Deakin Research Online
Deakin University's institutional research repository

This is the published version (version of record) of:

Horan, B., Najdovski, Z., Nahavandi, S. and Tunstel, E. 2008, 3D virtual haptic cone for intuitive vehicle motion control, *in 3DUI 2008 : Proceedings of IEEE Symposium on 3D User Interfaces*, IEEE, Piscataway, N.J., pp. 67-74.

Available from Deakin Research Online:

http://hdl.handle.net/10536/DRO/DU:30018230

Copyright : ©2008 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

3D Virtual Haptic Cone for Intuitive Vehicle Motion Control

B. Horan, Z. Najdovski, S. Nahavandi and E. Tunstel[1]
Intelligent Systems Research Lab, Deakin University, Australia
[1]Applied Physics Laboratory, John Hopkins University, USA

ABSTRACT

Haptic human-machine interfaces and interaction techniques have been shown to offer advantages over conventional approaches. This work introduces the 3D virtual haptic cone with the aim of improving human remote control of a vehicle's motion. The 3D cone introduces a third dimension to the haptic control surface over existing approaches. This approach improves upon existing methods by providing the human operator with an intuitive method for issuing vehicle motion commands whilst simultaneously receiving real-time haptic information from the remote system. The presented approach offers potential across many applications, and as a case study, this work considers the approach in the context of mobile robot motion control. The performance of the approach in providing the operator with improved motion controllability is evaluated and the performance improvement determined.

KEYWORDS: Haptic motion control, haptic mobile robot control, bilateral haptic robot control.

INDEX TERMS: H.5.2 [User Interfaces]: Haptic I/O; I.2.9 [Robotics]: Operator interfaces

1 INTRODUCTION

Haptic technology provides the ability for a system to recreate the sense of touch to a human operator, and as such offers wide reaching advantages. The ability to interact with the human's tactual modality introduces the haptic human-machine interaction to replace or augment existing mediums such as visual and audible information. A distinct advantage of haptic human-machine interaction is the intrinsic bilateral nature, where information can be communicated in both directions simultaneously. This paper investigates the bilateral nature of the haptic interface in controlling the motion of a remote (or virtual) vehicle and presents the ability to provide an additional dimension of haptic information to the user over existing approaches [1-4]. The 3D virtual haptic cone offers the ability to not only provide the user with relevant haptic augmentation pertaining to the task at hand, as do existing approaches, however, to also simultaneously provide an intuitive indication of the current velocities being commanded.

Teleoperated (or remotely controlled) mobile robots are used in many important applications such as hazardous materials handling [5], urban search and rescue (USAR) [6] and explosive ordnance handling and disposal [7], where the terrain may be harsh, the particular task not known *a priori* and successful execution is critical. As such, fully autonomous systems are not likely to provide a feasible solution. The utilisation of the human-in-the-loop philosophy to the control of mobile robots in such tasks provides the valuable ability to exercise human-level cognitive capabilities in real-time during execution of the particular task. Despite the apparent advantages of human-in-the-loop control in critical scenarios, the need to physically displace the operator from hazardous environments presents a challenge in achieving adequate telepresence or immersion within the robot's operating environment. Telepresence refers to the degree to which the teleoperator feels physically present in the remote environment and, as such, becomes an important consideration when controlling any robotic system remotely. Given limitations in communication bandwidth and consideration of operator loading, the teleoperator is generally provided with a single 2-D camera view of the remote environment [2-4, 10-12]. While some research focuses on improving telepresence through improved visual information [8], other work suggests that telepresence can be increased through inclusion of haptic human-robotic interaction [1-3, 9]. Haptic interaction techniques offer the ability for the operator to interact bilaterally with the system using their tactual sensory modality. Given this bilateral capability, that is to send and receive haptic information simultaneously, the applicability of the haptic approach to improving telepresence and immersion has become the subject of an increasing research focus. In the context of teleoperated mobile robotics, haptic technology has the potential to improve operator performance subject to limited visual information, from the onboard camera, of the remote environment.

While total robot autonomy may not be a feasible solution in diverse, unstructured environments such as those found in hazardous materials handling, USAR, and explosive ordnance handling and disposal, the robot's intelligence is still of importance and should not be neglected. The robot's computational intelligence can offer advantages over human intelligence in various tasks including numerical computation, sensing and measurement.

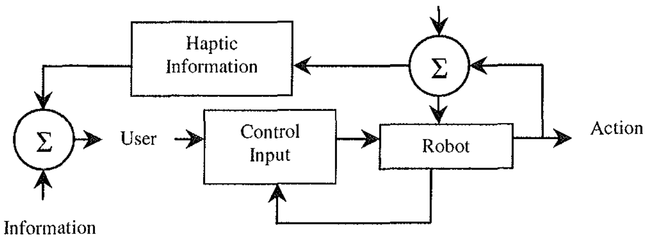


Figure 1. Semi-autonomous control approach to teleoperation

Given the desire to keep the human operator in control of the robot due to their superior cognitive and reasoning capabilities, as well as the inherent value in the robot's computational

ben.horan@deakin.edu.au, zoran@deakin.edu.au
nahavand@deakin.edu.au, edward.tunstel@jhuapl.edu

IEEE Symposium on 3D User Interfaces 2008
8-9 March, Reno, Nevada, USA
978-1-4244-2047-6/08/$25.00 ©2008 IEEE

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.

intelligence, the absolute operator control approach to teleoperation of the mobile robot is presented. The absolute operator control to teleoperation provides the human with ultimate control of the robot's actions, however the operator still receives information regarding what the robot perceives to be a suitable action. This arrangement is facilitated through the bilateral haptic control arrangement presented in this paper.

