Haptic Control of a 6-Legged Running Machine

Tomas Szabo, Sarjoun Skaff, and Ralph Hollis

***Abstract*— We present initial efforts concerning haptic interaction (feed forward control and reflective force feedback) of a highly dynamic six-legged running machine. The haptic master is a newly-developed 6-DOF magnetic levitation haptic device with high position bandwidth and motion resolution. The six-legged running machine is a slightly modified version of the RHex robot. In addition to haptics, real-time video streaming was added to create a visio/haptic operator workstation for wirelessly controlling the motions of the remote robot. It is hypothesized that the addition of visio/haptic feedback will provide operators with improved situational awareness of the robot in the remote environment.**

I. Introduction

Teleoperation of robots has shown the benefits of combining the inherent physical capabilities of the machine with the cognitive capabilities of the human [1], [2]. For the past several decades, teleoperation of mobile robots has incorporated joysticks, switch closures, and other simple mechanisms for commanding the machine, combined with visual feedback from an on-board video camera to help guide the operator. Recently, however, there has been a growing recognition that teleoperation efficacy can be markedly improved by the addition of haptic feedback. Haptic control of mobile robots is not an entirely new topic. This paper, unlike previous work, explores haptic control of a legged mobile robot having significant dynamics.

II. Background

The work of Barnes and Counsell in 1999 is one of the earliest efforts to integrate haptic feedback in the control of mobile robots [3]. Several experiments were performed which showed improved operator performance when haptics was used. Fong, *et al.* describe wireless visual/haptic control of a small skid-steered mobile robot using a 3-DOF Delta haptic device [4], [5]. In this work, the 3-DOF haptic device was constrained to a pair of DOFs defining planar motion, where the master's forward/backward position was mapped to the slave vehicle's forward/backward speed, and the master's left/right position was mapped to the slave vehicle's left/right turning rate. An array of infrared sensors mounted on the vehicle provided range to nearby obstacles, and this information was used to impart a repulsive obstacle-avoidance force back to the haptic master. Khatib, *et al.* describe efficient algorithms supporting haptic interaction with realistic physical models of mobile robots [6]. Rosch, *et al.* used a force-feedback joystick to control a small mobile robot equipped with force sensors [7]. Ott, *et al.* describe and evaluate a multi-modal virtual reality interface using a multi-DOF Haptic Workstation from Immersion Corp. for controlling a small Lego robot [8]. Several visual and graphical feedback interfaces were also incorporated. When collisions were detected by contact sensors on the robot, minimal haptic feedback cues such as bursts of vibration were generated. Park, *et al.* consider the teleoperation of a mobile robot for hazardous environment applications using a distance-based repulsive force for obstacle avoidance [9] with a novel 6-DOF haptic master [10]. Diolaiti and Melchiorri demonstrated haptic teleoperation of a small Activmedia Pioneer differential-drive mobile robot using a 3-DOF PHANToM haptic interface [11], [12]. The authors consider virtual interaction forces computed from sensed obstacles surrounding the mobile robot in order to prevent collisions, and explicitly consider the passivity of the overall system to preserve stability. Lee, *et al.* provide one of the most complete descriptions of haptic teleoperation of a mobile robot [13]. The authors adopt a "car-driving" metaphor that maps the position of a 2-DOF haptic device to the speed and turning rate of a car-like mobile robot. Results were analyzed both objectively and subjectively, indicating a statistically significant positive benefit for the inclusion of haptic feedback in the teleoperated control of the robot.

Recently, several groups have considered haptic control of mobile robots over the Internet. Here, additional issues of bandwidth and latency come into play. Elhajj, *et al.* have explored a non-time based event form of control over the Internet [14], [15], and Lim, *et al.* have implemented a virtual impedance model similar to that of [11] over the Internet [16]. Lee and Spong have recently provided a complete treatment of passivity issues for bilateral teleoperation of a mobile robot over a medium with constant time delay [17].

