Exploiting Ungrounded Tactile Haptic Displays for Mobile Robotic Teleoperation

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Abstract—Teleoperated mobile robotics offer potential use in a variety of different real-world applications including hazardous materials handling, Urban Search and Rescue and explosive ordnance disposal. Recent research discusses the use of Haptic technology in increasing task immersion and teleoperator performance. This work investigates the utility of low-cost, ungrounded tactile haptic interfaces in mobile robotic teleoperation. In order to achieve the desired implementation using only tactile sensation presents distinct challenges. Innovative Haptic control methodologies providing the teleoperator with intuitive motion control and task-relevant haptic augmentation are presented within this paper.

I. INTRODUCTION

Teleoperated mobile robotics provides a valuable solution for a variety of tasks such as hazardous materials handling [1], Urban Search and Rescue [2] and explosive ordnance disposal [3,4]. At the other end of the spectrum, fully autonomous robots provide feasible solutions for structured, repetitive tasks. The teleoperated approach to mobile robotics provides the capability to introduce many desirable attributes to the control of a remote robotic system. Haptic technology provides the capability to interact with the teleoperator’s tactial modality in the aims of improving operator immersion and task performance. The integration of Haptic technology in the teleoperation of a mobile robot is discussed in [5-15].

This paper, however, investigates ungrounded tactile-Haptic displays for achieving Haptic teleoperative control of a mobile robot. The ungrounded tactile-Haptic devices are unable to display actual forces to the operator, and therefore present distinct challenges to the human-robotic interaction. These types of Haptic devices are capable of only providing tactile sensation, however, they do represent a simple, cost-efficient technology, and as such investigation of their capabilities in mobile robotic teleoperation is warranted. Whilst the non-existent force rendering capabilities do prove a disadvantage, these devices do in fact provide a theoretically unlimited workspace, unlike a traditional grounded Haptic interface.

The iFeel™ mouse from Logitech [16] is a low-cost, off-the-shelf, tactile haptic interface setting the focus of this work. The capabilities of this type of Haptic interface are investigated and suitable control methodologies introduced. Ultimately, simulation results demonstrate the applicability of this type of device in the Haptic teleoperative control of a mobile robot.

II. TACTILE-HAPTIC INTERFACES

The tactile-Haptic interface discussed in this work utilises vibration as its basis of operation. As this type of device is ungrounded it is incapable of exerting any forces to the teleoperator, however it is advantageous in that it is not subjected to the same workspace restrictions as the grounded-type of device. In order to achieve the adequate human-robotic interaction required for effective Haptic teleoperative control this work investigates the capabilities of such devices and presents suitable methodologies attempting to overcome any such limitations. This work investigates the relevant capabilities of the iFeel™ mouse by Logitech as a representation of tactile-Haptic interfaces. These capabilities are determined in order to develop an appropriate Haptic control methodology for mobile robotic teleoperation.

Firstly, it is identified that ungrounded Haptic displays are not subject to the same space constraints as traditional Haptic devices. The workspace of the iFeel™ haptic mouse is theoretically unbounded (except for its tether) given a suitable supporting planar surface. Secondly, in order to achieve a suitable control methodology the Haptic rendering capabilities of the device need to be investigated. As aforementioned this particular device relies on vibration, which provides the basis to render tactile sensations to the operator without the need to exert forces to the operator as in [8]. In the aims of achieving the desired teleoperative control the relevant tactile effects can be classified as spatial and temporal effects as discussed below.

A. Spatial Effects

The spatial effects able to be rendered by this device correspond to a relationship to the x, y displacement of the device across the planar operating surface. The texture and grid effects were identified as relevant to this work and are created by displaying vibration in response to spatial variance as shown below.
III. TELEOPERATION CONTROL ARCHITECTURE

The human-in-the-loop approach to the control of a remote robotic system provides the capability to overcome several limitations by introducing several desirable human attributes. Such attributes include adaptability to a diverse range of situations, a relatively high-level of intelligence, advanced sensory capabilities as well as human judgment and intuition. Many critical real-world applications such as Urban Search and Rescue and other such rescue missions require such attributes in order to achieve successful task execution. Therefore, having identified the suitability of teleoperated robotic systems to a range of applications, this work presents the tactile-Haptic approach to teleoperation of all-terrain mobile robotics.

A literature review identifies two fundamentally conflicting approaches to the teleoperation of a remote robotic system. The first approach is that the human operator controls the remote system in a shared autonomy scenario where the robot has the capability to influence its own actions. This scenario may arise in situations where the robot’s autonomy may be considered as equal or more valuable than that of the teleoperator. This scenario is depicted in Figure 3. In this scenario the teleoperator does not have absolute control of the robotic system, which will inevitably result in conflict between the intent of the operator and that of the robot.

Figure 1. Rendering spatial effects with the Tactile-Haptic device [17]

Given Figure 1, the distance/space between consecutive vibrations for the texture effect is given by

$$\Delta \text{distance} = \frac{x_{n+1} - x_n}{\cos(\phi)} \quad (1)$$

and for the grid

$$\Delta \text{distance} < \frac{\tan \phi \cdot (x_{n+1} - x_n)}{y_{n+1} - y_n} \quad (2)$$

where $\Delta \text{distance}$ represents the actual distance between rendered vibrations and $\phi$ is the direction of movement.