As a basis for comparison, in the context of haptic teleoperation, the semi-autonomous approach to teleoperation is presented by Figure 1. In this arrangement, while the operator does control the actions of the robot, the robot has the capability to directly control its own action independent of operator control. Even though the operator receives haptic information regarding the robot's desired action, the operator does not have complete control, which is likely to result in a conflict of control where the operator directs an action and the robot performs a different action. The semiautonomous approach to teleoperated robotic systems provides the ability for a robot to utilise a shared human-robotic autonomy for any particular task.

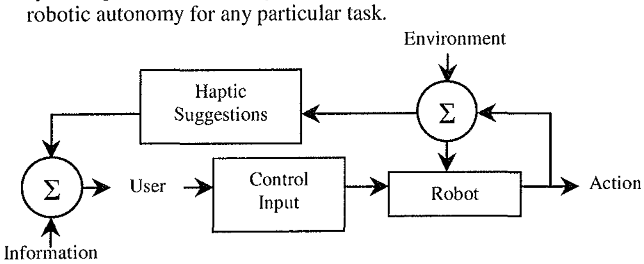


Figure 2. Absolute operator control approach to teleoperation

The absolute operator control approach to teleoperation is presented in Figure 2, and overcomes this conflict of control. The operator has ultimate control of the robotic system, whilst still receiving haptic information regarding the robot's desired action. This is facilitated though bilateral single point haptic interaction at the same point in haptic space. This work utilises a single point manipulator style haptic device [15]. Depicted graphically by Figure 3, the operator and haptic device both apply forces to the common point in haptic space. The resulting motion or displacement of the single point of haptic interaction then corresponds to an action in the robot space, and to haptic suggestions in haptic space.

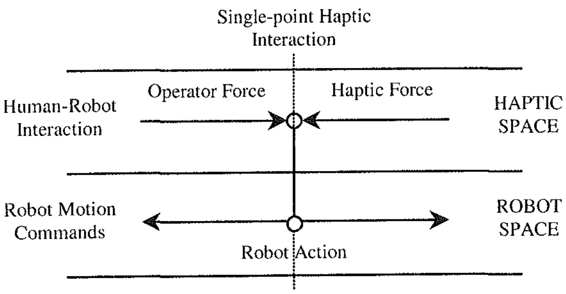


Figure 3. Bilateral single-point haptic human-robotic interaction

The 3D haptic interaction environment is configured in such a way that the human operator can easily overpower the maximum displayed haptic force and, as such, results in the operator having ultimate control of the robot's actions. This simultaneous human-robotic interaction facilitates a teleoperative control approach whereby the robot can provide important haptic information regarding its suggested course of action, while the operator is exercising their own judgement and in ultimate control. The robot's intelligence is utilised to provide the operator with 'Haptic Suggestions' or 'Haptic Augmentation' specific to the task at hand. The above presented control approach, in conjunction with the implemented haptic interface, ensures that no conflict of control can exist and that the teleoperator remains in ultimate control of the robotic system.

The work by [2,9] discusses the use of haptic technology for the purpose of improving teleoperator performance through application-specific haptic task augmentation. Application-specific augmentation is an extremely valuable contribution to improving operator performance in a particular task. This work, however, concentrates on the development of a generic approach to improving 3D haptic motion control, whilst remaining able to operate with any such haptic augmentation.

2 Related Work

Haptically controlled mobile robotics has been discussed by several researchers in recent years [1-4, 9-12]. Our previous work [4] discusses the two main components in the haptic control of a mobile robot. The first component is responsible for the kinematic mapping between the haptic device and mobile robot so that the teleoperator has a method by which to control the motion of the robot. It is this component which is the major focus of this work. The second component is the relevant methodology for providing appropriate haptic augmentation to assist the operator in the performance of a particular task. These two components are integral to the haptic control of a mobile robot and occur simultaneously on the same point in haptic space (Figure 3). As such, this necessitates that these components are not considered in isolation.

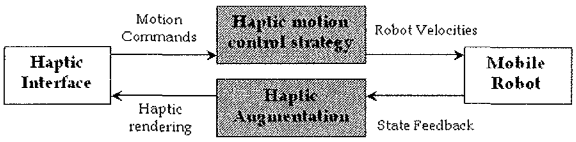


Figure 4. Main components of the haptic teleoperation

Figure 4 graphically depicts these two components. The haptic motion control strategy and the haptic augmentation must be designed such that operation of one cannot impede operation of the other. This design constraint is also faced by [2-3], where the task-relevant haptic augmentation cannot diminish the teleoperator's motion control process and similarly, motion control cannot adversely affect the augmentation process. Given this consideration, this work focuses on the development and evaluation of an improved 3-D haptic motion control strategy, designed in such a way to work synergistically with existing augmentation methodologies [2-3, 9-10], ultimately providing the teleoperator with an additional dimension of haptic information. The existing works by [1-3, 9] present 2-D approaches to the kinematic mapping between the dexterous haptic device and the motion of the mobile robot.

In the work presented by [1-3, 9], motion control is achieved through 2-D kinematic mapping of the displacements of the haptic device across a horizontal plane, (X, Y), to linear and angular velocities of the robot. Haptic augmentation acts across this planar surface providing task relevant haptic information to the teleoperator. Therefore, under normal conditions, that is, in the absence of haptic augmentation, the haptic device moves freely

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.

across the 2D plane providing motion control inputs from the operator to the robot. The limitation of the 2-D approach is that given a robot velocity (dictated by an X, Y displacement of the haptic probe), it may prove difficult for the operator to return the robot to a zero motion state, being an X,Y position of (0,0). Even if the teleoperator were to have a mechanical aid to return the haptic device to a zero motion command state, such as a spring type system, this would interfere with the haptic augmentation provided to the user. In such an arrangement, a pertinent question to ask would be: how can the user infer if it is the haptic augmentation or mechanical aid indicating for them to move the haptic device in a certain direction?