The previous studies cited above, while laying the

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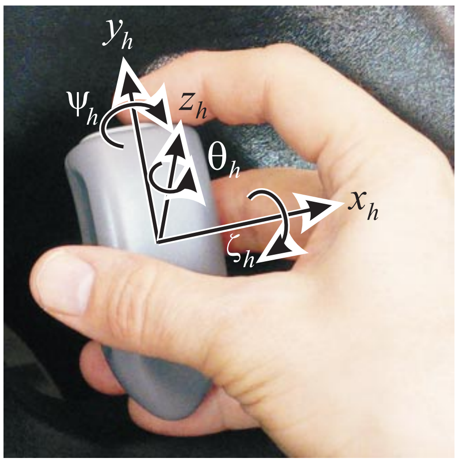

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Fig. 1. New second-generation 6-DOF magnetic levitation haptic device: (a) overall view showing the spherical swivel mounting in a desktop which allows re-orientation to suit users' preferences, (b) closeup of the modular handle with superimposed embedded coordinate frame.

foundation for an important body of work, concern haptic interaction and control of wheeled mobile robots whose dynamics can safely be ignored. This simplification is not warranted for highly dynamic running machines such as the Rhex robot used in our studies. The exploration of haptic control of running machines provides a new and exciting opportunity to engage haptics in the human-robot interaction loop.

III. Magnetic Levitation Haptic Interface

The haptic master system features a newly developed desktop-mounted magnetic levitation haptic device (MLHD) shown in Fig. 1. The device has a light weight bowl-shaped "flotor" containing six spherical coils that is levitated in strong magnetic fields created by NdFeB permanent magnets. An interchangeable handle is rigidly attached to the flotor. Three LEDs attached to the flotor are tracked by optical position sensors, thereby enabling closed-loop control. The device exhibits extremely high fidelity since there are no motors, gears, bearings, cables, or linkages present as in conventional haptic devices. Its high stiffness range and frequency response characteristics not only engage the user's proprioceptive senses, but also to a significant degree the touch sensors in the skin such as the Pacinian corpuscles having a peak sensitivity at about 250 Hz [18]. The haptic master behaves as an almost ideal "impedance" device, where handle positions and angles are sent to the remote robot, and pure forces and torques are displayed to the hand in return. Compared with the popular 3-DOF PHANToM haptic interface, the MLHD has a bandwidth of 130 Hz compared to about 10 Hz, and maximum stiffness of 40 N/mm compared with about 1 N/mm. The small motion range of the device is easily overcome by scaling, rate control, and indexing. We believe the MLHD master is an ideal device for conveying accurate, subtle, high-frequency information from teleoperated mobile robots. Table I briefly summarizes its main performance characteristics.

Attribute	**Value**
Degrees of freedom	6
Maximum impedance	40.0 N/mm
Translational workspace	spherical
Minimum impedance	0.002 N/mm
Translation range	±14 mm
Impedance ratio	20,000:1
Rotation range	±8°
Flotor mass	503 g
Position bandwidth	130 Hz (-3 dB)
Levitation power	4.5 W
Position resolution	3μm (1σ)
Device pose	adjustable
Peak force	40 - 100 N
Handle	interchangeable
Peak torque	4.5 - 8.8 Nm
Handle buttons	2
RT operating system	QNX Neutrino 6.3
User interface	structured API

TABLE I

Abbreviated performance characteristics of 2nd generation magnetic levitation haptic interface systems.

IV. The RHex Running Machine

RHex is a six-legged machine (Fig. 2) that can execute a collection of dynamic behaviors, including walking, jogging, and running. These behaviors are made possible by synchronizing the legs three by three to produce an alternating tripod gait, and by designing the legs to have specific compliance properties. Compliance allows the legs to store and release energy in the form of elastic deformation, thus enabling energy-efficient locomotion.

