A Haptically Enabled Low-Cost Reconnaissance Platform for Law Enforcement

James Mullins  
Intelligent Systems  
Research Lab  
Deakin University  
Geelong Australia  
jmullins@deakin.edu.au

Ben Horan  
Intelligent Systems  
Research Lab  
Deakin University  
Geelong Australia  
benpatri@deakin.edu.au

Mick Fielding  
Intelligent Systems  
Research Lab  
Deakin University  
Geelong Australia  
mrf@deakin.edu.au

Saeid Nahavandi  
Intelligent Systems  
Research Lab  
Deakin University  
Geelong Australia  
nahavandi@deakin.edu.au

Abstract—Traditionally, the control system of a modern teleoperated mobile robot consists of one or more two-dimensional joysticks placed on a control interface. While this simplistic interface allows an operator to remotely drive the platform, feedback is limited to visual information supplied by on-board cameras. Significant advances in the field of haptics have the potential to meaningfully enhance situational awareness of a remote robot. The focus of this research is the augmentation of Deakin University’s OzBot™ MkIV mobile platform to include haptic control methodologies. Utilising the platform’s inertial measurement unit, a remote operator has the ability to gain knowledge of the vehicle’s operating performance and terrain while supplying a firmer level of control to the drive motors. Our development of a generic multi-platform ActiveX allows the easy implementation of haptic force feedback to many computer based robot controllers. Furthermore, development of communication protocols has progressed with Joint Architecture for Unmanned Systems (JAUS) compliance in mind. The haptic force control algorithms are presented along with results highlighting the benefits of haptic operator feedback on the MkIV OzBot™ chassis.

Keywords: Haptic, mobile robot, OzBot, ActiveX, JAUS.

I. INTRODUCTION

Significant advances are being made in the fields of teleoperated and semi-autonomous mobile robot technology. Sensory systems, on-board intelligence, mobility and to some extent even communication systems appear to be moving forwards in capability and feature set. One area of technology that seems to be sluggish however is adoption of new human interface elements to control stations. Several companies are adding PlayStation™ or Xbox™ controllers as an option to their operator control panels in an effort to increase user familiarity with their robots. These devices however do not assist with operator immersion into the remote environment.

In the past decade the development of relatively low cost three-dimensional haptic interfaces from several companies have allowed experimentation in control with one important addition, force feedback.

Our work has led to the addition of sensory systems to the OzBot™ mobile platform with the goal of aiding the navigation and control of the remote robot by providing additional information to the user.

Hazardous material handling and neutralising Improvised Explosive Devices (IED) are two applications requiring fine levels of control on often-inconsistent surface conditions. Given the complexities encountered in controlling a mobile robot in ground missions, the ability for the operator to achieve full environmental awareness is vital. Due to the nature of teleoperation, the human-in-the-loop control methodology is imperative to mission success. Two trains of thought have evolved from battlefield robotics research, semi-autonomous robotics or increased immersion for robot operators.

Traditionally, operators of IED disposal robots fear automation due to the lack of predictability of the remote robots actions and as a result only limited or semi-autonomous robots have been employed on the battlefield [1,2]. An example of semi-autonomous capability is found in the robotic preceder/follower project [3]. The preceder/follower project aims to reduce the number of supply truck drivers placed in harms way on a battlefield by automating the follower vehicles in a convoy. A manned preceder vehicle leads the semi-autonomous unmanned vehicles to avoid obstacles.

The second fundamental approach to increasing remote IED disposal robot capability and effectiveness is to enhance operator immersion [4,5]. Improved operator immersion can be achieved by augmenting the traditional remote vehicles sensors (usually vision and sound) with an inertial measurement unit (IMU) providing data of the robots pose or orientation, wheel slip information, individual wheel loading and motor current draw. Conveying this additional information without overloading the operator with visual cues has been, up until now quite challenging.
Over the past decade the use of haptic technology has been accepted into academia for simulation and modeling [6]. Current inroads are being made into medical simulation and surgical teleoperation [7]. Controlling robot manipulators with haptic devices has known benefits for grasping and positioning tasks [8] but there has been limited adoption of haptic technology for controlling mobile platforms. As mobile robotic platforms often operate in three-dimensional environments, it has often been argued that haptic technology should be portable to navigation and control in 3D teleoperation as an aid to operator immersion [9].

