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WIRELESS MODULAR CONTROL HARDWARE ARCHITECTURE FOR HYBRID MECHANISM MOBILE ROBOT

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ABSTRACT

This paper presents a new generalized control hardware architecture based on embedded on-board wireless communication network between robot's links and modules such as the actuators and sensors. This approach results in modular control hardware architecture since no cable connections are used between the actuators and sensors in each of a given mobile robot subsystems (links). The effectiveness of this approach is experimentally demonstrated and validated by implementing it with a hybrid mobile robot mechanism as a case study. The hybrid mobile robot mechanism integrates the locomotion mechanism and manipulator arm mechanism as one entity to support both locomotion and manipulation simultaneously and interchangeably.

1 INTRODUCTION

Control architecture issues are 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 paper presents the development of a new systematic approach for a modular control hardware architecture that dramatically increases the functionality of the hybrid mechanism 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.

Increasingly, mobile robotic systems are required to perform difficult mobility and manipulation tasks in rough terrains since they 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 [1],[2], also referred to as "articulated tracks", were proposed to improve rough-terrain mobility. Examples of other robots are: Talon [3], PackBot [2], Andros Mark V robots [1], AZIMUT [4], Helios VI and VII robots [5],[6], Variable configuration VCTV [7], and NUGV [12]. One of the major issues with the design of mobile robots for field operations is the ability to provide sufficient functionality to ideally account for both locomotion and manipulation capabilities simultaneously. Often, the mechanical architecture of a mobile robot is restricted by the control/electrical hardware architecture constraints. For instance, among the mobile robots that can provide manipulation capability, the manipulator arm platform is typically attached on top of the locomotion platform. The platforms provide distinct functions. Namely, the locomotion platform provides mobility (with a pair of tracks, wheels or the combination of both) and the arm platform provides manipulation (manipulation of hazardous materials,

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neutralization of bombs or landmines, etc).

The implementation of the new proposed control hardware architecture with wireless interfaces significantly assisted with the development of the new hybrid mobile robot mechanism design [8],[9]. It has the ability to interchangeably provide locomotion and manipulation capability, both simultaneously. This was accomplished by integrating the locomotion mechanism and the manipulator arm mechanism as one entity resulting in a hybrid mechanism rather than two separate modules. The manipulator arm can be used as part of the locomotion platform and vice versa.

In order to provide for the required modular mechanical and control system architecture, the links or subsystems constituting the mobile robot are connected wirelessly. This, along with independent power source in each subsystem, also eliminates the need for physical wiring and slip ring connections between the rotating links.

2 HYBRID MOBILE ROBOT MECHANISM DESIGN

In this section, we briefly introduce the mechanical design architecture of the Hybrid Mobile Robot (HMR) mechanism as a case study for the implementation of the newly proposed control hardware architecture.

The proposed idea is two-fold and is described as follows: (i) Integrate the manipulator and the mobile platform as one entity resulting in 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) Design the overall mobile robot platform in a 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 Paradigm:

The prototype embodying the proposed idea is depicted in Fig. 1. If the platform is inverted due to flip-over, the fully *symmetric* 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, end–effector and passive wheels. To support the symmetric nature of the design, all the links are nested into one another. Link 2 is connected between the two base link tracks via joint 1 (Fig. 1(b)). Passive wheels are inserted between links 2 and 3 and connected via joint 2 and another passive wheel is inserted between link 3 and the end-effector via joint 3 (Fig. 1(b)). 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^{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(b).

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 manipulability. The pair of base links 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.

