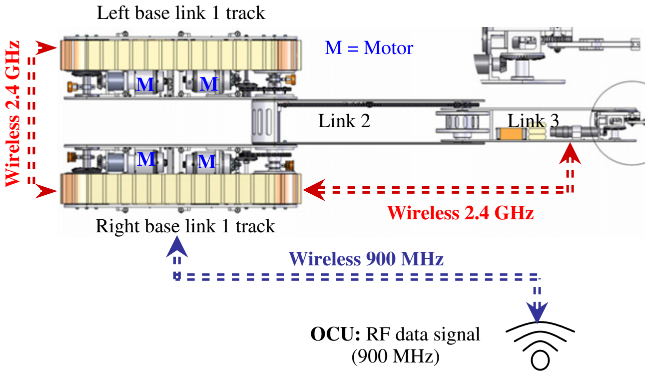
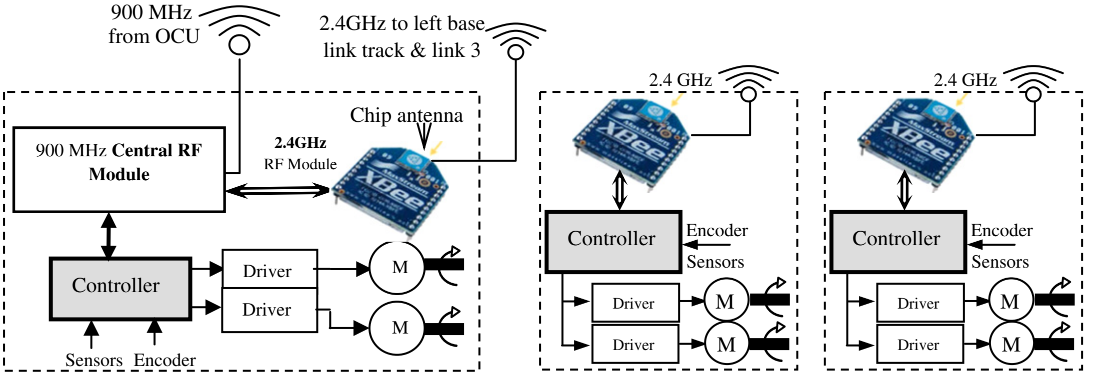


Fig. 6. On-board wireless communication layout for the HMR.



(a) Right base link track (b) Left base link 1 track (c) Link 3 – gripper mechanism

Fig. 7. Hardware architecture for the HMR: (a) right base link track; (b) left base link track; (c) link 3 – gripper mechanism.

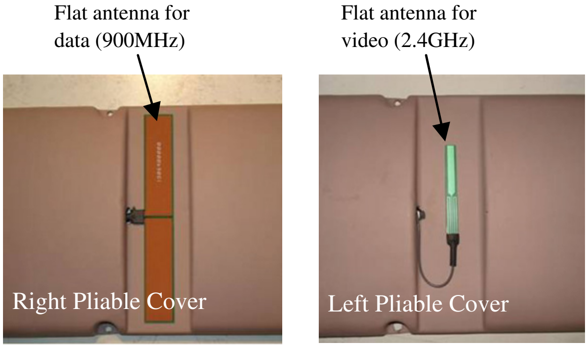


Fig. 8. Embeddable flat antennas for video and data RF communication.

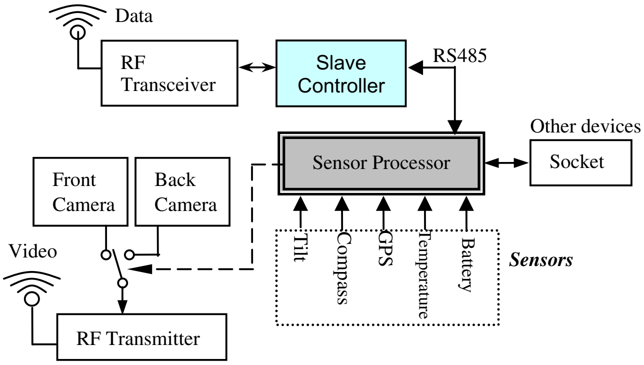


Fig. 9. Sensors and cameras layout.

in subsection C) decides the image of which camera is being transmitted.