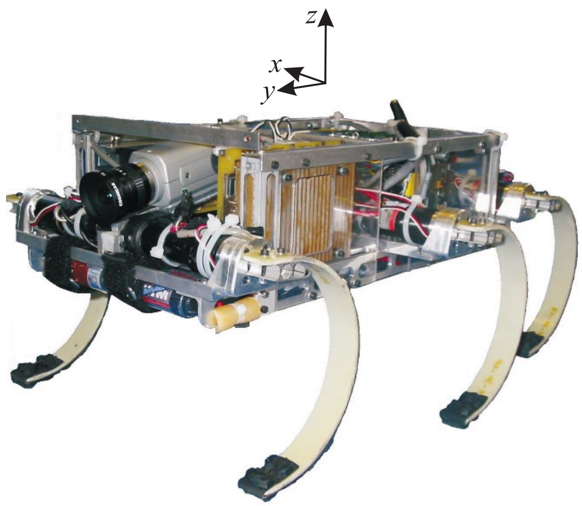

Fig. 2. RHex 6-legged running robot.

These characteristics are particularly important for producing jogging and running behaviors which alternate flight and stance phases akin to animal running, and propel the body at speeds up to five body lengths per second [19], [20].

The machine has an on-board video camera and an on-board IMU. The IMU has MEMS accelerometers and fiber-optic gyros, providing orthogonal accelerations and body attitude information. It is normally controlled through a wireless Ethernet link from a Logitech game controller. In the usual case, the operator directly observes the robot visually while commanding forward/backward speed and turning rate. The robot's internal gait pattern generating software takes care of the details which are of little concern to the operator. The robot's ability to run and scramble through forests, rubble, mud, and other harsh terrain is unprecedented.

V. Visio/Haptic Interaction Scheme

Our developed visio/haptic interaction scheme is illustrated in Figure 3. Here, the haptic master handle y_h position and θ_h orientation are mapped to RHex's forward/backward speed v and turning rate ω, much as is currently done with the Logitech hand controller. Forces F_y and F_z, as well as the torque τ_y are fed back to the operator. Other haptic interaction modes are possible. In addition to haptics, there is real-time video from the on-board camera as well as a graphical presentation of the robot's status for the operator. As RHex bounds along, rocking from side to side due to its alternating tripod gait, we hypothesize that haptic feedback will give the operator a greater appreciation of the dynamic mechanical environment the robot is operating in. Figure 4 shows typical acceleration data from RHex's on-board accelerometer.

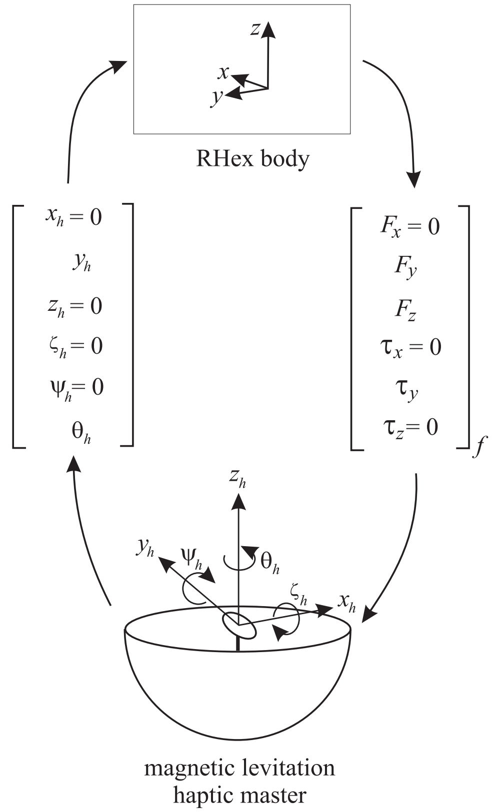

Fig. 3. One possible mapping between the MLHD and the robot. The haptic master provides position and orientation commands to the robot while forces and torques are fed back to the operator's hand.