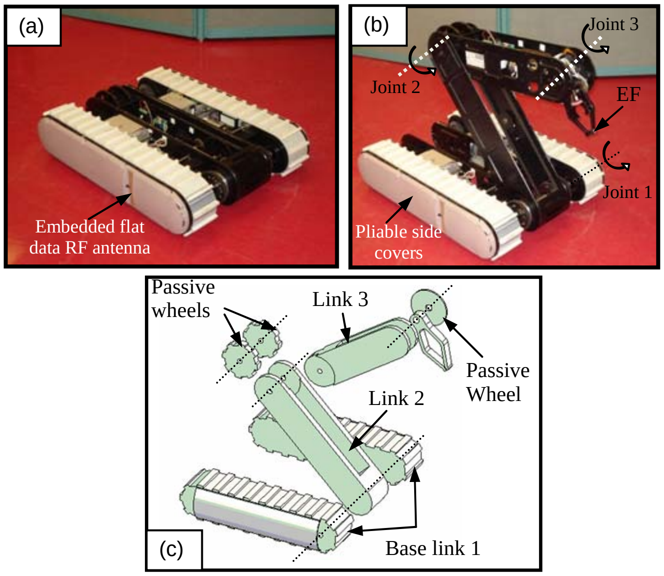


Figure 1. Photos of the prototype: (a) stowed-links configuration mode; (b) open configuration mode (all other covers removed); (c) exploded view.

3 ON-BOARD WIRELESS SENSOR/ACTUATOR CONTROL PARADIGM

The proposed generalized wireless and modular control hardware architecture is depicted in Fig. 2. This scheme provides on-board wireless hardware control interfaces between several subsystems constituting a given mechanical system and fulfills 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 (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 specific 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) 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); (ii) slip ring connections (which greatly complicate the system design, and increase weight due to increased number of mechanical components).

(3) Avoid direct RF communication between each robot segment and the OCU (Operating Control Unit) in order to:
  - Eliminate stand-alone vertically sticking 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, the data pertaining to all robot links is received in one location on the robot, and then transmitted and distributed to the other links wirelessly.

Solutions:

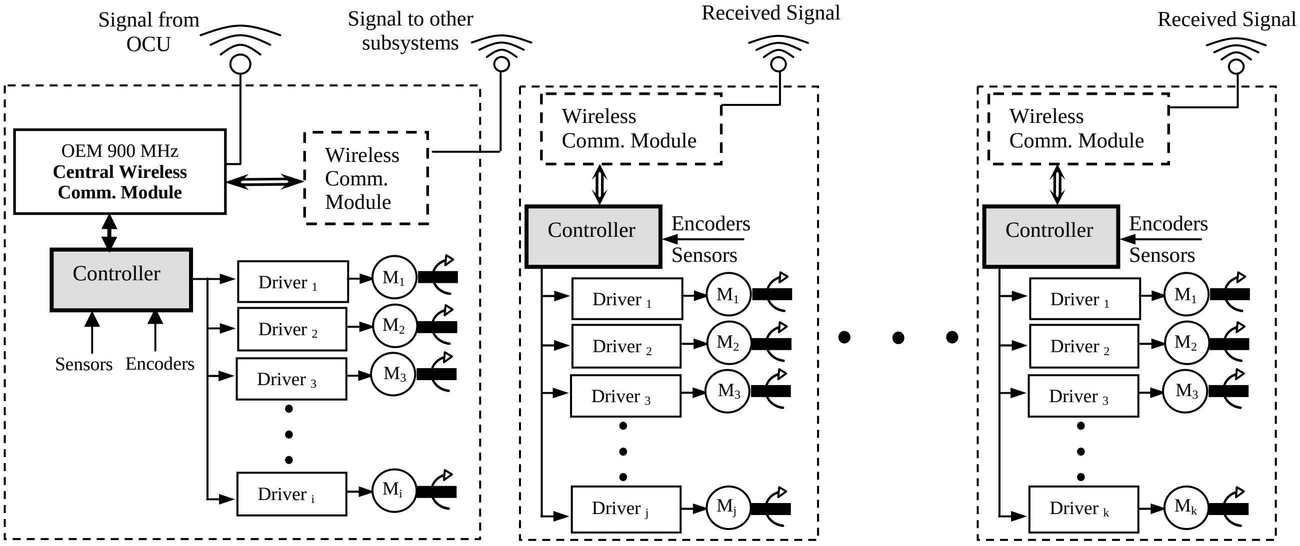
(1) Provide independent power source for each robot link/subsystem (using Li-Ion battery packs).
(2) Enable on-board wireless communication between robot links/subsystems:
  - Ensures that data pertaining to robot links is received in one location and then distributed to other subsystems.