It is acknowledged that other spatial effects may be achievable, however, for the purposes of this work the above two are considered.

B. Temporal Effects

The temporal effects achievable by this device correspond to a relationship between magnitude and time.

Figure 2. Rendering temporal effects [17]

The periodic and pulse effects were identified as relevant to this work and are created by varying the frequency of vibration as a function of time, as demonstrated above.

Given Figure 2, these vibrations are a function of time. The periodic vibration is given by

$$\alpha = A \cdot \sin(2 \cdot \pi \cdot \beta \cdot t) \quad (3)$$

and for the pulse vibration

$$\alpha = \begin{cases} -r \cdot t, & \gamma + p \leq t \leq \lambda \\ 0, & \gamma < t < \gamma + p \end{cases} \quad (4)$$

where $\alpha$ is the vibration, $\beta$ is the frequency of the vibration and $t$ is time.

Identification of the above-discussed effects forms the basis for development of the following Haptic control methodology.

Figure 3. Shared autonomy control scenario [8]
the operator rather than directly intervening in the control process. This ensures that the teleoperator remains in absolute control, while still utilizing the capabilities of the robot’s computational intelligence. This scenario eliminates conflict of control as the teleoperator has total control of all of the robot’s actions. This situation is depicted in Figure 4.

![Figure 4. Absolute human control [8]](image)

The absolute human control approach is supported by the control methodologies presented below. This is achieved by decoupling of the motion control and application-specific Haptic augmentation components of the presented control methodologies. The teleoperator’s motion control is not directly affected by any Haptic augmentation. The teleoperator can determine whether or not to react to the robot’s display of any information Haptically, as in Figure 4. The following sections explain the two components of the tactile-Haptic teleoperative approach to the teleoperation of a mobile robot.

IV. MOTION CONTROL

The motion control component of the Haptic control methodology is responsible for providing a mechanism for the teleoperator to provide motion commands to the robot. In order to achieve the desired approach to motion control of the mobile robot, the theoretically unlimited workspace of the device is utilised. Rather than mapping the displacement of the Haptic device to corresponding rover velocities as in [9], the presented approach utilises continuous teleoperator motion in order to command the motion of the mobile robot.

The distinct advantage of this approach is the teleoperator is always aware of the velocities being commanded to the robot given that they are providing continuous motion. The teleoperator can also easily provide a zero motion command by stopping their motion of the Haptic device. The ungrounded nature of this type of device allows this to be achieved. There are of course some limitations in this approach, in that for a long continuous motion the teleoperator may need to reset the position of the device. In reality lifting the device and replacing it in a logical position can achieve this. While this may prove a limitation, this approach does allow the operator to intuitively infer the velocities being commanded to the robot at any particular time.

The mapping between the motion of the tactile-Haptic device to the motion of the mobile robot is depicted by

Figure 5. As the teleoperator’s movement of the device travels from $p_1$ to $p_2$, the corresponding linear and angular velocities are commanded to the robot. The speed of the operator’s motion relates to the magnitude of the commanded velocities, as per (5) and (6). It is important to note, that in this particular approach, the commanded velocities are applied in open loop and it may take some time for the robot to achieve the desired velocities, and as, such the teleoperator needs to compensate accordingly.

![Figure 5. Haptic Motion Control](image)

Given Figure 5, the mapping between movement of the Haptic device and the linear velocity is given by

\[ V = \dot{\delta} = \lambda_1 \cdot \frac{\delta_{t+1} - \delta_t}{\Delta t} \]  \hspace{1cm} (5)

and the angular velocity

\[ \omega = \dot{\theta} = \lambda_2 \cdot \frac{\theta_{t+1} - \theta_t}{\Delta t} \]  \hspace{1cm} (6)

where $\Delta t$ is chosen suitably and $\lambda_1$ and $\lambda_2$ are constants of proportionality.

Given the motion control methodology presented above typical Haptic device movements and corresponding rover velocities are presented below in Figure 6.

![Haptic device movements](image)
where $k_3$ scales to the suitable frequency, and is chosen according to the appropriate magnitude of the tactile effect. It is also necessary to limit the maximum allowable range so that the HGF does not affect the robot for any possible position in space. The suitable $P_{\text{max}}$ can be chosen empirically.

As mentioned above, when the teleoperator's displacement of the haptic device exceeds the provided planar surface, the position of the haptic device needs to be reset in order to provide adequate maneuverability.

**IV. APPLICATION-SPECIFIC HAPTIC AUGMENTATION**

This section presents the application-specific Haptic augmentation methodology designed to assist the teleoperator in a particular scenario. This methodology presents distinct challenges because the particular device is unable to provide forces to the operator specifying an appropriate indication [7,9] or corrective action.