Given a 2-D approach, in order for the teleoperator to perform a zero motion command to the robot, the teleoperator must rely on their visual sense to infer the motion being commanded to the mobile robot. This may impede the teleoperator's ability to concentrate on other aspects of the task at hand. It becomes apparent that this may prove contradictory since the primary reason for introducing the haptic component is to utilise the teleoperator's tactual sensory modality, however the operator is relying heavily on his/her visual sense in order to achieve such motion commands.

As discussed earlier, the two components of the haptic teleoperation are required to operate without impeding one another. As such, when considered independently, the haptic cone motion control capability is required to allow free motion whilst being constrained to the control surface. This then provides the capability for the task relevant augmentation to act across this surface and as such, to be easily interpreted by the teleoperator.

3 3D Haptic Cone Control Methodology

As discussed above, the haptic capabilities of the presented approach to the teleoperation of a mobile robot comprise two distinct but complimentary components to achieving improved teleoperative performance. The component addressed in this paper is the haptic motion control strategy. This component facilitates the kinematic mapping between the manipulator-style haptic interface (bottom right of Figure 5) and the mobile robot [4,10]. The haptic cone control surface was developed to provide the operator with the ability to intuitively control the motion of the robot. Unlike a 2-D approach to controlling the motion of the mobile robot, the operator's movement of the single point in haptic space is constrained to a 3-D conical surface.

This approach exploits the haptic attributes of the system in utilising a vertical (Z) displacement for any commanded velocities. As such, any haptic interface capable of providing grounded force feedback and an adequate 3-D workspace can be utilised.

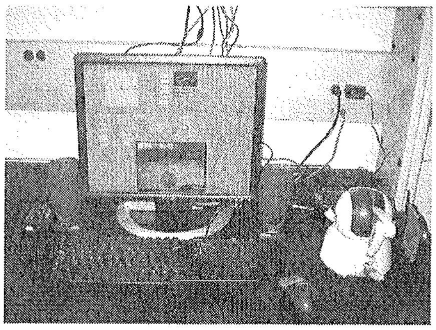


Figure 5. Haptically enabled operator control station

This approach also provides the teleoperator with the ability to achieve the zero velocity position, dictated by (0,0,0), independent of visual information. Importantly, using the 3D virtual haptic cone control surface, the user can infer the current velocities being commanded to the robot, while still having unimpeded motion constrained to the cone surface. This is an essential requirement, as it provides the ability for task-relevant haptic augmentation to be introduced. This haptic augmentation acts across the surface without impeding in the motion control process. Furthermore, it is suggested that an experienced user would be able to use the current vertical displacement for any point on the conical surface as an intuitive indication of the current velocity commanded to the robot. Figure 5, depicts the prototype haptic operator control station.

The second haptic contribution to the discussed haptic teleoperation system is the task-relevant haptic augmentation provided to the teleoperator. This application-specific haptic augmentation acquires the relevant data and employs an appropriate augmentation methodology to assist the operator with the task at hand. The particular haptic augmentation is only considered in respects to the requirement for simultaneous operation with 3D virtual haptic cone motion control. Particular implementations of the haptic augmentation component can be found in [2-4, 9-11].

The haptic cone control surface represents a 3-D approach to the kinematic mapping between the teleoperator's manipulation of the haptic device and the motion control of the mobile robot. Figure 12, shows the OzBot MkVI tracked mobile platform [10-12] in the Webots [13] simulation environment. In order to achieve the desired robot motion for given command velocities, a suitable kinematic model is required. The kinematic model for an articulated track mobile robot presented in the work by [14] is utilised.

The kinematic model for an articulated track mobile robot in a world co-ordinate system is given by

$$\dot{x} = \frac{r}{2}[\omega_o(1-i_o)+\omega_i(1-i_i)][\cos\phi(t)] \tag{1}$$

$$\phi = \frac{r[\omega_o-\omega_i]t}{B} \tag{2}$$

$$\dot{\phi} = \frac{r[\omega_i(1-i_i)-\omega_o(1-i_o)]}{B} \tag{3}$$

where r is the track pulley radius, ω_o and ω_i are the angular velocities of the inner and outer track pulleys respectively, i_o and i_i are coefficients of slip of the inner and outer tracks respectively, B is the distance between tracks, ϕ represents the difference between the inner and outer track velocities and $\dot{x}$ and $\dot{\phi}$ correspond to the linear (v) and angular (ω) velocities of the robot respectively.

The velocities of each track are then given by

$$\omega_o = \frac{2v-\omega B}{2r} \qquad \omega_i = \frac{\omega B}{r}+\omega_o \tag{4}$$

where ω is the angular velocity of the robot and v is the linear velocity of the robot.

Given the assumption that the human operator is an adequate compensator, the coefficients of slip i_o and i_i were set as 0. The kinematic parameters of the OzBot Mk VI platform are presented in Table 1.

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.