5.2. On-board power system and signal flow design and implementation

One of the constraining factors for small mobile robot design is generally the on-board power system design. In order to generate the required high torques for each joint, rechargeable Lithium-Ion battery units in a special construction were developed and used. In addition to the power source, a proper selection of brushless DC motors and harmonic gear-head drives were integrated in the design in order to generate the high torques required.

A modular and expandable power system design was developed and implemented for the hybrid robot. The power system design is presented in a generalized form such that it can be easily adapted to other mobile systems. It has two major key elements that allow for easy reconfiguration and expansion: (i) Li-Ion battery packs; and (ii) power/signal distribution boards, as discussed as follows.

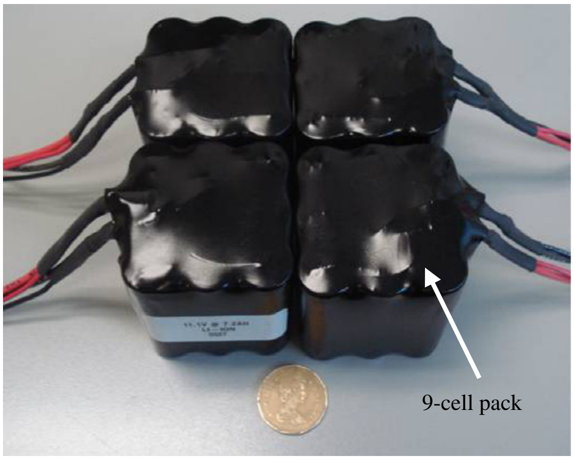


Fig. 10. Li-Ion battery packs assembly.

5.2.1. On-board power (Li-Ion battery packs)

Each tracked link of the hybrid robot carries four 9-cell Li-Ion battery packs in a series connection as shown in Fig. 10. Each Li-Ion battery cell nominally provides 3.7 V at 2.4 Ah. Smaller Li-Ion cells were used in order to increase the voltage capacity and continuous current discharge due to the increased number of cells used in a given volume. A number of cells and protection circuits were used to achieve a specified current discharge of up to 15 A. According to the tests performed, this special construction provides a battery unit with nominal voltage of ~45 V and continuous current discharge of 13.2 A with a max current discharge of 15 A due to the Protection Circuit Modules (PCM). Considering the very compact size of the battery pack (110 × 110 × 70 mm) and overall weight of only 1.6 kg, this electrical performance is advantageous for mobile robot applications with strict hardware space restrictions.

5.2.2. Power/signal distribution board – base link tracks

The power and data signal distribution board is used in each of the base link tracks in the hybrid robot (Fig. 11). 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 designed and manufactured in a layered manner, while providing

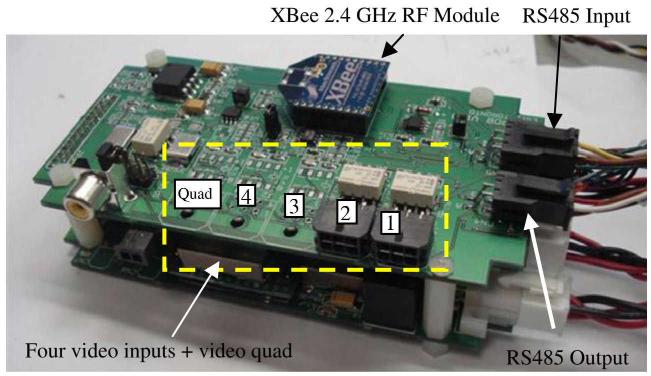


Fig. 11. Power/signal distribution board for base link tracks.

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), and various sensors. 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. 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.

5.2.3. Gripper mechanism power/signal distribution board and hardware architecture

As shown in Fig. 12, the analog RabbitCore provides a processor and analog input subsystem for OEMs to integrate into the custom design power/signal distribution board for the gripper mechanism. 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.

The gripper wrist is driven by an external motion controller that can perform the following tasks: 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.

5.3. Sensor processor board

The sensor processor PCB design shown in Fig. 13 is equipped with a digital compass used for precision robot inclination measurements. The compass includes a MEMS accelerometer for a horizontal three-axis, tilt compensated precision compass for performance up to a ±60° tilt range.

The 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 12 V input into the board to generate required voltage level for onboard instruments. The PCB was designed with additional RS485 inputs in order to interface additional sensors/devices as necessary.

