

# Towards Real-Time Haptic Exploration using a Mobile Robot as Mediator

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## ABSTRACT

In this paper, we propose a new concept of haptic exploration using a mobile manipulation system, which combines the mobility and manipulability of the robot with haptic feedback for user interaction. The system utilizes and integrates heterogeneous robotic sensor readings to create a real-time spatial model of the environment, which in turn can be conveyed to the user to explore the haptically represented environment and spatially perceive the world without direct contact. The real-world values are transformed into an environmental model (an internal map) by the sensors, and the environmental model is used to create environmental feedback on the haptic device which interacts in the haptically augmented space. Through this multi-scale convergence of dynamic sensor data and haptic interaction, our goal is to enable real-time exploration of the world through remote interfaces without the use of predefined world models. In this paper, the system algorithms and platform are discussed, along with preliminary results to show the capabilities of the system.

**KEYWORDS:** Haptics, haptic exploration, mobile manipulation

## 1 INTRODUCTION

Haptics is a mature field of engineering research, with varying applications in medical training, rehabilitation, virtual reality, and teleoperation [1][2][3][4]. Its ability to transfer tactile and textural feelings along with force feedback adds another dimension of interaction between the human and the system. Unfortunately, a common characteristic we find in conventional haptic applications is that haptic feedback is typically generated from a static source. For example, in virtual environments, elements in the world commonly use 3D models suitable for direct representation of haptic features. Also, in haptic display systems for real-world objects, the sensor system and the target object interact in a fixed environment, which confines the operational workspace of the haptic device.

To address these issues, our approach integrates the advances in robotic capabilities with the haptic concept. Previous related efforts have shown that combining these systems provides enhanced capabilities in haptically guided robotic navigation [5] and medical operation systems with haptic controllers [6]. Major efforts have integrated haptic teleoperation with mobile systems and have proven its efficiency [7][8][9]. However, these previous works combine the haptic device's high dimensional controllability with the force feedback generated from a robotic sensor in a pre-designed fashion, i.e. 2D force guidance for

mobility control. Instead, our goal is to capitalize on the dynamic nature of a mobile manipulation robotic system to increase the robustness in control and to maximize the range of environmental feedback available to the haptic system.

We propose the concept of Haptic Exploration with Mobile Manipulator (HEMM) system which 1) enables a bidirectional linkage between a haptic device and mobile manipulation robotic system and 2) conveys the dynamic environmental data through haptic exploration. The benefits we expect with our paradigm are three-fold: first, the utilization of heterogeneous sensory data can enable multi-scale ranged environmental feedback through the haptic device; second, the mobility of the HEMM system can turn conventionally static haptic display into dynamic and wide-range, haptic interface; and thirdly, the multi-scale environmental haptic feedback can aid in increasing the operational safety of the mobile manipulator robot.

In Section 2, we provide an overview of the hardware and software components of the HEMM system. Detailed algorithms and architectural explanations follow in Section 3, where we discuss the haptic control framework and the virtual proxy based exploration algorithm. Finally, results of deploying our system in a simulated home environment and concluding remarks are provided in Section 4.

## 2 SYSTEM OVERVIEW

Mobile manipulation is a fast growing field [10] due to advances in robotic systems, increases in computing power, and a rising interest in applications for the home environment. One of the current issues arising in this area is the process of synergistically integrating human users into the system – i.e how do we enable novice users to provide directions and assistance to the robotic device in a natural manner [11]. To address this issue, our concept of Haptic Exploration with Mobile Manipulator (HEMM) is to integrate a haptic device in two ways - both as the controller for the mobile manipulation system and as the generator for the environmental feedback to the human user. And the mobile manipulation robotic system becomes the mediator between the user and environment – it works both as the agent that executes the human operator's commands and as the active agent that collects the environmental data utilizing on-board sensors and enables the human user to explore the 3D environment haptically.

