ROSE 2007 - IEEE International Workshop
on Robotic and Sensors Environments
Ottawa - Canada, 12-13 October 2007

# Implementation of Sensors and Control Paradigm for a Hybrid Mobile Robot Manipulator for Search and Rescue Operations

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***Abstract*—This paper presents the control paradigm and embedded sensors for a mobile robot manipulator whereby the mobile platform and manipulator arm are designed as one entity to support both locomotion and manipulation simultaneously and interchangeably in several configuration modes. Along with the description of the novel design architecture, we developed, constructed and tested a novel paradigm for on-board RF data communication among robot's joints. This paper also describes the sensor and camera layout and their implementation in the mobile robot manipulator. A modular and extensible power source system design with major key elements that allow for easy reconfiguration and expansion was also developed, implemented and tested for the hybrid mobile robot manipulator.**

***Index Terms*—mobile manipulator, robot sensors, control architecture, search and rescue.**

## I. Introduction

In the aftermath of September 11, 2001, mobile robots have been used for USAR (Urban Search and Rescue) activities such as: searching for victims, searching paths through the rubble that would be quicker than to excavate, structural inspection, detection of hazardous materials, etc. 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, which were not used at all. Some 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 [1].

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). Various robot designs with actively controlled traction [2],[3], also called "articulated tracks", were proposed to improve rough-terrain mobility. Efforts are continuously made in designing robots that allow a wider control over COG (Center of Gravity) location [7] to produce robustness to effects attributed to terrain roughness.

There are various good designs of 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 [4], PackBot [3], Andros Mark V robots [2], Wheelbarrow MK8 [5], AZIMUT [6], LMA [7], Matilda [8], Helios VI and VII robots [9],[10], Variable configuration VCTV [11], Ratler [12], and MR-7 [13]. Helios VII robot, from the Helios series robots of Hirose & Fukushima Robotics Laboratory, provides a very good design of tracked mobile robot for disaster response [10]. Some legged robots [14] 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 capabilities.

Typically, a tracked mobile robot's structure consist of a mobile platform propelled with the aid of a pair of tracks and a manipulator arm attached on top of the mobile platform to provide the required manipulation capability (neutralization of bombs or landmines, manipulation of hazardous materials, etc). However, the presence of an arm limits the mobility. On the other hand, there are several designs of mobile robots with enhanced mobility capability on the account that they are not equipped with a manipulator arm on top. We bridged this gap in our approach by providing a new mobile robot design that provides compounded manipulation and locomotion capabilities. The new design architecture is based on hybridization of the mobile platform and manipulator arm as one entity for robot manipulation and locomotion. 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 II B.

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

A thorough review of the literature assisted us in deriving a conceptual function-oriented analysis in order to qualitatively identify the major issues of mobile robots in field operations in functionality level that have led to the new design approach. A summary of the issues, related research problems and proposed solutions are outlined in Table I.

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TABLE I
FUNCTION-ORIENTED ANALYSIS - ISSUES, RELATED RESEARCH PROBLEMS, AND PROPOSED SOLUTIONS

| **Issue** | Manipulator arm and mobile platform are separate modules | Manipulator arm mounted or folded on top | Flip-over occurrence: invertibility vs. self-righting |
|---|---|---|---|
| **Research problem** | Each module contributes to design complexity, weight & cost | Arm susceptible to breakage and damage | To provide self-righting without special purpose active means |
| **Proposed solution** | Design the manipulator arm and mobile platform as one entity | Integration of arm and platform as one entity in a *symmetric* design eliminates exposure | Symmetric platform to allow flip-over and enhance mobility |

## II. CONCEPTUAL DESIGN ARCHITECTURE

In order to address the design and operational problems mentioned above, the paper introduces new mechanical design architecture of a mobile manipulator system. The approach is a systematic and practical design method that attempts to address the overall system's operational performance.

The proposed idea is two-fold and is described as follows:
(i) Integrate the manipulator and the mobile platform as one entity to yield a hybrid mechanism rather than two separate and attached modules. Consequently, the same joints (motors) that provide the manipulator's dof's also provide the mobile platform's dof's;
(ii) In order to enhance the robot's mobility, when a flip-over takes place, instead of trying to prevent the robot from flipping-over or attempting to return it, the platform will be "allowed" to flip-over and continue to operate from its new position. Therefore, when a flip-over takes place, it will only be required to command the robot to continue its task from the current position, with no need of self-righting or added active means to return it. The two parts (i) and (ii) of the idea complement each other.