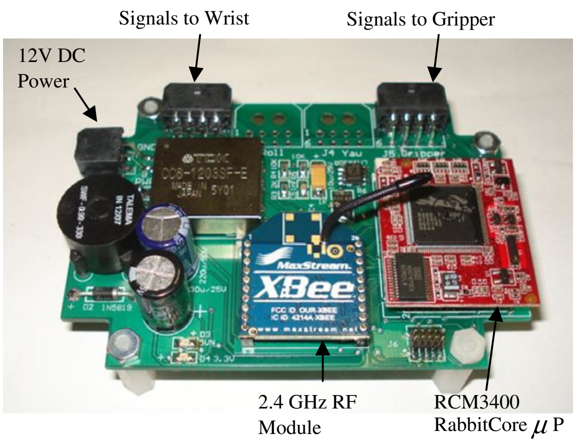


Fig. 12. Power/signal distribution board for gripper mechanism.

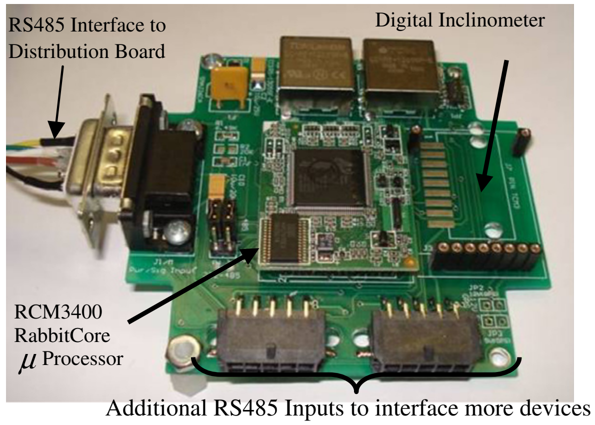


Fig. 13. Sensor processor board.

5.4. Robot DOF and Operator Control Unit (OCU)

The OCU for the current mobile robot prototype, as shown in Fig. 14, consists of two control sticks (LS-731, from Logosol), controller LS991 with text monitor, 900 MHz RF data transceiver (XTend modem, from Maxtream), and 12 V battery and battery charger. The OCU for this prototype currently does not include a video monitor and video/audio RF receiver.

The two control sticks in the remote OCU are used by the operator in order to remotely coordinate the robot degrees of freedom when generating the motions required for a given task. The

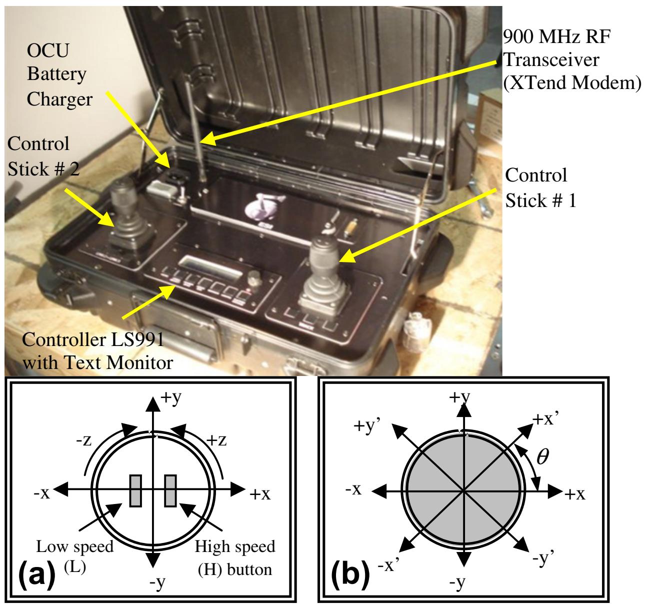


Fig. 14. Operator Control Unit (OCU) and robot DOF: (a) control stick # 1 (C1) motions layout and (b) control stick # 2 (C2) motions layout.

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 dof's. 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 CW and CCW 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. 14) 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 C2in 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.

Fig. 14 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. The control angle θ in C2 provides speed variability to each of the links 2 and 3 when operated simultaneously.

6. Experimental setup and results

Following the integration of the physical prototype shown in Fig. 15, a series of extensive experimental tests were performed to assess the robot's mobility, manipulability, and durability characteristics. Throughout the experiments, the robot was remotely controlled by an operator using the OCU as described in Section 5.4. The obstacle course consisted of various test rigs including man-made and natural obstructions as a representative subset of the robot's possible hindrances to cross country movement related to pertinent applications, such as: search and rescue, reconnaissance, surveillance, hazardous site inspections, military and police missions. The integrated wireless control architecture provided the mobile robot with the ability to generate continuous rotations to each of its links without limiting their range of motion. This is one of the key features that significantly enhanced the mobile robot's functionality by being able to deploy the base link tracks, links 2 and 3 independently from the front and the back with various link sequences. The other important key feature is the overall geometrically symmetric design (in stowed-links configuration – Fig 15a) that allows the platform to invert itself and continue to operate with no need of special purpose active means to re-invert it.