Lee [10] provided a novel method of controlling a mobile platform via haptic interface but unfortunately, this methodology required significant effort to enable the integration of one type of robot into the haptic controller. The work by [11], follows a similar control scheme to Lee but once again limits the feedback due to platform constraints. Elhajj [12] examined several issues relating to haptic teleoperation, stability, synchronization, and transparency. This work suggests that event-based planning was adequate for control and haptic feedback. This work was largely based on obstacle avoidance and force reflectance of external stimuli. Limited depth was delivered on the effects of robot pose, and rough terrain operation.

Quite often in IED disposal robotics, an operator wishes to push an object [8]. Research has focused on collision avoidance with haptic feedback, but to truly benefit from haptic technology, feedback from the robot has to be a natural extension of the operator’s senses.

II. OZBOT MOBILE PLATFORM

The basis for all haptic teleoperation research presented in this paper is the OzBot™ MkIV (Figure 1). The OzBot series of platforms have been developed at Deakin University in conjunction with a local government agency. OzBot MkIV was designed and constructed in a very short period in order to satisfy the requirements of the agency during an important security exercise in Melbourne, Victoria in early 2006.

OzBot was used during this exercise due to its ability to maneuver under vehicles and stadium seats to inspect for potential IED’s. OzBot was developed to compliment the group’s larger Teodore™ and Cyclops™ teleoperated vehicles. While haptic control was not used for this exercise, the platform itself was developed with haptic control in mind. An IMU was included on the main controller board of the platform and sufficient bandwidth for streaming haptic information to an operator was developed into the communication protocol.

Figure 1. OzBot MkIV mobile platform

Figure 2. OzBot MkIV with off-road wheels installed

Capable of operating at ranges up to one kilometre line-of-site, OzBot uses full duplex 900Mhz low-latency data modems for control and system status feedback. A 2.4Ghz analogue video link is used for video streaming of the platforms low light (black and white) camera and colour camera.

Constructed from 1.5mm stainless steel with structural aluminium ribs, the robot houses four planetary gear motors capable of moving the robot at speeds of up to twelve kilometres per hour with a payload of up to 40kg. Mission duration with built in lithium polymer batteries stands at around 1 – 2 hours depending on usage. Quick-change wheels have been developed that allow OzBot to transform from a low height under vehicle inspection system, to an off-road reconnaissance robot in under a minute (Figure2).
OzBots on-board IMU consists of an Analog Devices ADXL330 triple-axis accelerometer combined with an InvenSense IDG-300 angular rate gyroscope capable of detecting yaw and pitch changes at up to 500°/second. The IMU outputs are sampled by the on-board micro-controller (PIC16F877A) at 10-bit resolution at 150Hz. The IMU, accelerometer, gyroscope and motor drivers are all mounted on a custom printed circuit board with power filtration and switching (figure 3).

Figure 3. OzBot MkIV control board

III. HAPTIC ALGORITHM

The addition of haptic feedback to a mobile platform to increase operator performance can be accomplished in a number of ways. This paper focuses on increasing vehicle stability in an unstructured control task by augmenting user input with force feedback from the remote robots IMU. Parallel research work conducted by Deakin’s Intelligent Systems Research Lab investigates the addition of haptic gravitational fields and how best to lead an operator to a known goal. Vehicle stability is a function of robot pose and orientation relative to a required input action. In most real-world reconnaissance tasks, all user inputs and IMU data cannot be pre-computed. In order to map user input to control of the remote robot, a kinematic model is required.

This map for OzBot MkIV is a linear approximation of robot forward velocity in the Y-plane of the Phantom Omni and rotational velocity mapped in a logarithmic relationship to the X-axis of the Omni (figure 4). To reduce operator fatigue, the model does not require the user to maintain a Z-axis position input at any time. The Z-axis is not used for control at this stage. As determining the 0,0 point in the X and Y coordinate space can be difficult and is required for bringing the remote platform to a complete stop, a gravwell is employed. A gravwell or gravity well is defined as "attractive basins that can pull the cursor toward a target" [13]. The gravwell applies a small force to the users hand whenever the 3D cursor is positioned away from the 0,0 point in the 3D space. Feedback to the user of OzBots change in pose is provided by a deflection of the X-axis for an angular rotation about the platforms axis proportional to the commanded value. The OzBot platform axis is defined as an intersecting line drawn from the hub of each wheel (w in Figure 5).

Figure 4. 2-D Kinematic mapping [9,10,15]

Figure 5. OzBot pose

The Y-axis of the Omni provides feedback to the user as a function of motor current draw and IMU data. An assumption is made that an operator requires both pose and terrain information for remote robot controllability.

\[
\text{Force}_{y-axis} = (a \cdot \theta) + (b \cdot l)
\]

(1)

Where: a and b are constants determined experimentally to give maximum force for maximum inclination and current draw. \( \theta \) is the angle of inclination of the robot and \( l \) is the total current draw of the robots motors.