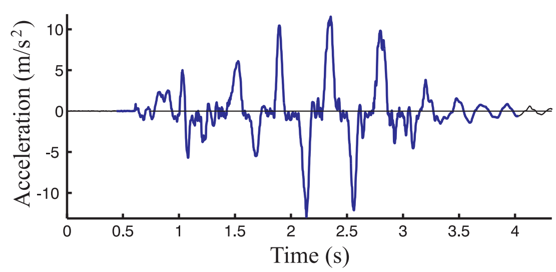

Fig. 4. RHex z-axis acceleration during a short run.

VI. Implementation

Interfacing the magnetic levitation haptic system to RHex involved combining functionality of the haptic system API with the robot software based on RHexLib [21]. RHexLib is a general purpose software library for creating real-time control systems which was originally developed for RHex, but has evolved to a collection of tools which have been applied to other robots as well. Its main components are a Module Manager which is a synchronous scheduler for simple periodic tasks; facilities for configuration and message display;

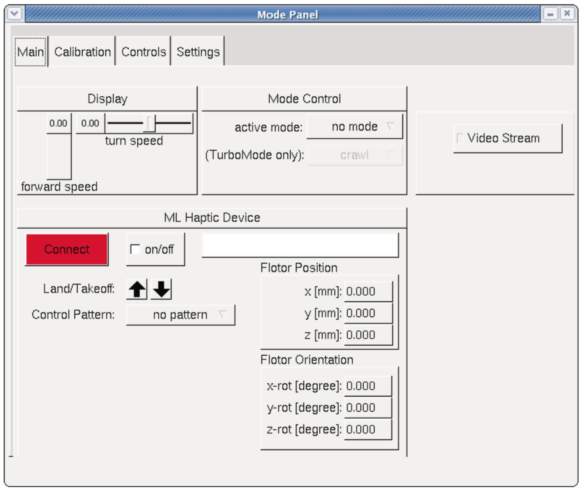

Fig. 5. Sample page from operator's interface.

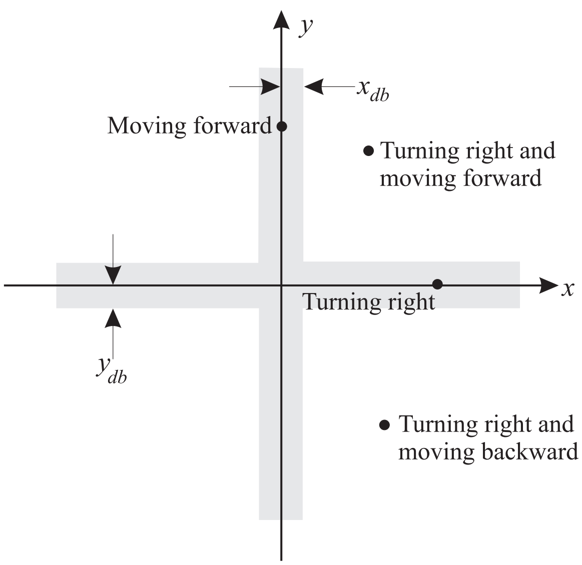

Fig. 6. Mapping of haptic handle y position and θ_z orientation to robot velocities. Dead bands of half-width x_{db} and y_{db} (shown in gray) were implemented to improve stability and lesson operator fatigue.

state machine tools for designing controllers as formal state machines; communications middleware based on a client/server model; a distributed database (blackboard) shared over a network; services for logging data in real time; a Mode Supervisor which enables switching between a number of pre-defined operating modes; and a Hardware Interface to facilitate code re-use across different physical platforms.

Server code runs on the robot, while client code runs on the operator's haptic/graphic workstation. The haptic system consists of the Magnetic Levitation Haptic Device (MLHD) and its local controller. Figure 5 is a snapshot of the operator interface.

A. Controlling RHex's motion from the MLHD

For the present purposes, the motion of RHex is completely defined by the vector

$$\dot{\mathbf{x}} = \begin{bmatrix} v \\ \omega \end{bmatrix}. \tag{1}$$

It was found necessary to add a dead band around the zero position and orientation of the haptic handle to avoid inadvertent small motions from resulting in unwanted commands to RHex. Figure 6 shows the mapping between the haptic handle position and orientation and the robot velocities.