6.1. Robot mobility

The proposed design of the hybrid mobile robot was tested in simulations in Section 3. The simulations demonstrated a compact articulated hybrid mechanism that is able to exhibit new mobility, manipulation, and compounded locomotion and manipulation capabilities. The experimental results in this section demonstrate the validity of the proposed design paradigm hypothesis as well as the validity of the simulations. The experimental results shown in Fig. 16 accurately coincide with the simulation results shown in Fig. 4. The simulations are claimed to be valid by showing that the functionalities of the virtual prototype robot shown through simulations can be replicated with the actual physical prototype in real-world environments.

Different types of terrains such as flat roads, obstacles, stairs, ditches, ruble piles and ramps, were tested with different shapes and sizes. These types of obstacles are typical challenges mobile robots face during applications for search and rescue, reconnaissance, military operations, hazardous site inspections, etc. By providing the new locomotion and manipulation capabilities with the HMR system, the functionality performance of mobile robots in those applications is expected to be dramatically improved.

Some of the challenging tests that were used in order to test the hybrid robot are as follows (the experimental results are also summarized in a graphical format in Fig. 17):

(a) Climb and descend stairs (Fig. 16a) with different materials (wood, metal, concrete, plastic plastered, etc.), different stair riser and run sizes, and inclinations (50° stair slope);
(b) Step obstacle climbing and descending (Fig. 16b and c): different heights of step obstacles were tested. According to the experimental results, the HMR could climb steps up to 0.7 m (28 inch) height and descend even greater heights of 0.85 m. This can be achieved since during descending, link 3 can be extended in addition to link 2 to support the front of the robot while descending as shown in Fig. 16d. It should be noted however that in this case a "hard landing" of the front end of the robot on the ground occurs. The transition between configurations (c)-(3) and (c)-(4) may cause flipping over of the robot. But in this case, the new robot

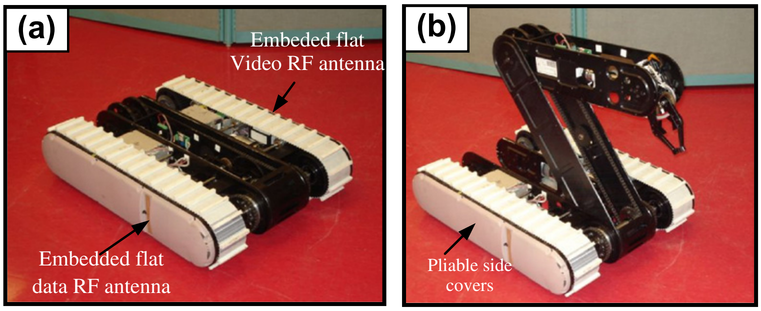


Fig. 15. Mobile robot prototype: (a) stowed-links configuration mode and (b) open configuration mode (all other covers removed).

Fig. 16. Experimental results: (a) stair climbing; (b) step climbing with tracks; (c, and d) step descending; (e) surmounting tall cylindrical obstacles; (f) ditch crossing.

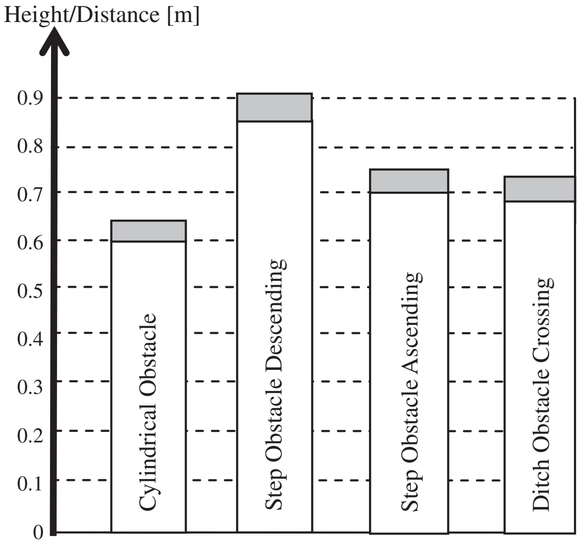


Fig. 17. Experimental results: metrics for obstacle traversal.

configuration will be as the one shown in Fig. 16(a)-(2), in which case the step descending process is completed with the tracks' rotation about joint 1 with link 2 used as a support.