This control methodology requires that a user exert the same force to the haptics device in the Y-axis to climb a hill at a known speed as on thick carpet on a level slope. As current draw is a function of platform velocity, the faster the user commands the robot to go, the more the haptic interface will resist the change in velocity. This has the effect of minimising operator control error due to shakes and fatigue.

IV. ON-BOARD SOFTWARE AND ALGORITHM

When developing any form of haptic control software it is important not to overcomplicate main functional control code. Any code redundancy will severely reduce the haptic feedback rate and as a result reduce the quality of operator
experience. The development of HOCX a custom Haptic Control Extension (OCX) enables low-level control of haptic devices in real-time with high-level software. Multi-platform server software is then utilised to connect to HOCX and configured as per the operator’s requirements. When developing the haptic OCX, significant time was spent optimising the data packet structure for possible adoption within Joint Architecture for Unmanned Systems (JAUS). It is expected that when further developed, the OCX will meet all requirements of message definition, component behavior and data format for JAUS. At this stage of development JAUS compliance level 1 is under development. As the Mk4 OzBot platform is based around a single processor, level two compliance is moot. Given the relatively high data bandwidth requirements, transmission of high-speed pose information for haptic rendering monopolises the JAUS link when enabled.

V. HAPTIC EXTENSIONS

In order to increase the effectiveness of haptic control in mobile robotics a simplified method of interacting with Commercial Off-The-Shelf (COTS) haptic devices was required. This standard interface dubbed HOCX allows the development of haptic control for mobile robotics without significantly increasing coding time.

To create the required flexibility without sacrificing functionality, new software that built upon the original HD and HL libraries that were supplied with the Sensable Omni [14] haptic device was required. This higher-level language is able to function with most other Windows based software on the market; it also fits the requirement of communicating via TCP/IP, RS232 and UDP. The HOCX software is also capable of taking advantage of every property and method the attached haptic device possesses. The project requirement called for low-cost haptic devices that can be integrated into a wide range of markets. As a result, the Phantom range of haptic devices from Sensable® [14] were chosen for development.

The resultant HOCX can call all the Sensable functions, pass data via multiple protocols, communicate with force/torque sensors and be programmed to pass position, velocity, acceleration and force data to any client efficiently. Table 1 shows the compression of the Sensable HD and HL libraries into a higher level OCX. One of the major benefits for the control of OzBot MKIV is that when telemetry data is interrupted between the mobile platform and the control station, HOCX maintains a 1000Hz servo loop to the attached haptic device as required for haptic feedback [14].

VI. TELE-PRESENCE CONTROL STATION

The Tele-prence Control Station or TCS is the main interface to the robot operator. The TCS consists of three main components (Figure 6).

1. OzBot MkIV operator control pendant
2. Laptop computer with HOCX and custom robot specific interface software
3. Sensable Omni haptic device

The operator control pendant is a fully self contained user interface with analogue control sticks for motor control, a large colour display for remote video feed and a number of switches and status LED’s for the various robot functions. The control pendant was designed with haptic augmentation in mind with the addition of a serial port connected to the micro-controllers on-board UART and an analogue to digital video converter. The main processor in the TCS is an Apple Macbook laptop computer. The laptop is connected to the control pendant via USB to serial adaptor.

A Phantom Omni haptic device from Sensable Technologies [14] is then connected to the laptop as the main human interface device. The Phantom Omni is capable of delivering up to 3.3N of force feedback to the operator’s hand in 3-DOF.

Figure 6. OzBot MkIV Teleoperator Control Station

<table>
<thead>
<tr>
<th>Table 1. HOCX code simplification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensable’s HDAPI / HLAPI</td>
</tr>
<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td>bool result;</td>
</tr>
<tr>
<td>HDErrorInfo error;</td>
</tr>
<tr>
<td>HHID=hdInitDevice(HD_DEFAULT_DEVICE);</td>
</tr>
<tr>
<td>if (HD DEVICE, ERROR(error=hdGetError))</td>
</tr>
<tr>
<td>{ result = FALSE;</td>
</tr>
<tr>
<td>Return result;</td>
</tr>
<tr>
<td>} Else }</td>
</tr>
<tr>
<td>result = TRUE;</td>
</tr>
<tr>
<td>hdEnable(HD FORCE OUTPUT);</td>
</tr>
<tr>
<td>hdStartScheduler();</td>
</tr>
<tr>
<td>return result;</td>
</tr>
</tbody>
</table>

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VII. RESULTS

Adding haptic capability to the control system of OzBot MkIV increased operational task effectiveness significantly. In a series of tests carried out by both skilled and non-skilled operators the benefits of haptic augmentation to control strategy were observed.