The robot's forward speed is thus given by

$$v = \begin{cases} k_1 \cdot g(y, y_{db}, y_{offset}), & \text{if } |y| > y_{db} \\ 0 & \text{otherwise ,} \end{cases} \tag{2}$$

and rotation rate is given by

$$\omega = \begin{cases} k_2 \cdot g(z, z_{db}, z_{offset}), & \text{if } |z| > z_{db} \\ 0 & \text{otherwise ,} \end{cases} \tag{3}$$

where

$$g(a,b,c) = \begin{cases} (a-c)-b, & \text{if } a > 0 \wedge a > b \\ (a-c)+b, & \text{if } a < 0 \wedge a < b \\ 0 & \text{otherwise ,} \end{cases} \tag{4}$$

where k_1 and k_2 are scalar gains.

B. Getting Haptic Feedback from RHex

RHex is equipped with many different sensors, however most of them are for use in control loops, *e.g.* leg positions, currents, and voltages. Additionally, there is a tri-axial accelerometer and fiber-optic gyro which are used to help stabilize RHex's attitude during high-speed running and path tracking operation. Our initial experiments with haptic feedback have so far used only data from the accelerometer.

In the past, these accelerometer data were recorded by RHexLib's data logger for later analysis. For haptic feedback, it was necessary to modify the software to provide real time data. This was achieved by adding a new module, HapticFeedbackModule, to RHexLib. Due to limited on-board computational power and the need to transmit the data wirelessly, we were able to achieve an update rate of approximately 100 Hz. This was deemed adequate for haptic feedback.

The vertical acceleration of RHex was mapped to the z axis of the MLHD using the simple linear equation

$$feedback_z = \begin{cases} a_z \cdot \frac{A_{max}}{a_{input}}, & \text{if } a_z \leq a_{input} \\ A_{max} & \text{otherwise} \end{cases} \tag{5}$$

where

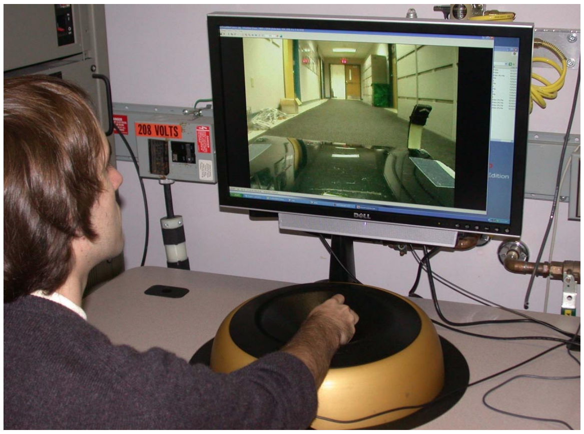

Fig. 7. Controlling RHex through the visio/haptic interface, showing a typical run through a hallway.

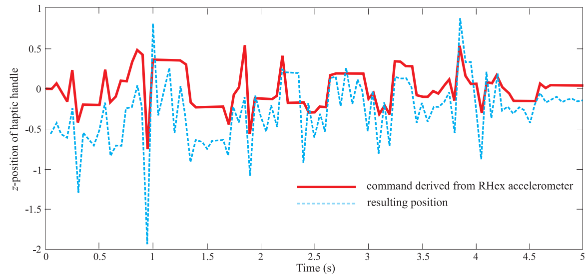

Fig. 8. Haptic handle position for a 5s interval during a typical run.

a_z : vertical acceleration of RHex,
a_{input} : user defined input range of the acceleration,
A_{max} : user defined maximal rendered amplitude. (6)

This simple mapping in z was chosen to avoid direct interaction with the haptic y and θ_z control actions.