(c) Traversing cylindrical obstacles of different diameters (Fig. 16e). The experiments show that the hybrid robot is able to traverse up to 0.6 m (24 inch) obstacle diameter;
(d) Ditch crossing: different widths of ditches were tested (Fig. 16f). According to the experimental results, the hybrid robot could cross up to 0.7 m (28 inch) ditch width.

The graphical representation of the above results is presented in Fig. 17 in order to show the height/distance variances between different tasks. The white regions represent the "safe region" where the robot was able to successfully accomplish the prospective task without failure. The gray region represents a feasible region as well, but the task's successful accomplishment was not guaranteed – namely, failure may occur. Beyond the gray region, the robot fails to accomplish the prospective task due to physical limitations of the links length and interactive conditions between the links and the obstacle (mainly due to insufficient traction).

In order to test the wireless control hardware architecture operational fault-tolerance capability, the communication to the motor that drives the left or right track was deliberately interrupted in some of the experiments (e.g., when the robot was descending the table as shown in Fig. 16c or (d)). It was observed that the motion of the right or left base link track alone was sufficient in order to change the position of the robot from (c)-(1) to (c)-(2) or from (d)-(2) to (d)-(3) in Fig 16. The rest of the links functioned properly in order to successfully complete the step descending procedure.

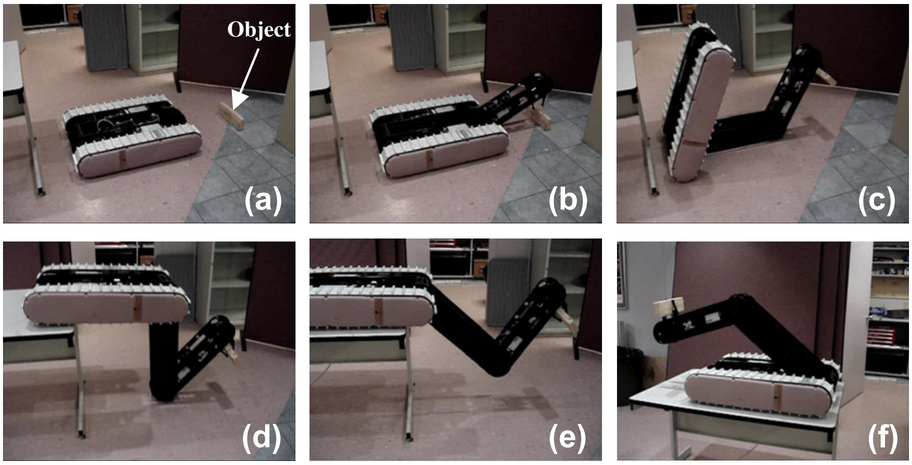


Fig. 18. Simultaneous climbing and manipulation.

6.2. Simultaneous locomotion and manipulation

The various climbing and descending tasks presented in the previous section can be incorporated simultaneously with manipulation of objects. Various experiments were performed in order to demonstrate this 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, Sections 6.2.1 and 6.2.2 present two cases where the robot climbed and descended a 0.7 m step obstacle while holding an object.

6.2.1. Simultaneous obstacle climbing and manipulation

Fig. 18 demonstrates 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. This step climbing is similar to the one shown in Fig. 16b except that link 3 remains deployed in order to manipulate the object simultaneously.

6.2.2. Simultaneous obstacle descending and manipulation

Fig. 19 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. 16d with the exception that link 3 remains deployed in order to manipulate the object at the same time.

6.3. Configurations of mobility for traversing rubble piles

Fig. 20 depicts a simulated earthquake scenario in an office building. The robot's task was to traverse a rubble pile in its way to access and reach a target and search for survivors. This scenario demonstrates the hybrid robot's capability to easily climb over the 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 the base link tracks, links 2 and 3. Some of the configuration steps in Fig. 20 also show how the platform effectively utilizes its ability to adjust the level of traction to effectively traverse the rubble pile.