For the purposes of these tests, skilled operators where selected from the Intelligent Systems Research Lab and generally had significant knowledge and experience in controlling mobile platforms. Unskilled operators were selected from outside the lab and generally hadn’t controlled a remote vehicle with the exception of radio control toys.

Task 1 – Operators were asked to drive OzBot MkIV up a twenty-degree incline with under-vehicle wheels attached. The operator was required to drive up the slope and maintain the vehicle's position (within ±20mm) for a period of 5 seconds. These wheels supplied limited traction and as a result this task is difficult to complete due to the vehicle continually yawing due to operator over- steer on the slippery surface. Figure 7 shows the progression of an operator’s attempt to move the robot up the incline and the resultant over- steer without the use of haptic feedback.

Five operators from each group (skilled and unskilled) performed this task and the results were averaged (figure 8). In general skilled operators performed twenty-nine percent faster than unskilled operators without haptic augmentation, but this gap was reduced to twenty-four percent when the haptic algorithm was turned on.

Unskilled operators performed eleven seconds faster or twenty-three percent, which is higher than skilled operators who reduced their task time by eighteen percent.

Task 2 – Involved operators driving over an off road course with pneumatic tires installed. The goal was to get from a starting position to a finishing point in the quickest possible time. This task was made difficult due to the undulating terrain and the presence of slippery dried leaves and grass in the path of the robot. Once again due to the small size of OzBot and the differential drive configuration, it is possible for an operator to over correct slippage resulting in over- steer. As shown in figure 8, there was a significant skill gap between skilled operators and unskilled drivers (47%).

It was noted that operators improved their course times by fourteen percent when provided with haptic augmentation from the on-board IMU. Once again unskilled operators performance increased with haptic reinforcement at a faster rate to that of their skilled counterparts.

The results of these tasks suggest that haptic technology has the potential to reduce the amount of training an operator requires.

Figure 8. Haptic augmentation test results

The difference in operator skill level is more notable between tasks one and two. Task one was completed with the operator in direct view of the robot. Task two was accomplished via OzBots built in colour camera. It becomes apparent that visual servoing is more effective when in direct site of the robot, but in both tasks, haptic augmentation makes a significant difference in the time taken to complete the goal.

The development of the HOCX has been beneficial to the development of a number of haptic systems within the ISR Lab. Programmers have noted that they have saved many hours by using the high-level function calls and as a result have had more time to develop functionality within their haptic programs.

Figure 7. OzBot MkIV climbing a 20° slope with no haptic augmentation
VIII. FUTURE WORK

Development of the OzBot series of platform continues to move ahead. OzBot MkV and MkVI will continue to evolve with more capability and functionality. A stair capable variant of OzBot is undergoing testing and will benefit greatly from the application of haptic technology. The ISR team is working towards JAUS compliance and is currently investigating ways in which a haptic user interface can be adapted to suit multiple robot controllers. Development with the OpenJAUS team is being considered for integration into the HOCC as an alternative to full development of in-house code. MkV and MkVI variants of OzBot are expected to gain JAUS compliance level 2 as they will require multiple embedded processors as their feature set increases. As haptic technology reduces in cost, it seems inevitable that the adoption rate of this input device will increase as the benefits of mobile platform control become apparent.

IX. CONCLUSION

This paper discusses the development of a haptic augmentation methodology for OzBot MkIV. The inclusion of an on-board IMU combined with a high bandwidth low-latency data link allows multiple haptic control schemes to be evaluated. The software developments of the HOCC ActiveX and the enabling hardware have been presented for review. In-house use of the HOCC has been shown to reduce code development time significantly. Compared with alternative rapid haptic development environments, the HOCC system increases capability for real world robot interaction tasks. OzBot MkIV has benefited greatly from the addition of the haptic control methodology presented, in both tasks shown above, skilled operators performed fourteen percent faster with haptic augmentation and unskilled operators performed twenty percent faster. Haptic technology also appears to bridge the gap between skilled and unskilled operators and greatly increases the effectiveness of OzBot in standard reconnaissance roles.

REFERENCES