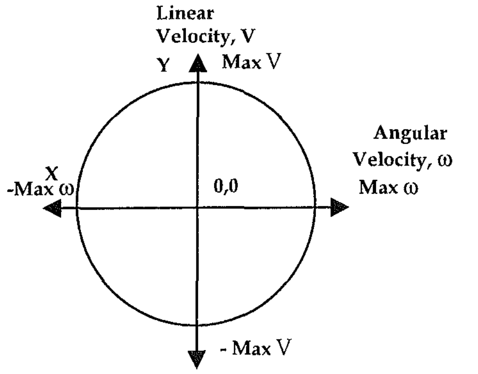
Parameter	Value
r (pulley radius)	0.15m
ω_i *(inner track pulley)*	Max ± 4.9 (rad/s)
ω_o *(outer track pulley)*	Max ± 4.9 (rad/s)
i_i *(inner slip coeffficient)*	0.00
i_o *(outer slip coeffficient)*	0.00

Table 1. OzBot MkVI Kinematic parameters

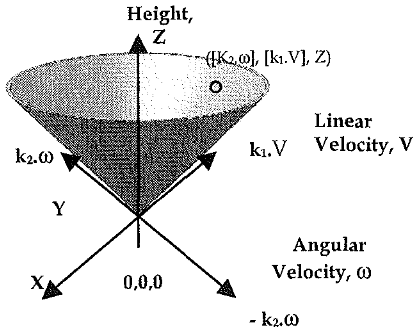
The haptic control strategy is the interaction technique that governs the way the operator interacts with the haptic interface in order to provide motion control to the particular system.

As discussed above, this research focuses on the absolute human control approach to teleoperation. In this implementation, the vehicle's onboard autonomy is responsible for providing intelligent haptic cues to the teleoperator rather than direct intervention in the motion control process. In the work presented by [2,3], motion control is achieved by the 2D kinematic mapping of X, Y displacements of the haptic device across a horizontal plane to corresponding linear and angular velocities of the robot. Such an approach can be depicted by Figure 6a.

The limitation of the 2-D approach is that given a robot velocity (dictated by an X, Y displacement of the haptic probe), it may prove difficult for the operator to return the robot to a zero motion state, being an X,Y position of 0,0. The 3D virtual haptic cone control surface introduces a third dimension to the kinematic mapping between the grounded haptic display and the mobile robot.



a) 2-D kinematic mapping [2,3]



b) 3-D Haptic cone control surface

Figure 6. Different approaches to kinematic mapping

As the operator moves the probe of the haptic device across the virtually rendered surface, the robot is commanded with corresponding linear (V) and angular (ω) velocities. Functionally they are similar, in that the X and Y displacements of the haptic probe correspond to linear and angular velocities of the robot. The cone strategy, however, provides a Z displacement for any allowed X and Y position, serving as an intuitive indication of the current commanded velocity. The haptic cone control strategy is presented above in Figure 6b.

The 3D virtual haptic cone control surface is given by

$$[(k_1.v)^2 + (k_2.\omega)^2 = [k_3.z]^2 \tag{5}$$

where k_1 and k_2 scale v and ω relative to each other and k_3 is a constant related to the slope of the cone; and any point on the cone surface is given in the form

$$([k_1.v],[k_2.\omega],Z) \tag{6}$$

Therefore, when the teleoperator needs to perform a zero motion command, this can be achieved independent of visual information by following the geometry of the cone surface to its origin. Given that the haptic cone is a virtually rendered haptic surface, and that haptic surfaces are inherently not as precise as real-world surfaces, it is not realistic to expect the teleoperator to achieve exactly (0.00, 0.00, 0.00), (ω,V,Z) position at the origin of the cone. As such a dead-zone is introduced in the ω-V plane, where anywhere within this region is considered as exactly (0.00, 0.00), (ω,V) and no velocities are commanded to the robot. Upon exiting the dead-zone the commanded velocities are considered as zero and increase appropriately in the v and ω directions. The introduced dead-zone is depicted by Figure 7, where v_{dz} and ω_{dz} denote the dead-zone thresholds and r_{dz} the radius of the dead-zone, chosen empirically as 3mm.

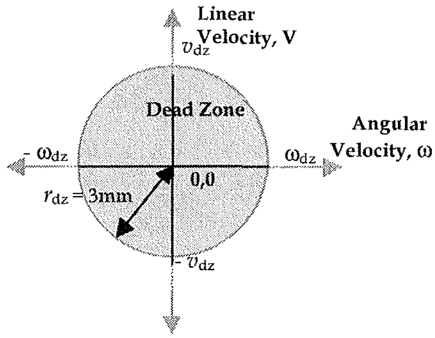


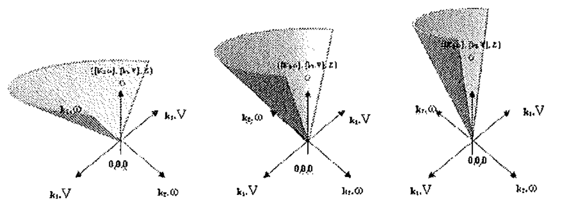
Figure 7. Dead-zone around origin

3.1 Haptic Cone Configuration and Rendering

The novelty of the cone approach is that it provides the teleoperator with a means to easily locate the origin position (0,0,0) corresponding to zero motion. As the conical surface converges to the point of origin, a continuous downward force will inevitably return the haptic point of interaction to the dead-zone at the bottom of the conical surface providing a zero motion to the robot (0,0,0). When no haptic force augmentation is being applied, the teleoperator's manipulation of the haptic probe is unconstrained across the conical control surface, meeting the requirement that this approach does not impede the implemented haptic augmentation. This allows the user to control the motion of the mobile robot with an intuitive indication of the current commanded motion, whilst not interfering with the force

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.