6.4. End-effector payload capacity for manipulation

The following experiments demonstrate the dramatically increased actuator strength capacity for manipulation purposes due to the articulated hybrid mechanical structure. The end-effector load capacity for different manipulation configurations was also evaluated. The graph shown in Fig. 21 describes the load

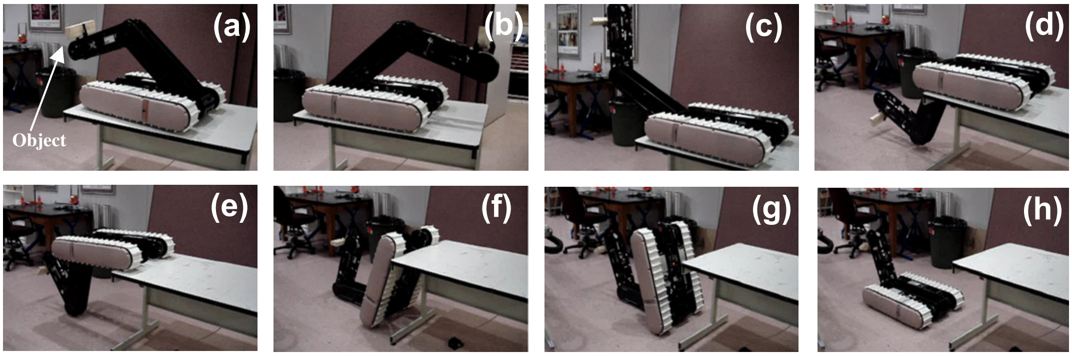


Fig. 19. Simultaneous descending and manipulation.

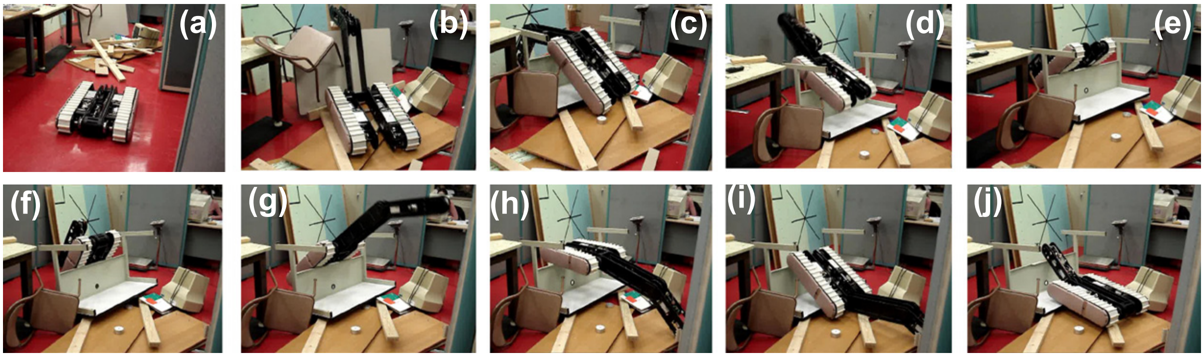


Fig. 20. Combined mobility configurations for rubble pile traversal.