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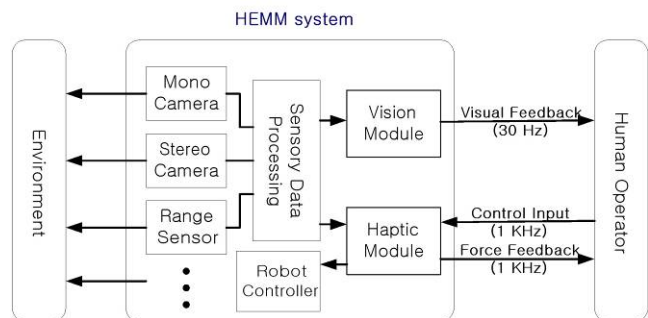


Figure 1. Basic Architecture of HEMM system

Our HEMM system (Figure 1) is composed of a haptic interface, mobile manipulation robotic system, and the software environment that governs the overall system. We first implement our HEMM system in a simulated environment (Figure 2) to evaluate the proposed concept, and analyze differences in robot task performance with and without the haptic feedback.



Figure 2. HEMM system with a simulated environment

### 2.1 Haptic Interface

We select a 6 DoF haptic device PHANToM Omni for providing haptic feedback in the HEMM system. It is capable of taking 6 DoF input and generating 3 DoF force feedback on the stylus. It has a smaller workspace (160 W x 120 H x 70 D mm) than the other versions of PHANToM models, but it is suitable for the desktop environment, and most importantly it is cost-wise efficient, which is important for commercializing the system and broadening the area of haptic applications to the home.

### 2.2 Mobile Manipulation System

The mobile manipulation robotic system used is the Pioneer3 AT mobile robot with the Pioneer2 Arm. Pioneer 3AT is a 4-wheel drive skid-steer mobile robot system (500 W x 490 D x 260 H mm) capable of all terrain navigation with up to 45° slope angle, at the speed of up to 0.7 m/sec, and payload of up to 30 kg. The Pioneer2 Arm is a 5DoF manipulator with reachable distance of 50 cm from the base joint and payload of 150g. The sonar sensors can be attached to the body frame, and currently a webcam is mounted on the wrist. We have also created a simulated representation of the hardware platform using a 3D model and integrated into a virtual environment. The simulated model consists of a mobile base, range sensor, and a 4DoF robotic arm on top as depicted in Figure 3.

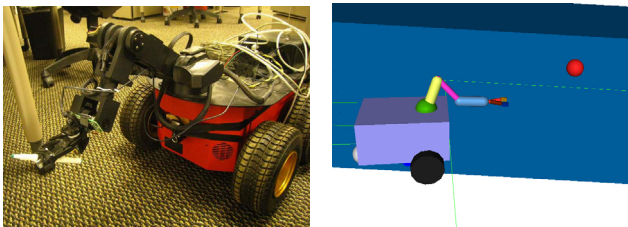


Figure 3. HEMM system with a simulated environment

### 2.3 Software Environment

We utilize the ARIA library [13] to develop the algorithms for controlling the mobile manipulator. For control of the haptic interface, we utilize the Open Haptics Academic Edition (OHAE) 2.0 [14] and HAPTik library [15]. We also developed a simulation environment to test and validate the HEMM system. A virtual home environment was designed where the mobile manipulator robot could navigate as well as “explore” – i.e. feel the environment, with the 6DoF PHANToM Omni. The mobile

manipulation system and sensor feedback was modeled using a rigid multi-body dynamics engine “srLib” (SNU Robotics Library) [12].

## 3 ARCHITECTURE AND ALGORITHMS

The control methods and algorithms for our HEMM architecture are described here. To control the mobile manipulation system with the haptic device, we first explain the workspace transformation process. We then describe an algorithm that generates virtual proxy forces from the sensor readings of the robotic agent. The value in this algorithm is that the environmental data comes not from the 3D virtual model, but from the sensor readings, and is processed dynamically by the HEMM system. As such, these proxy forces enable the human user to haptically explore the environment through the eyes of the robotic agent.

### 3.1 Robot Control Framework

Five workspaces must first be defined:  $B$ ={set of points in the base frame},  $H$ ={set of reachable points in the haptic device’s workspace},  $E$ ={set of reachable points for haptic exploration in the real/virtual environment with the haptic device},  $N$ ={set of control points for navigation of the mobile agent with the haptic device}, and  $M$ ={set of control points for the manipulation system with the haptic device} (Figure 4).