rendering used for intelligent haptic augmentation. The 3D virtual haptic cone control surface is defined by equation (5) where k_3 defines the relative slope of the surface. It is acknowledged that different values of k_3 will vary the effectiveness of the haptic cone control surface in achieving the aims. Figure 8 graphically depicts the effects of k_3 on the ability of the haptic cone control surface to assist the user in returning the robot to a zero motion state three in scenarios; k_3 =0.5, k_3 =1 and k_3 =2.



a) $k_3 = 0.5$, b) $k_3 = 1$, c) $k_3 = 2$

Figure 8. 3D Haptic cone cross-sections for various values of k_3

If k_3 is too small, (e.g., Fig 8a) then there is little difference to a 2D control surface and finding the zero velocity command position, i.e., the origin of the cone may be difficult, and in contrast if k_3 is too large, (e.g., Fig 8c) then it may be hard for the operator to infer the robot velocity commands they are providing. Given the physical limitations of the implemented haptic device, the possible geometries of the 3D virtual haptic cone control surface are considered with respects to the device's workspace restrictions.

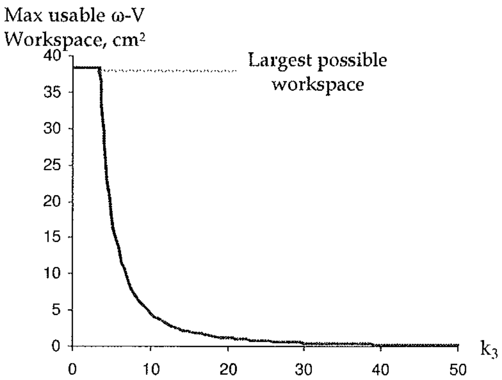
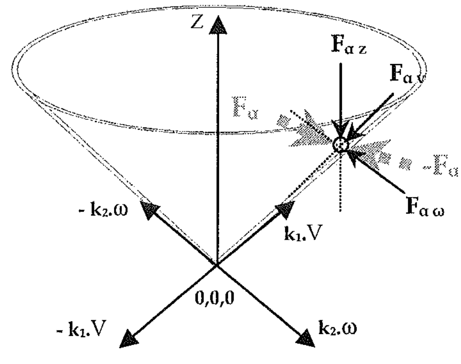
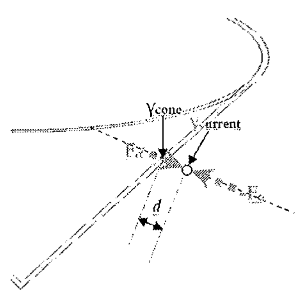


Figure 9. Workspace versus k_3 given the physical limitations of the implemented haptic device

The Phantom Omni from Sensable Technologies [15] offers a workspace of 160 W x 120 H x 70 D mm. Given the desire to use largest possible workspace of the relatively small device, the maximum usable ω-V workspace becomes dependant on k_3. As demonstrated by Figure 9, as k_3 increases, the maximum usable workspace decreases. Whilst, the slope k_3 provides the operator with the ability to intuitively control the motion of the mobile robot too great a slope will likely prove detrimental to the control process. The relationship between the usable ω-V workspace and k_3 for this particular implementation was investigated through experimentation and empirically chosen as $k_3 = 0.7$. As shown by Figure 9, for the chosen value of k_3, the corresponding ω-V workspace is at the largest possible value. This value was empirically determined as sufficient for the operator to haptically infer the geometry of the haptic cone control surface. In order to haptically render the 3D virtual haptic cone control surface and to also render any required haptic augmentation, a suitable methodology is required. Figure 10 illustrates how the 3D virtual haptic cone control surface is rendered.



a) Haptic cone rendering through the *normal-to-cone* force



Proportional control for *normal-to-cone force*

Figure 10. Haptic rendering of the cone control force

F_α is the force vector for rendering the 3D virtual haptic cone control surface (F_α is normal to the conic surface), d is the distance of the point in 3D haptic space from the theoretical cone surface (along the direction normal to the cone surface) and γ denotes the position in 3-D haptic space. The force vector (F_α) is given by conventional proportional control

$$F_\alpha = K_p.e(t) \tag{7}$$

where K_p is the proportional gain, and $e(t)$ is the distance error in positioning (normal to the cone surface) at the current time, given by

$$e(t) \; = \gamma_{cone} - \gamma_{current} \tag{8}$$

The units of the error e are mm and K_p =0.5N. In a scenario where no haptic augmentation is necessary and the teleoperator's manipulation of the haptic probe is unopposed across the 3D virtual haptic cone control surface, only F_α needs to be considered, and thus the overall haptic force, f is given by $f = F_\alpha$. However, when haptic augmentation is required, both F_α and the haptic augmentation F_β need to be considered simultaneously in order to provide the teleoperator with the necessary information. The haptic augmentation F_β, acts across the conic surface. Depicted from above, Figure 11 demonstrates how F_β provides suggestions to the operator regarding the robot's suggested action. It is

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.

important to note that as F_β acts across the non-planar cone surface it does contain a $F_{\beta\ z}$ component however is not visible given the plan view of the diagram.

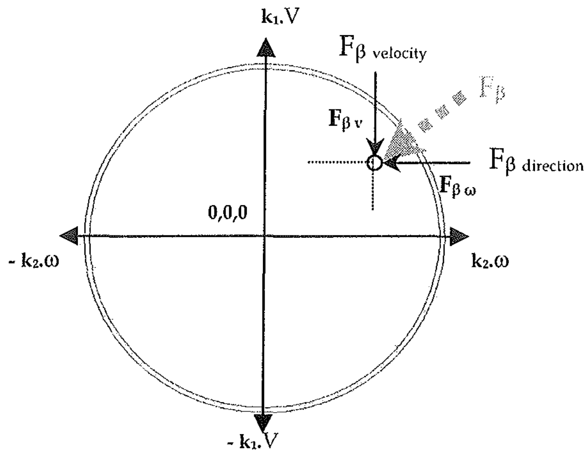


Figure 11. Rendering of the haptic augmentation acting along the 3D conical control surface.