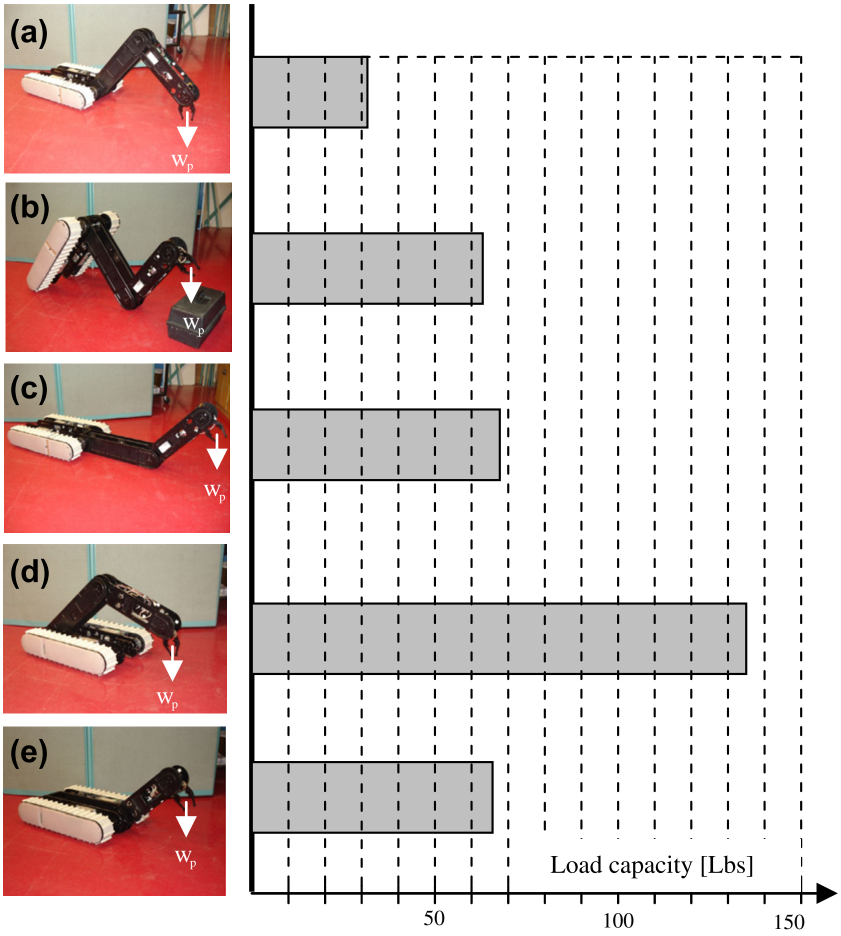


Fig. 21. Configurations for manipulation.

capacity of the end-effector for several possible manipulation configurations.

In some of the cases, the limiting factor in testing the end-effector payload capacity was the robot's ability to sustain structural stability (e.g., tilt forward due to the heavy payload at the end-effector). In other cases, joint torques 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. 21, for a given torque capacity in joint 1, configuration (d) is optimal with a maximum dynamic 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 joints 1 and 2 torque capacities are increased. This result is a direct consequence of the new design – namely, the hybrid nature of the platform and manipulator arm and their ability to be interchangeable in their roles.

7. Conclusions

This paper presented the complete development and experimental results of a new mobile robot system that can be used in a vast variety of pertinent applications, such as: search and rescue missions, reconnaissance, inspection, surveillance, planetary exploration, and police and military tasks. This is by the virtue of its ability to provide new locomotion and manipulation capabilities that greatly help to overcome challenging obstacles that are typically encountered in those applications. The new mobile robot design was based on hybridization of the mobile platform and manipulator arm mechanisms as one entity for robot locomotion as well as manipulation. As part of the development, we presented new distributed wireless electrical/control hardware architecture for mobile robots, which was implemented in the new articulated mobile robot design. The design, construction and experimental validation of the novel control hardware architecture for on-board inter-segmental wireless communication among the robot's links were successfully accomplished. Various other mobile robot configuration, where similar mechanical/control hardware design characteristics are required, can adopt this control hardware architecture. It provides a wireless communication network between subsystems of a given mechanical system in order to avoid any wire connections. This approach, along with expandable independent power source for each subsystem, resulted in modular control hardware architecture that also provided operational fault-tolerance.

The hybrid mobile robot's simulated locomotion and manipulation modes, such as those shown in Figs. 2 and 4 were experimentally validated with a physical prototype, as was shown in Fig. 16. The new 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. Some of the tasks include: traversing tall cylindrical obstacles (up to 0.6 m); climbing and descending stairs (variety of slops, materials, and sizes); climbing and descending tall obstacles (up to 0.7 m); crossing ditches (up to 0.7 m); lifting payloads of up to 61 kg (135 lbs) in manipulation mode and carrying payloads of up to 187 kg (410 lbs) in locomotion mode; and tasks that require simultaneous manipulation and climbing/descending of obstacles. The hybrid mobile robot's versatile and agile functionality has also shown the ability to traverse rubble piles, which also demonstrate the durability characteristics of the new mobile robot design. The presented new locomotion, manipulation and hybrid functionality modes can be used to overcome pertinent locomotion and manipulation challenges in a wide range of practical applications, such as search and rescue missions, earthquake sites, reconnaissance, planetary exploration, military and police operations, etc. Video clips showing the robot performing the functionalities described in the experiments section and various other tasks are available online in the following link: http://www.seas.gwu.edu/~bentzvi/HMR/HMR_Videos.

As part of the future work, we plan on developing a new OCU that includes a video monitor and video/audio RF receiver so that the camera images can be communicated and displayed for out of sight remote operations. We will evaluate the technological aspects of such implementation and the practicality of the camera position on the robot and controllability of the vehicle (out of sight and based on the camera images only).

Acknowledgments

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