3.1 Generalized On-Board Wireless Communication Layout:

Fig. 2 shows a mechanical system with *n* subsystems. A central wireless communication module can be embedded in any of the *n* subsystems (e.g., Fig. 2(a) shows the central comm. module in subsystem 1) for communication with the OCU (Operator Control Unit), while each of the remaining subsystems contains a wireless comm. module for inter-segmental on-board wireless communication. This, along with independent power source in each subsystem, facilitates wireless communication between the rotating and 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 comm. module that can be situated in any of the *n* subsystems as shown in Fig. 2(a). This wireless comm. 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 module in a wire connection. This data is then transmitted wirelessly to the remaining (*n-1*) wireless modules (subsystem 2–subsystem *n*), thus providing on-board wireless data communication among robot subsystems.

This hardware architecture provides expandability in terms of the number of subsystems that can be added or removed in order to construct a given 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 in the subsystem.



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

Figure 2. Generalized On-Board Wireless Communication Layout.

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 comm. module fails. In order to solve this problem, a *central* wireless module can be imbedded in each of the subsystems rather than only in one of them and triggered in a predetermined sequence to act as a router in case the neighboring subsystem that contained the central comm. module failed.

3.2 Case study – Wireless Hardware Architecture for the Hybrid Mobile Robot using RF Comm.:

To experimentally demonstrate the validity of the scheme provided in Fig. 2, it was implemented as a case study on the Hybrid Mobile Robot using RF communication in the manner shown in Fig. 3. In this case, the OCU includes MaxStream [10] 900MHz RF Modem. The data transmitted by the stand alone RF modem on the OCU is received by an OEM RF Module that is situated in the right base link track as shown in Fig. 4(a). This RF module 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 links (left base link track and link 3) to a XBee OEM 2.4 GHz RF Module in a wire connection. This data is then transmitted wirelessly to two other XBee OEM 2.4 GHz RF modules – one for the left base link track and the other for link 3 (Figs. 4(b) and (c)), thus providing on-board wireless RF data communication among robot joints.

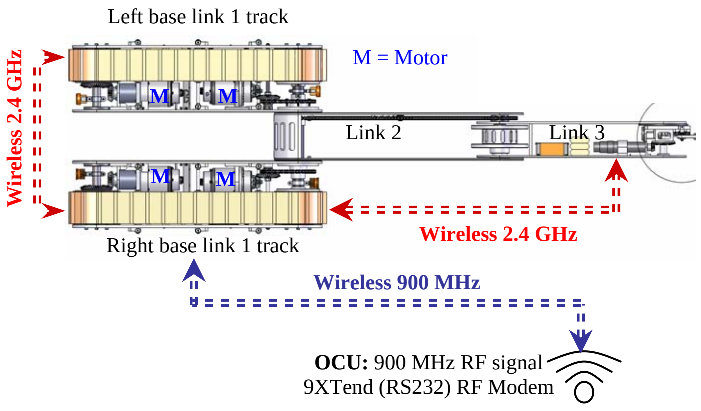
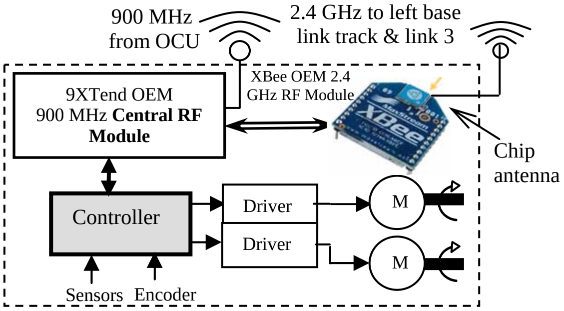


Figure 3. On-board wireless communication layout for the HMR.