As such, when F_β is required to haptically augment the operator's control across the haptic cone control surface, the overall force F is given by

$$f = F_\alpha + F_\beta \tag{9}$$

where

$$F_\beta = F_\beta velocity + F_\beta direction \tag{10}$$

The operator's movement of the haptic probe is constrained to the virtually rendered cone surface providing information regarding the velocities being commanded to the robot. The haptic augmentation then acts along this virtually rendered surface, providing the operator with task-relevant information such as the presence of obstacles.

The haptic force rendering is maintained at a rate of 1000Hz. The 3D virtual cone control surface has been presented with respects to the teleoperation of the OzBot MkIV mobile robot. It should be acknowledged, however, that this approach has potential applicability to other applications requiring intuitive haptic motion control, such as passenger vehicle control, aircraft speed control etc. This approach enables the operator to intuitively control the motion of the system whilst being able to simultaneously receive application-specific haptic augmentation, and as such the potential application domains are widespread.

4 Experimentation and Evaluation

The novelty of the 3D virtual cone control approach is the ability to provide the operator with intuitive motion control, whilst not impeding any required haptic augmentation. In order to validate the approach the following experimentation and evaluation was deemed necessary.

As previously discussed, the precursor to the haptic cone strategy is the 2-D kinematic mapping presented by [2-3], as depicted in Figure 6a. This 2D approach provides a benchmark for analysis of the presented 3D cone methodology. The validation of this approach is considered with respects to the teleoperation of the OzBot MkVI mobile reconnaissance platform. To achieve ease of experimentation the virtual OzBot MkVI robot was considered, simulated within the Webot's simulation environment [13]. Webot's utilises the ODE (Open Dynamic Engine) for the simulation's physics and for the purposes of this experimentation provided an adequate testing environment.

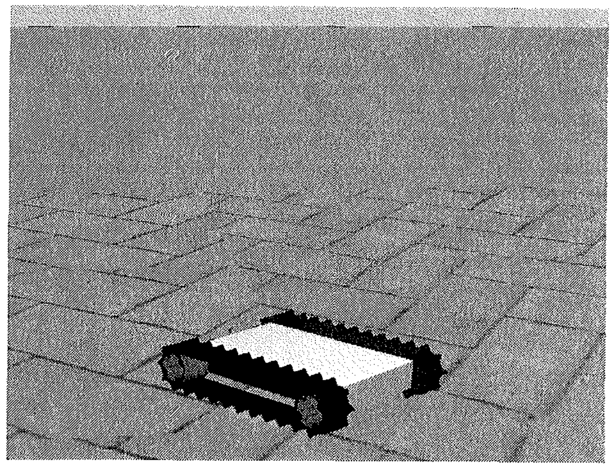


Figure 12. OzBot MkIV within the virtual environment

Figure 12 illustrates the OzBot MkVI in the virtual environment. The virtual world was modelled as a planar surface with four bounding walls. The premise of the presented approach is that the operator is provided with limited visual information in the robot's operating environment.

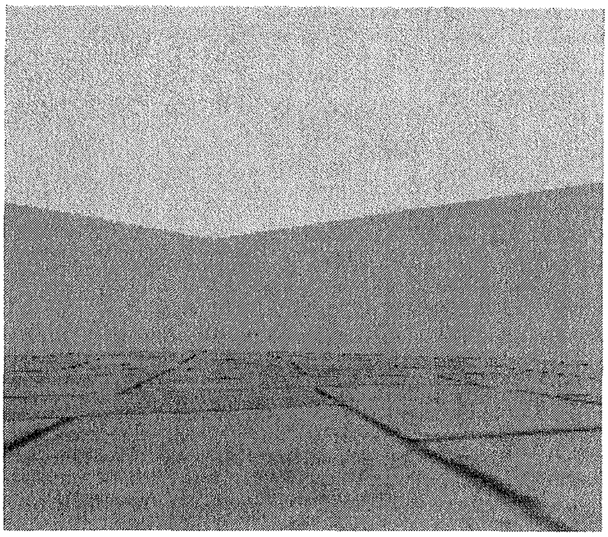


Figure 13. Operators view from the OzBot MkIV onboard camera

As such, the subjects were provided with a view of the remote environment only provided by the robot's onboard camera. The camera colour camera with a 60° Field of View was mounted facing forward. Figure 13 depicts the view provided to the subjects during the experimentation.

The following experiment investigates the ability of the presented approach to improve operator performance when attempting to stop the motion of the robot.

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.

4.1 Experimental Procedure

Firstly, the operator was instructed to provide a velocity command to the OzBot Mk VI mobile platform with a magnitude and duration specified by (11-13) as listed below.

$$0.75\cdot(MaxV) \le v \le 0.90\cdot(MaxV) \quad (11)$$

$$-0.20\cdot(MaxV) \le \omega \ge 0.20\cdot(MaxV) \quad (12)$$

$$\text{for } t \ge 3\,\text{seconds}. \quad (13)$$

The operator was provided with a visual indication of the magnitudes of the velocities being commanded. Once the teleoperator's motion command satisfied the above conditions, the operator is informed visually that the experiment had begun. The operator was then required to maintain the velocity command, according to (11-13) and to wait a random duration, satisfying the below constraint (14), at which point they are informed visually that they need to achieve a zero motion state (stop the robot) as quickly as possible.

$$2 \le t \le 5\,\text{sec} \quad (14)$$

Once the operator achieves the motion state satisfying the below constraint, (15), according the dead-zone in Figure 7, for the required duration (16) the teleoperator is informed visually that the task is completed.

$$(\omega^2 + v^2) \le {r_{dz}}^2 \quad (15)$$

$$t \ge 1\,\text{sec} \quad (16)$$

The above procedure was completed for both the 2D planar and 3D Virtual Cone Control approaches to mobile robotic motion control.