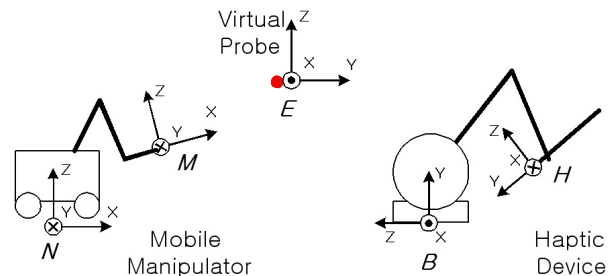


Figure 4. Workspaces in HEMM system

In order to enable a mapping between haptic-based commands and robot operation in the real world, three major workspace transformations exist between the five workspaces (Eq. 1). Letting  ${}^B T_A$  represent the transformation matrix for the rotation and translation from  $A$  to  $B$ , then,

$$\begin{aligned} {}^E T_H &= {}^V T_B \cdot {}^B T_H \\ {}^N T_H &= {}^N T_B \cdot {}^B T_H \\ {}^M T_H &= {}^M T_B \cdot {}^B T_H \end{aligned} \quad (1)$$

where  ${}^V T_B$  is a multi-scale linear mapping between the virtual workspace and the haptic workspace based on the choice of the sensor,  ${}^B T_H$  is given by the haptic interface, and  ${}^N T_B$  is a navigation mapping of 3D Cartesian position to a 2D vector of velocity and heading which are translated into the differential speed values for each left/right wheels of the robot.

${}^M T_B$  is a 5 DoF kinematic transformation of the robotic manipulator explained in Eq. 2-4.

$${}^M T_B = \begin{bmatrix} {}^M R_B & {}^M l_B \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{14} \\ \vdots & \ddots & \vdots \\ a_{41} & \cdots & a_{44} \end{bmatrix} \quad (2)$$

Here,  ${}^M R_B$  is the rotation matrix,  ${}^M l_B$  the translation matrix, and each member being defined as:

$$\begin{aligned}
a_{11} &= c_1 s_{23} c_4 s_5 + c_1 c_{23} c_5 + s_1 s_4 s_5 \\
a_{12} &= -c_1 s_{23} s_4 + s_1 c_4 \\
a_{13} &= -c_1 s_{23} c_4 c_5 + c_1 c_{23} s_5 - s_1 s_4 c_5 \\
a_{14} &= A_5 (c_1 s_{23} c_4 s_5 + c_1 c_{23} c_5 + s_1 s_4 s_5) + A_4 c_1 c_{23} \\
&\quad + A_2 c_1 c_2 + A_1 c_1 \\
a_{21} &= s_1 s_{23} c_4 s_5 + s_1 c_{23} c_5 - c_1 s_4 s_5 \\
a_{22} &= -s_1 s_{23} s_4 - c_1 c_4 \\
a_{23} &= -s_1 s_{23} c_4 c_5 + s_1 c_{23} s_5 + c_1 s_4 c_5 \\
a_{24} &= A_5 (s_1 s_{23} c_4 s_5 + s_1 c_{23} c_5 - c_1 s_4 s_5) + A_4 s_1 c_{23} \\
&\quad + A_2 s_1 c_2 + A_1 s_1 \\
a_{31} &= -c_{23} c_4 s_5 + s_{23} c_5 \\
a_{32} &= c_{23} s_4 \\
a_{33} &= c_{23} c_4 c_5 + s_{23} s_5 \\
a_{34} &= A_5 (s_{23} c_5 - c_{23} c_4 s_5) + A_4 s_{23} + A_2 s_2 \\
a_{41} &= a_{42} = a_{43} = 0, \quad a_{44} = 1
\end{aligned} \tag{3}$$

given that

$$\begin{aligned}
s_i &= \sin \theta_i, \quad c_i = \cos \theta_i \\
s_{ij} &= \sin(\theta_i + \theta_j), \quad c_{ij} = \cos(\theta_i + \theta_j) \\
A_i &= \text{length of Arm's joint } \#i, \quad i = 1, 2, 3, 5 \\
\theta_i &= \text{angle between } A_{i-1} \text{ and } A_i, \quad A_0 = \text{base frame}
\end{aligned} \tag{4}$$

Once we've calculated the transformation sequence, we now need to develop a methodology for dynamically mapping robot sensory data into haptic feedback

### 3.2 Virtual Proxy from Robotic Sensor Data

Multiple scaled transformation algorithms for the haptic exploration can exist in the HEMM system since the robotic agent typically has several heterogeneous sensory modules. But the core translation is the generation of 3D environmental feedback based on the multiple sensory data. To enable this feedback, we introduce the virtual proxy method based on 2D robotic range sensor readings.