### *A. Description of the Concept*

The embodiment of the proposed idea is depicted in Fig. 1. If the platform is inverted due to flip-over, the fully *symmetric* nature of the design (Fig. 1(a)) 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, two wheel tracks, end-effector and passive wheel(s). To support the symmetric nature of the design, all the links are nested into one another. Link 2 is connected between the two base link tracks via joint 1 (Fig. 1(b)). Two wheel tracks are inserted between links 2 and 3 and connected via joint 2 and a passive wheel is inserted between link 3 and the end-effector via joint 3 (Fig. 1(c)). The wheel tracks and 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$^o$ rotation and can be deployed separately or together from either side of the platform. To prevent immobilization of the platform during a flip-over scenario, rounded and pliable covers are attached to the sides of the platform as shown in Fig. 1(a).

### *B. Configuration Modes of Operation*

The links can be used in three different modes: (a) All links used for locomotion to provide added level of maneuverability and traction; (b) All links used for manipulation to perform various tasks; (c) 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.

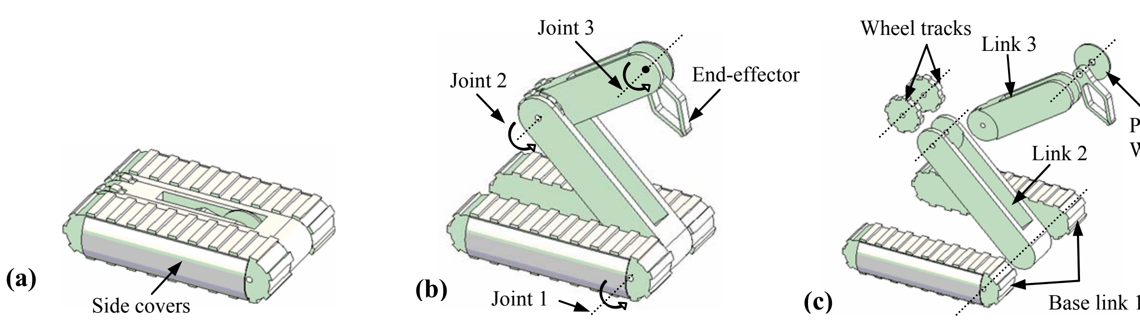


Fig. 1 (a) closed configuration; (b) open configuration; (c) exploded view.

### C. Manoeuvrability, Traction and Manipulation

Fig. 2(a) shows the use of link 2 to support the platform for enhanced mobility purposes as well as climbing purposes. Link 2 also helps to prevent the robot from being immobilized due to high-centering, and also enables the robot to climb taller objects (Fig. 2(b)). Link 2 is also used to support the entire platform when moving is a tripod configuration while using the other links for manipulation (Fig. 2(c)). For enhanced traction, the articulated nature of the mobile platform allows it to be adaptable to different terrain shapes and ground conditions (Fig. 2(e)). Fig. 4(c) and (d) depict two of the different configurations for manipulation purposes. While some links are used for locomotion, others are used simultaneously for manipulation.

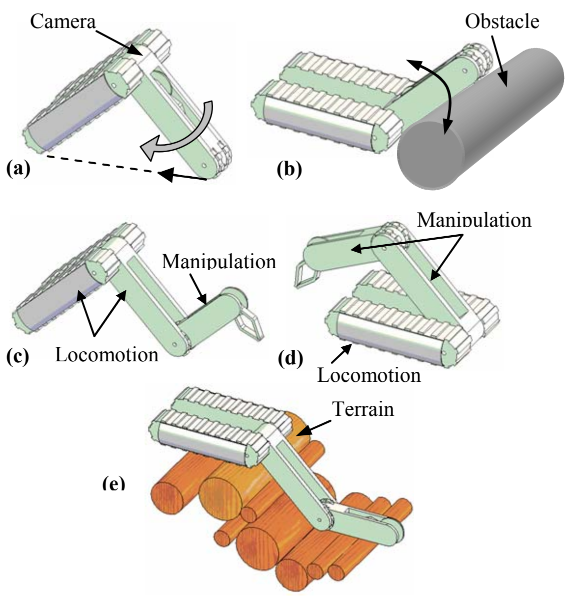


Fig. 2 (a),(b) sample mobility configurations; (c),(d) sample manipulation configurations; (e) configurations for enhanced traction.