C. Real-time Video Stream from RHex

RHex is equipped with a small monochrome CMOS USB camera which has been used for control in line tracking experiments [22]. It was decided to replace this camera with an Axis 207W MPEG-4 802.11g wireless web camera whose CMOS image sensor provides 640×480 pixel color images at up to 30 fps. The horizontal field of view with the provided lens is 55°. The operator's workstation was equipped with an Edimax 802.11g wireless LAN PCI adapter, allowing display of the streamed images in a browser window.

At first, the camera was mounted on a bracket at the front of the robot. The rather narrow field of view afforded by the camera lens made it difficult for operators to immediately appreciate the robot's surroundings. In later trials, the camera was mounted about 100 mm above the robot's top side toward the back, looking forward with the front part of the robot in the field of view. This proved to be a satisfactory arrangement. Figure 7 shows an operator controlling the robot through the developed visio/haptic interface.

VII. Initial Results

Once the system was operational, and all communication links were established, a number of runs were made in a laboratory and hallway environment. The robot was found to be easily controllable when out of direct view of the operator. The actions of moving the haptic handle forward or backward were quite effective in smoothly controlling the robot's forward or backward speed. Likewise, twisting the haptic handle in z caused smooth left or right rotations of the robot. These actions were understandably similar to controlling RHex with a game controller. The addition of streaming video for visual feedback served to give the operator the natural point of view of being attached to the robot and looking forward.

The addition of haptic feedback to control the z-motion of the haptic handle based on RHex's vertical accelerations was quite interesting but could be greatly improved in the future. It was easy for the operator to experience changes in frequency as the robot changed speeds, but it was not clear at the time of this writing whether the haptic information helped the operator's awareness. Figure 8 shows the z-position of the haptic handle for a 5s interval during a typical run. The solid trace is the commanded handle position derived from RHex's acceleration according to Eq. 5, whereas the dashed trace is the actual handle position provided by querying the haptic device through an API function. A moderately stiff PD controller was running in the haptic device, causing it to track commanded positions. As can be seen from the plots, the haptic handle tends to track the acceleration data, but the motion in any case is quite jerky and a bit confusing to the operator. If the operator grasps the handle lightly, he or she will be aware of its vertical motion. If the operator grasps the handle firmly, it will not move much, but forces will be felt, due to the action of the PD controller.

VIII. Discussion

There are many fundamental research questions remaining. In the work to date, the environment is unmodeled and the only haptic information is from the robot's on-board accelerometer. Choice of reference frame may be critical. With the frames illustrated in Fig. 3, the metaphor is like having one's hand holding a vertical handle attached to the top side of the robot. Choice of which DOFs to communicate and which to suppress to insure stability and minimize crosstalk between axes forms a very interesting set of questions.

We are not aware of previous efforts concerning haptic control of a highly dynamic running robot. It would seem that putting the human in the loop in real time in the best possible way is of vital importance for effective teleoperation of advanced-mobility robots. The methods and initial results presented in this paper will hopefully serve to inform future developments in many kinds of mobile systems exhibiting highly dynamic behavior.

IX. Future Work

This work may be extended in many ways. We have so far used only the z-component of acceleration for haptic feedback. The robot also has significant rolling (side-to-side rocking) motion while running, which can also be fed back to the haptic handle in a way that is uncoupled from the command DOFs. Utilization of attitude data from the on-board fiber optic gyro could provide haptic feedback as well.

With the addition of short range proximity sensors on the robot, haptic repulsion from sensed nearby obstacles obstacles can be fed back to the operator. If there is some means of localizing the robot within a known environment or if there is a capability for using simultaneous localization and mapping techniques (SLAM), then it will be possible to present visio/haptic haptic constraints to the operator in a manner similar to that presented in [11], [12].

Finally, work must be done to quantitatively measure the degree of benefit (positive or negative) to the operator in his or her control of the robot performing typical tasks. As part of this study, it will be necessary to remotely operate the robot in varying outdoor environments while assessing the operator's ability to haptically discriminate between different conditions. Psychophysical measurement techniques can be exploited for determining the ultimate efficacy of providing visio/haptic feedback for this class of highly dynamic running machines.

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