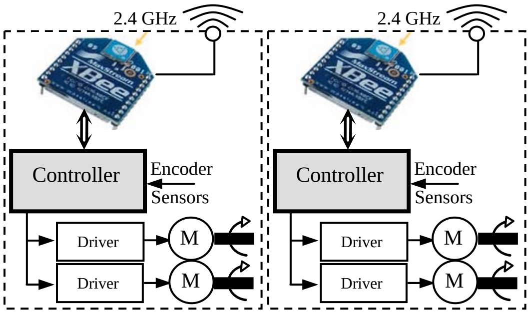
The XBee OEM RF module is advantageous in several ways: (i) eliminates the need for a vertically sticking out antenna for each link segment of the mobile manipulator since it is available with a PCB chip antenna or miniature whip antenna (Fig. 4(a)); (ii) its operating frequency is 2.4 GHz – namely, different operating frequency than the primary RF module; and (iii) its small form factor (2.5 x 3 [cm]) saves 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. Due to the short and fixed distances between the robot's links, low-power on-board RF modules between the left and right base link 1 tracks and link 3 were used. The XBee RF module with a chip antenna has an *indoor* wireless link performance of 24 [m] range approx., which is much less than the max fixed distance between the base link tracks and link 3 (<0.5 [m]).

Vertically sticking out antennas are avoided by designing flat antennas [11] (Fig. 1(a)) and embedding them into the robot side covers for wireless data communication between the OCU and the right base link track, as shown in Fig 1(a).



(a) Right base link track



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

Figure 4. Hardware architecture for the HMR: (a) right base link track; (b) left base link track; (c) link 3 – gripper mechanism.

4 EXPERIMENTAL VALIDATION

Following the completion of the prototype, a series of tests were performed to assess the performance of the proposed wireless and modular hardware architecture with the hybrid mobile robot.

The experimental results shown in Fig. 5 demonstrate the robot's mobility and manipulability characteristics and some challenging tasks that the mobile robot was able to accomplish with the integrated wireless control architecture. Specifically, it provided the mobile robot with the ability to generate continuous rotations to each of its links without limiting each of its links' range of motion. This is one of the key features