## III. Mechanical Design Architecture

The mechanical architecture of the mobile robot shown in Fig. 3 embodies the conceptual design paradigm as described in Section II. Excluding the end effector, the design includes four motors (including gear-heads); two are situated at the back of each base link track to propel the tracks independently and the other two at the front to propel links 2 and 3 (Fig. 5).

The design also includes a built-in dual-operation track tension and suspension mechanism situated in each of the base link tracks. It includes spring suspended supporting planetary pulleys; three situated at the bottom of each track and another three at the top. While the bottom three supporting pulleys are in contact with the ground, they act as a suspension system. At the same time, the upper three supporting pulleys will provide a predetermined tension in the tracking system. The role of the pulleys at the bottom and top is interchangeable when the platform is inverted, thereby accounting for the symmetric design and operation of the mobile robot. Another usage of the spring array is to absorb some of the energy resulting from falling or flipping, thus providing compliance to impact forces.

A fully loaded depiction of the mobile manipulator is shown in Fig. 3. General specifications of the robot are provided in Table II.

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 (arm stowed) | 179 [mm] |

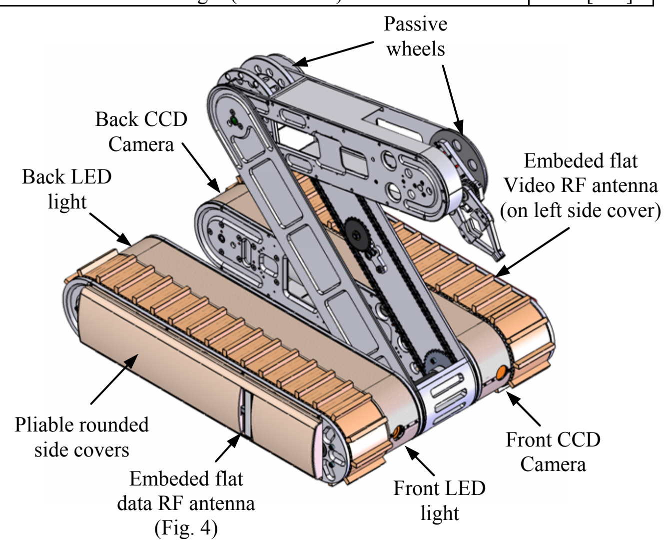


Fig. 3 Fully loaded mobile manipulator.

## IV. On-Board RF Control Paradigm

All electrical hardware (such as batteries, controllers, drivers, sensors etc) is situated in the left and right base link tracks. Other motors and associated electrical hardware for the gripper mechanism (end-effector) are situated in the space available in link 3 (Fig. 5).

### A. On-Board Inter-segmental RF Communication Layout

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

The right base link track contains a central RF module (Fig. 6(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 also assists in eliminating 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 [15] were designed (Fig. 4) and embedded into the side covers of the robot for RF video communication and RF data communication as shown in Fig. 3.

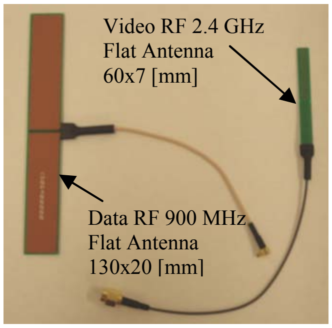


Fig.4 Embeddable flat antennas for video and data RF communication.

*B. RF Hardware for the Hybrid Robot*

As shown in Fig. 5, the OCU includes MaxStream [16] 9XTend 900 MHz RF Modem. The data transmitted by the stand alone RF modem at the OCU is received by a 9XTend OEM RF Module that is situated in the right base link track as shown in Fig. 6(a). The 9XTend module communicates with the controller that controls the electronics (motors and associated drivers, sensors, etc.) in the right base link track while at the same time sends data pertaining to the other segments (left base link track and link 3) to a MaxStream XBee OEM 2.4 GHz RF Module in a wire connection. 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 the other for link 3 (Fig. 6(b) and (c)), thus providing on-board RF data communication among robot joints.