**A. Haptic gravitational field**

The Haptic Gravitational Field (HGF) is related to the Artificial Potential Force Field methodology [18] and provides a method to provide Haptic information pertaining to surrounding obstacles or a desired goal location. The utility of the HGF in respect to the tactile-Haptic control methodology is discussed in the following sections.

Given the current location of the robot $(x_r, y_r)$ and a location of interest $(x_i, y_i)$, the HGF is governed by

$$
\rho = k_2 + k_3 \cdot \left( \sqrt{\left( y_g - y_r \right)^2 + \left( x_g - x_r \right)^2} \right)^{-1}
$$

(7)

where $\rho$ is the strength of the HGF for any logical position.

In reality the location of the robot in respect to obstacles can be determined using ultrasonic or optical range finding methods, and the absolute location of the robot and goal locations can be determined using either Global Positioning System (GPS) or Differential Global Positioning System (DGPS) methods. The use of the HGF in Haptic obstacle detection and guidance to a goal location is discussed below.

**B. HAPTIC OBSTACLE DETECTION**

In order to provide the teleoperator with a Haptic indication of surrounding obstacles the HGF is utilised. A temporal tactile effect is used to provide the teleoperator with a tactile indication of the HGF and the corresponding obstacle or obstacles.

In order to inform the teleoperator of the HGF and the corresponding object of interest (in this case an obstacle) a period tactile effect is utilised. Varying the frequency of the periodic effect adequately can provide the teleoperator with an indication of the existence of the obstacle. As the mobile robot enters the Haptic Gravitational Field, as depicted by Figure 7, the frequency of the periodic effect is increased by a factor of $\rho$ according to (7).

As such, the tactile rendering is given by

$$
\alpha = A \cdot \sin(2 \cdot \pi \cdot \beta \cdot t)
$$

(8)

$$
\beta = (k_3 \cdot \rho)
$$

(9)

where $k_3$ scales to the suitable frequency, and is chosen according the appropriate magnitude of the tactile effect. It is also necessary to limit the maximum allowable range so that the HGF does not affect the robot for any possible position in space. The suitable $\rho_{\text{max}}$ can be chosen empirically.

**B. Haptic indication of goal location**

In order to provide the teleoperator with a method to haptically determine the distance to a desired goal location the Haptic Gravitational Field is again utilised.

**Figure 6. Haptic device – robot motions**

In addition to monitoring the movement of the tactile-Haptic device a grid-texture is used to provide the teleoperator with an intuitive-spatial indication of the speed and in which direction they are manipulating the Haptic device. The magnitude of the texture-grid vibration is chosen to be far less than that of the temporal Haptic augmentation so that the teleoperator can easily differentiate between the two vibratory effects.

**Figure 7. HGF in Obstacle Detection**

In order to provide the teleoperator with a Haptic indication of surrounding obstacles the HGF is utilised. A temporal tactile effect is used to provide the teleoperator with a tactile indication of the HGF and the corresponding obstacle or obstacles.
The Inverse of the HGF proves valuable in providing an indication of the direction of a goal location. As demonstrated by Figure 6, the period of the periodic vibratory effect (8) will actually decrease as the robot moves closer to the goal position.

The Inverse of the HGF is given by

$$\beta = (k_4 \cdot \rho)^{-1}$$  \hspace{1cm} (10)

where \( k_4 \) is a constant of proportionality and chosen appropriately.

The Haptic Gravitational Field (HGF) provides a valuable mechanism for augmenting the teleoperator’s control task utilising a tactile-Haptic interface. In this particular USR scenario we have considered the utility of the HGF in obstacle detection and guidance to a desired goal location. In order for the teleoperator to fully utilise this approach it becomes the responsibility of the teleoperator to attempt to achieve minimal frequency of vibration (\( \beta \)) of the vibratory effect in order to avoid obstacles and to traverse closer to the goal location.

V. SIMULATION RESULTS

In order to demonstrate the ability of the presented approach to provide a tactile-Haptic indication of both the presence of obstacles and goal location the following simulated results are presented. Figures 7 and 8 demonstrate the HGF in providing vibration according to surrounding obstacles and Figures 9 and 10 in relation to a desired goal location. The computed \( \beta \) is presented below each simulated trajectory as an in (9) and (10). In the first simulated trajectory presented by Figures 7 and 8, the robot is navigated from the Start to Stop locations. The location of the obstacles and corresponding HGF are shown. As the robot enters the corresponding HGF’s the associated change in vibratory frequency is depicted below.

![Figure 7. Simulation with obstacles](image7)

![Figure 8. Corresponding \( \beta \)](image8)

In the simulated trajectory depicted by Figures 9 and 10, the robot is again navigated from the Start to Goal locations. The location of the Goal and corresponding inverse HGF are shown. As the robot enters the inverse HGF the associated period is shown directly below.
VI. CONCLUSION
This paper presents a novel approach to the use of ungrounded haptic devices in the teleoperative control of a mobile robotic platform. The preliminary simulation results demonstrate how the approach can provide the teleoperator with the required information.

VII. ACKNOWLEDGEMENT
This work was supported by the ISR: Intelligent Systems Research Laboratory, at Deakin University, Australia.

VIII. REFERENCES