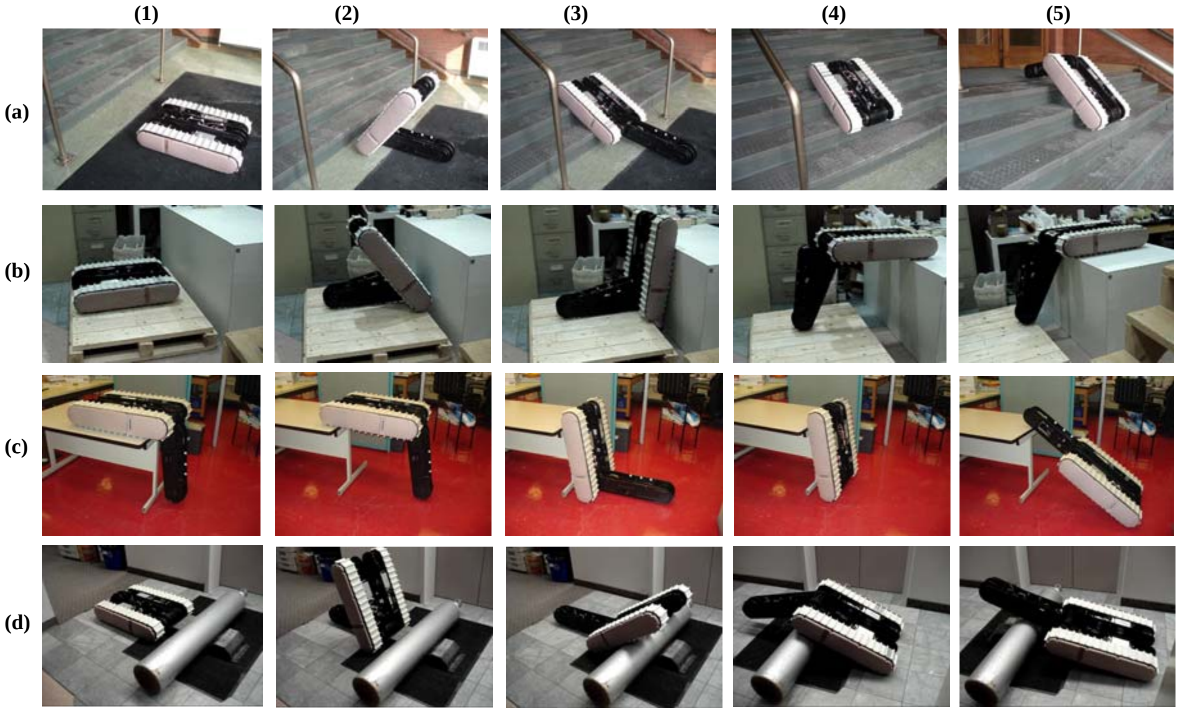


Figure 5. Experimental results: (a) stair climbing; (b) step climbing with tracks; (c) step descending; (d) surmounting tall cylindrical obstacles.

that significantly enhanced the mobile robot's functionality by being able to deploy the base link tracks, link 2 and 3 independently from the front and the back with various link sequences. Some of the tests are listed as follows:

(a) Climb and descend stairs (Fig. 5(a)) with different materials (wood, metal, concrete, plastic plastered, etc.), different stair riser and run sizes, and inclinations (up to 50^0 stair slope);

(b) Step obstacle climbing and descending (Figs. 5(b) and (c)): different heights of step obstacles were climbed by being able to deploy the base link tracks, link 2 and 3 independently from the front and the back. According to the experimental results, the hybrid robot could climb and descend steps up to 0.7 m (28 inch) height;

(c) Traversing cylindrical obstacles of different diameters (Fig. 5(d)). The experiments show that the hybrid robot is able to traverse up to 0.6 m (24 inch) pipe diameter.

In one of the experiments, when the robot was descending the table as shown in Fig. 5(c), the communication to the motor that drives the left track was deliberately interrupted in order to test the wireless control hardware architecture operational fault tolerance capability. It was observed that the motion of the right base link track was sufficient in order to change the position of the robot from (c)-(1) to (c)-(2) in Fig. 5. The rest of the links functioned properly in order to successfully complete the step descending procedure.

5 CONCLUDING REMARKS

This paper presented new wireless electrical/control hardware architecture for mobile robots. This architecture was implemented with a new mobile robot design that is based on hybridization of the mobile platform and manipulator arm as one entity for robot locomotion as well as manipulation. The design, construction and experimental validation of a novel control hardware paradigm for on-board inter-segmental wireless communication among the robot's links were successfully accomplished. Various other applications, where similar mechanical/control design characteristics are required, can benefit from this control architecture. This hardware architecture provides a simple solution when on-board inter-segmental wireless communication is required to avoid any wire, cable loop, and slip-ring mechanical connections between different parts of a given mechanical system. This approach, along with independent power source for each subsystem (link), resulted in modular control architecture that also provided operational fault tolerance.

The hybrid mobile robot's locomotion and manipulation functions, such as those shown in Fig. 5, were experimentally validated. The functions of locomotion, manipulation and hybrid locomotion and manipulation have been utilized to demonstrate a variety of challenging practical tasks the mobile robot was able to perform. Some 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 step obstacles (up to 0.7 m); crossing ditches (up to 0.7 m); and tasks that require simultaneous manipulation and climbing/descending of obstacles.

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