As shown in Figure 5, the range sensor data is represented in a cylindrical coordinate frame. To give intuitive meaning to the user, we first spawn a 2D map in Cartesian coordinates from the range sensor readings. Once we have a map of the robot's dynamic position, we either get a navigation point, a manipulation point, or a virtual exploration point using Eq. 1, according to the system mode. A navigation point is defined as the user's intention point for the mobile platform to move to in the navigation workspace. A manipulation point is a point in a manipulation configuration space that displays the intention of manipulative task of the human operator. A virtual exploration point is a position of the virtual proxy in the simulated or real world which interacts with the perceived environment and generates the force feedback if any interaction is detected. We group these parameters under one popular term, virtual proxy, and in any mode, we calculate the interaction between the virtual proxy and the generated 2D map from the dynamic range sensor data, and generate the force feedback. The magnitude of the force is proportional to the depth of penetration, and the penetration is computed as a normal vector to the object surface recreated in the map. Interpolation can be used if the sensor data is sparse, and a windowing method can avoid error at the discontinuity points.

The key point here is that the interaction data is not given by the 3D virtual model, but is purely collected from the real or simulated environment by the sensors of the mobile manipulation

system. This process makes it possible to transfer the environmental perception through the robotic agent to the human user with dynamic haptic exploration.

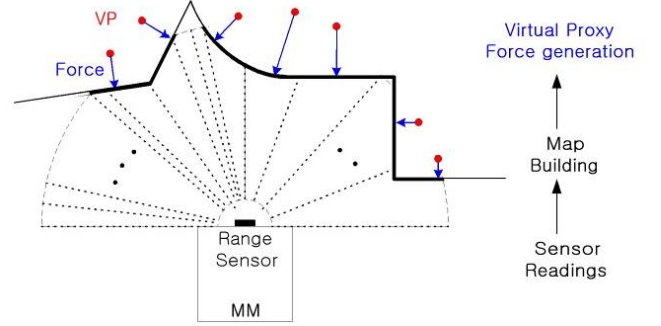


Figure 5. Virtual Proxy from 2D Range Sensor

## 4 RESULTS AND FUTURE WORK

In this section, we present our preliminary studies with the proposed HEMM system. We create a virtual home environment (Figure 6) where a mobile robot with a 5 DoF manipulator can navigate around and explore the spatial characteristics of the environment.

The force feedback from the HEMM system enables the human operator to control the robotic agent safely by helping to avoid collisions with any of the obstacles in the world. The user can receive environmental force feedback while controlling the robot, or can stop at any point and just explore, or 'feel' the environment. The haptic representation of the obstacles in the world through the virtual proxy method conveys the overall perception of the environment to the human user and enables active exploration of the environment (Figures 7 & 8).

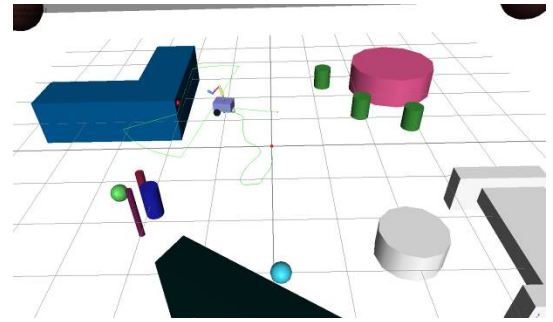


Figure 6. Haptic Exploration with a Mobile Manipulator in a Simulated Environment