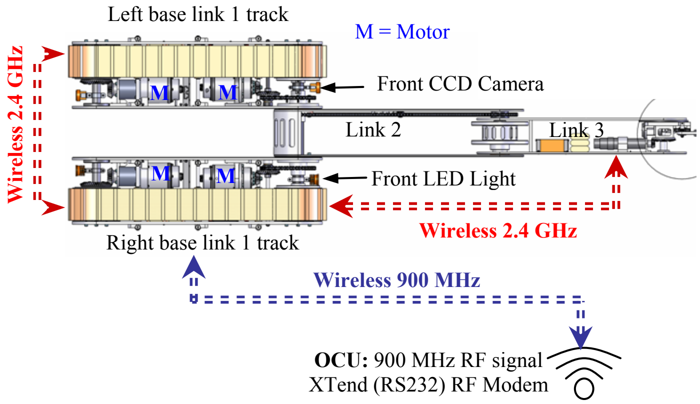


Fig. 5 RF communication layout.

The use of the XBee OEM RF module is advantageous in several ways: (i) the need for a vertically sticking out antenna for each link segment of the mobile manipulator is eliminated since the RF module is available with a PCB chip antenna (Fig. 6(a)); (ii) its operating frequency is 2.4 GHz – namely, different operating frequency than the primary 9Xtend RF module; (iii) fast RF data rate of 250 kbps; and (iv) its small form factor (2.5x3[cm]) saved valuable board space in the compact design of the robot.

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

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

Fig. 7 shows the experimental setup developed in collaboration with Engineering Services Inc., in order to perform preliminary RF communication tests between the distributed RF XBee modules in the system [17]. Using the joystick, we sent motor rotation commands through the OCU 9XTend RF Module to an on-board 9XTend RF Module that distributed the data to a local XBee RF module in a wire connection. The wireless data transmitted by the local XBee module was successfully received by the on-board XBee module in a wireless manner with no data loss even when the XBee modules were partially/fully enclosed and apart from one another.

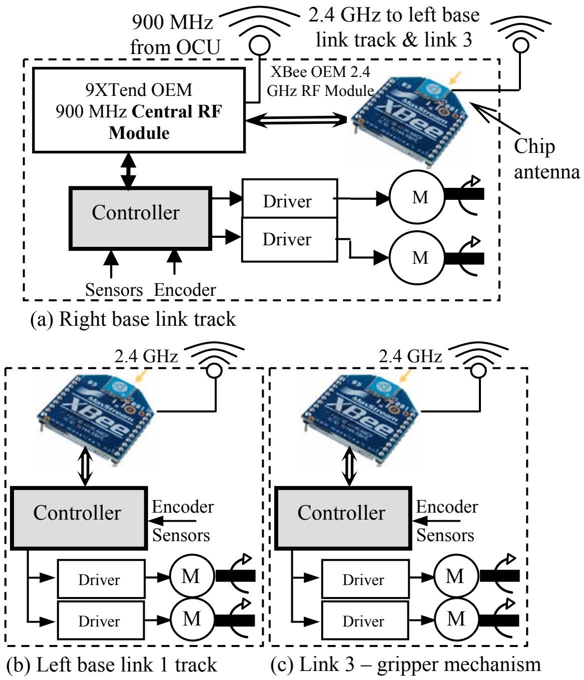


Fig. 6 Hardware architecture: (a) right base link track; (b) left base link track; (c) link 3 – gripper mechanism.

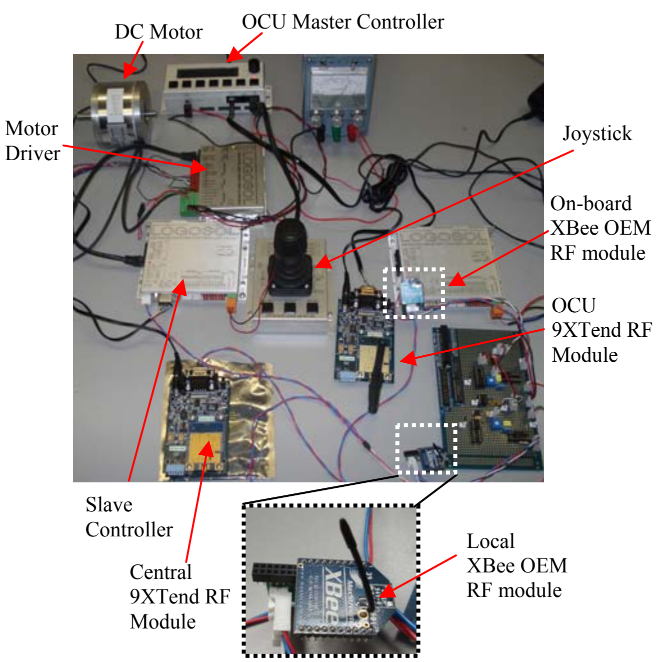


Fig. 7 Experimental setup for RF comm. testing.