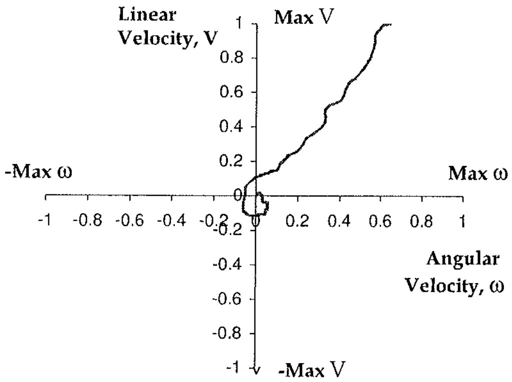


Figure 14. Typical response for 2D kinematic mapping

As a preliminary presentation of the operator responses to the 2D planar and 3D virtual cone control approaches to the control of the mobile platform the control behaviour of the operator was recorded in the aim of obtaining a typical representative teleoperator response as presented by Figures 14 & 15. As can be observed in Figure 14, the 2D planar control surface is prone to overshoot in the ω, v direction as the teleoperator attempts to achieve the zero motion state (dead zone region). This overshoot in the v direction is indicative of a forward-reverse direction change, whereas the overshoot in the ω direction represents a right-left change in steering direction. With respect to the linear velocity, the results show that a motion command of v = 0.12m/s in the reverse direction was performed as the teleoperator attempted to achieve a zero motion command, when this was not the intention of the operator. In order to achieve a zero motion control command to the mobile robot the 2D approach relies heavily upon visual information provided to the teleoperator.

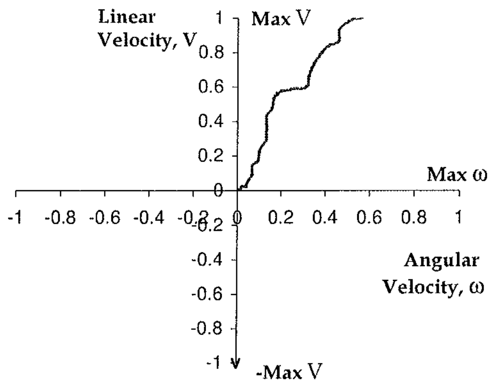


Figure 15. Typical response utilizing haptic conical control surface

Utilising the 3D haptic cone methodology a single representative teleoperator response is presented above in Figure 15. While the decreasing velocity commands are similar to that of the typical response of the 2D planar approach (Figure 14), it can be observed that no overshoot of the desired ω, v occurred. The novelty of this approach is that it provides the teleoperator with a means to easily locate the origin position (0,0,0) corresponding to zero motion. As the conical surface converges to the point of origin, a continuous downward force will inevitably return the haptic point of interaction to the zero motion state (0,0,0).

The representative responses presented above illustrate the typical performance of the approach. In order to evaluate the effectiveness of the 3D virtual haptic cone in achieving the stated objectives given the subjective nature of the human operator further experimentation was performed. The experiment was performed with 5 participating subjects, each completing 10 repetitions of the above-described experiment for both the 2D and 3D approaches. The 2D planar control surface was utilised as a benchmark. The ordering of the 2D vs 3D approaches was alternated until the total of 10 repetitions for each method were achieved. The 5 subjects were of varying age, gender and experience.

The time taken to achieve the zero motion command state (15-16) and % of Max ω and V overshoot represent significant performance metrics. The results of the experimentation are presented in Figure 16. The average time taken to achieve the zero motion command state (15-16), using the 3D virtual haptic cone was 2.1 seconds, while for the 2D planar approach the average time was far greater at 7.1 seconds. It becomes obvious that the 3D approach is of great benefit in reducing the time taken to achieve a zero motion command state.

Using the 2D approach the Maximum overshoot in the V direction was 15.9% of Max V and the Maximum overshoot in the direction 13.1% of Max ω. Using the 3D virtual haptic cone the Maximum overshoots were significantly lower in the V direction

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.

at 5.7% of max V and in the ω direction 5.2% of max ω. Using 2D the planar approach the average % Max overshoot in the V direction was 1.84 and in the ω direction the % Max overshoot was 0.29%. Again the 3D approach achieved a performance of an average %max overshoot in the V direction of 0.67% and in the ω direction the average %max overshoot of -0.56%, indicating that on average the operator did not overshoot at all in the ω direction.

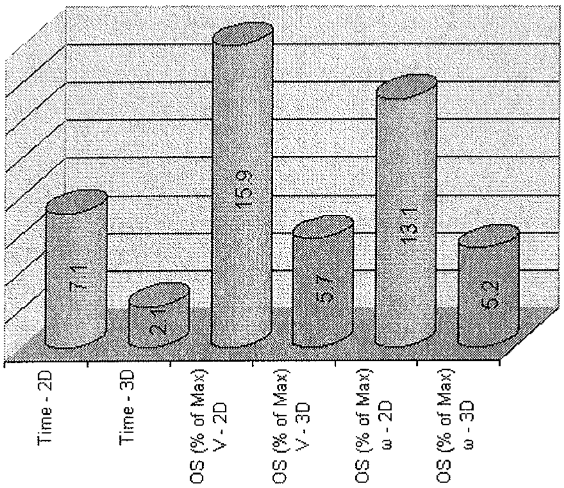


Figure 16. Experimental Results for the 2D vs 3D approach

It can be observed that for the given experiment the introduced 3D approach achieved better performance than the 2D approach. As mentioned earlier the effects of k_3, the slope of the cone surface will affect the effectiveness of the approach in achieving its aims. As such, this needs to be addressed in future work to determine a method for the optimal choice of the parameter.