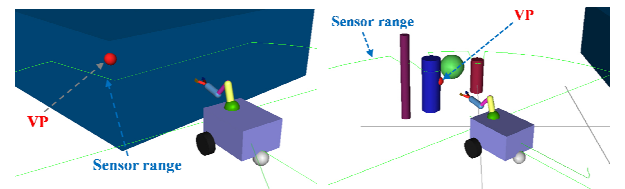


Figure 7. Haptic Exploration examples with the Virtual Proxy. (Left: detecting the edge of the wall, right: sensing multiple objects)

In Figure 8, we illustrate the resulting feedback forces that the user feels when approaching a stationary wall object in the environment which in turn changes the course of navigation in order not to collide with the wall. Force feedback during haptic

exploration, when the robot itself is stationary, is also depicted in Figure 9 where the user is moving the virtual proxy to feel the forces while examining the cylindrical object by cross-sectioning. Surface following with virtual probing is also achieved, but for visualizing the force differences we plotted the force distribution during the “cross-section” probing of the cylindrical object. The high-frequency artifacts in the force plot of Figures 8 and 9 are due to the quantization errors and the noise, and they are subtle enough not to generate any extra stress with the small haptic interface (unit of the force axis = 0.05N).

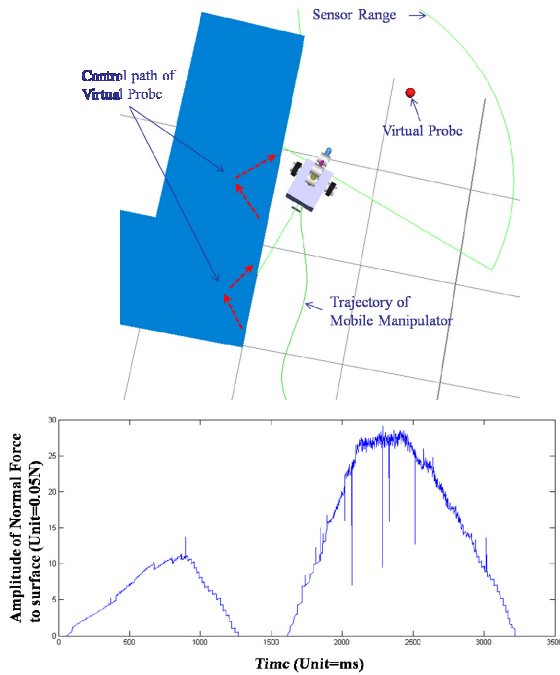


Figure 8. Haptic Feedback while navigating (up) and the force graph (down). (red arrow: path of the virtual proxy)

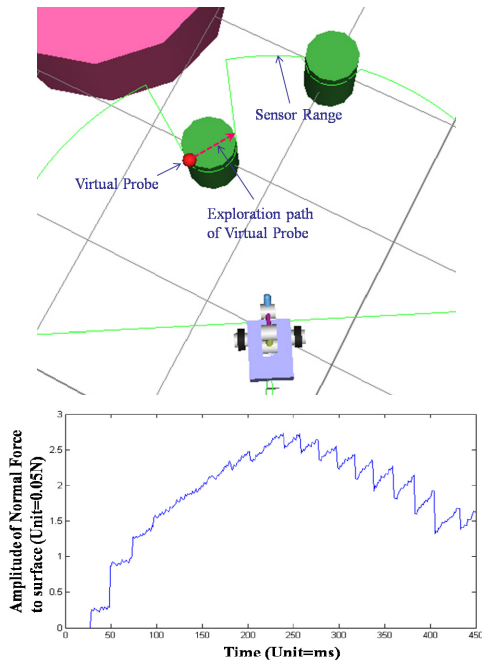


Figure 9. Haptic Exploration with the stationary robot (up), and the force graph (down). (red arrow: path of the virtual proxy)

Based on our preliminary studies, we have shown that by using the mobile robot as a mediator, dynamic feedback model can be created to allow haptic exploration of the real world. Our future work will focus on the integration of multiple sensory inputs from the robotic agent for unified haptic exploration. Monocular vision and stereo vision will be incorporated for the perception of the world from both mobile and manipulative perspectives. The switching controller for the mobile manipulation will be discussed in future work, and new ways to augment haptic reality will be studied while utilizing the full capabilities of the haptic system.

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