## VI. Electrical Hardware Architecture

### A. Controllers, Drivers, Sensors and Cameras Layout

The microcontroller in each link is a Rabbit based core module. There are several analog input channels on the module through which the microcontroller receives signals from the sensors. Each motor in the base link tracks is driven by a Logosol driver (LS-173s), which acts as a motor controller to provide position and speed control. Signals from encoders attached to the rear shaft of each motor are sent to the drivers as feedback. The sensors with which the robot is equipped with are a tilt sensor; thermometer, GPS, three-axis compass and battery-voltage monitor (Fig. 8). As shown in Figs. 3, 5 and 8, 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 decides the image of which camera is being transmitted.

### B. Power System Design and Implementation

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

A modular and extensible power system design was developed and implemented for the hybrid robot. It has two major key elements that allow for easy reconfiguration and expansion: Li-Ion battery packs and power distribution board.

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

According to the tests performed, this special construction provides a battery unit with nominal voltage of ~45V and continuous current discharge of 13.2 Amp with a max current discharge of 15 Amp due to the PCM. This electrical performance is advantageous considering the very compact size of the battery pack (110x110x70 mm) and overall weight of only 1.6 Kg.

*Power Distribution Board:* The power distribution board is an in-house designed circuit board used on the hybrid robot. Its sole purpose was to take the power provided by the battery charging boards and distribute it to the various on-board instruments. Flexibility is achieved through the use of commercial DC-DC converters. Power from the battery charging boards is funnelled through several DC-DC converters which regulate the voltage up or down as necessary before being distributed to the instruments. Since these units are available in many different output voltages, it was easy to mix and match converters as needed. Each power distribution board can be extended by stacking boards as necessary to provide additional output voltages or more power per voltage source.

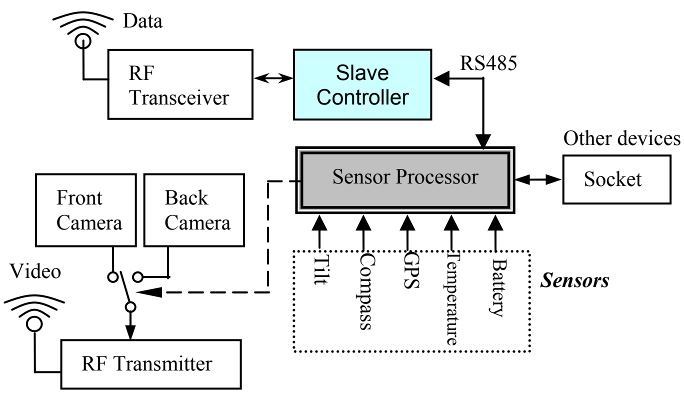


Fig. 8 Sensors and cameras layout.

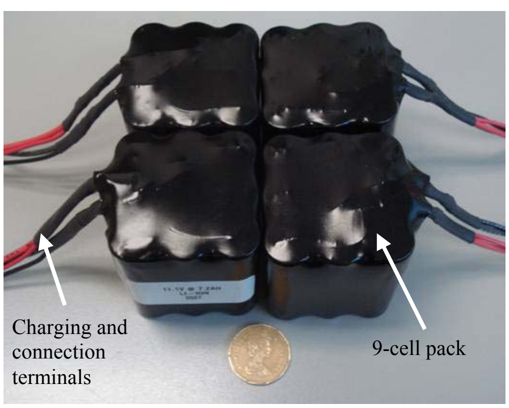


Fig. 9 Li-Ion battery packs assembly.

## VII. Conclusion

This paper presented solutions for electrical and control hardware architecture issues to sustain the new mobile robot design architecture that was based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. In addition to introducing the novel mechanical architecture of the mobile manipulator, we designed, constructed and experimented a novel technique for on-board inter-segmental RF communication among the robot's links and the associated electrical hardware architecture for the entire robotic platform. Various other applications, where similar mechanical design characteristics are required, can benefit from this control architecture. This hardware architecture 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. Furthermore, power source system design that exhibits extensibility and modularity characteristics was developed and tested.

## 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, and Engineering Services Inc. (ESI).

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