5 Conclusion and Future Work

The paper presents a new approach to the 3D haptic control of a remote mobile robot or similar system. The approach offers the ability to provide the operator with an intuitive indication of the current motion being commanded to the robot whilst not impeding haptic augmentation relating to the task at hand. Experimental results demonstrate the ability of the approach to improve upon an existing technique.

Future work includes the investigation of more efficient haptic rendering algorithms to achieve stiffer rendering of the 3D virtual haptic cone and the accompanying task-relevant haptic augmentation. The effects of the slope of the cone surface on user interpretation and performance also required additional information.

References

[1] J. B. Park, J. H. Lee, B. H. Lee, "Rollover-free navigation for a mobile agent in an unstructured environment", IEEE Trans. Systems, Man and Cybernetics, Vol. 36, No 4, 2006, pp. 835-848.

[2] S. Lee, G. S. Sukhatme, G. J. Kim, C. M. Park, "Haptic control of a mobile robot: A user study," Proc. of IEEE Int Conf on Intelligent Robots and Systems, 2002, pp. 2867-2874.

[3] Lee, S., Sukhatme, G. S., Kim, G. J. and Park, C-M., "Haptic control of a mobile robot: a user study", *Proc. Of IEEE/RSJ Int. Conf. On Intelligent Robots and Systems*, Lausannne Switzerland, October 2002.

[4] Horan, B., Creighton, D., Nahavandi, S., Jamshidi., "Bilateral haptic teleoperation of an articulated track mobile robot", IEEE Int Conf on System of Systems Engineering, 2007.

[5] Cox, D.J., "Mock-up of hazardous material handling tasks using a dual-arm robotic system", *World Automation Congress*, Orlando, June 2002.

[6] Casper, J. and Murphy, R.R., "Human-robot interactions during the robot-assisted urban search and rescue response at the World Trade Centre", *IEEE Trans. on Systems, Man, and Cybernetics (SMC)*, Vol.33, 2003.

[7] Kang, S., Cho, C., Lee, J., Ryu, D., Park, C., Shin, K-C and Kim, M., "ROBHAZ-DT2: Design and integration of passive double tracked mobile manipulator system for explosive ordnance disposal", *Proc. of IEEE Int. Conf. On Intelligent Robots and Systems (IROS)*, Las Vegas, October 2003.

[8] Thompson, R.L., Reid, I.D., Munoz, L.A., Murray, D.W., "Providing synthetic views for teleoperation using visual pose tracking in multiple cameras", IEEE Transactions on Systems, Man and Cybernetics, Part A, Vol. 31, Issue 1, 2001, pp. 43-54

[9] Diolaiti, N. and Melchiorri, C., "Teleoperation of a mobile robot through haptic feedback", *Proc. Of IEEE Int. Workshop on Haptic Virtual Environments and Their Applications*, Ontario, November 2002.

[10] B. Horan, S. Nahavandi, D. Creighton, E. Tunstel, "Fuzzy Haptic Augmentation for Telerobotic stair-climbing," Proc. of IEEE Int Cont. Systems, Man and Cybernetics, 2007.

[11] M. Fielding, J. Mullins, B. Horan, S. Nahavandi, "OzBot™ - A Teleoperated Robotic Platform for Search and Rescue Operations," IEEE Int Workshop on Safety, Security and Rescue Robotics, 2007.

[12] J. Mullins, B. Horan, M. Fielding, S. Nahavandi, "A Haptically Enabled Low-Cost Reconnaissance Platform for Law Enforcement," IEEE Int Workshop on Safety, Security and Rescue Robotics, 2007.

[13] *Webots,* a commercial mobile robot simulation software developed by Cyberbotics Ltd. (http://www.cyberbotics.com), 2007.

[14] Anh Tuan Le, "Modelling and Control of Tracked Vehicles", PhD Thesis, *The University of Sydney*, 1999.

[15] Sensable Technologies, http://www.sensable.com/, 2007.

[16] H. Azarnoush, B. Horan, P. Sridhar, A. Madni, M. Jamshidi, "Towards optimization of a real-world robotic sensor system-of-systems," World Automation Congress, 2006

[17] F. Sahin, P. Sridhar, B. Horan, V. Raghavan, M. Jamshidi, "System of Systems Approach to Threat Detection and Integration of Heterogeneous Independently Operable Systems," Proc. of IEEE Int Cont. Systems, Man and Cybernetics, 2007.

[18] K. Liang, L. Zhiye, D. Chen, X. Chen, "Improved Artificial Potential Field for Unknown Narrow Environments," IEEE Int. Conf. On Robotics and Biometrics, 2004, pp. 688-692.

[19] A. Kron, G. Schmidt, B. Petzold, M. I. Zah, P. Hinterseer, E. Steinbach, "Disposal of explosive ordnances by use of a bimanual haptic telepresence system," Proc. of IEEE Int Conf. on Robotics and Automation, 2004, pp. 1968-1973

Authorized licensed use limited to: DEAKIN UNIVERSITY LIBRARY. Downloaded on February 24, 2009 at 18:53 from IEEE Xplore. Restrictions apply.