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Haptic Control Methodologies for Telerobotic Stair Traversal

B. Horan, Z. Najdovski, S. Nahavandi and E. Tunstel

***Abstract*—Teleoperated mobile robots provide the ability for a human operator to safely explore and evaluate hazardous environments. This ability represents an important progression towards the preservation of human safety in the inevitable response to situations such as terrorist activities and urban search and rescue. The benefits of removing physical human presence from such environments are obvious, however challenges inhibiting task performance when remotely operating a mobile robotic system need to be addressed. The removal of physical human presence from the target environment introduces telepresence as a vital consideration in achieving the desired objective. Introducing haptic human-robotic interaction represents one approach towards improving operator performance in such a scenario. Teleoperative stair traversal proves to be a challenging task when undertaking threat response in an urban environment. This article investigates the teleoperation of an articulated track mobile robot designed for traversing stairs in a threat response scenario. Utilising a haptic medium for bilateral human-robotic interaction, the haptic cone methodology is introduced with the aim of providing the operator with a vision-independent, intuitive indication of the current commanded robot velocity. The haptic cone methodology operates synergistically with the introduced fuzzy-haptic augmentation for improving teleoperator performance in the stair traversal scenario.**

***Index Terms*—Haptic teleoperation, stair-climbing, haptic control**

1. INTRODUCTION

Teleoperated robotic systems have been widely used in applications such as hazardous materials handling [1], explosive ordnance disposal [2] and urban search and rescue [3]. Typical operating environments include unstructured outdoor terrain, damaged urban terrain, such as construction debris fields, and otherwise challenging man-made terrain such as stairs. The capability of the human operator to adequately control these systems in mission critical scenarios represents an important progression towards minimising human presence in the target environment. Physical teleoperator displacement is desirable in removing humans from immediate threat, however is likely to decrease task-relevant immersion in the remote operating environment. A decrease in telepresence, being the degree to which the teleoperator feels adequately present in the target environment, inevitably results in reduced task immersion, which, in turn, can adversely affect task performance. Haptic technology provides the ability to interact with a user's tactual modality and, if used appropriately, can recreate the sense of touch to the user. Several different approaches to improving teleoperative capabilities utilising haptic technology have been proposed [2,4-9].

Teleoperated mobile robots represent an important class of telerobotic systems, providing the mobility to explore and interact in different remote environments. In terms of mission success, it is therefore essential that the mobile robot is capable of safely reaching target locations within the environment in order to perform critical tasks, including those mentioned earlier. Considering the common operational scenario within an urban environment, the ability to achieve safe teleoperative traversal of stairs is an important requirement. The articulated track method of locomotion has a proven mechanical aptitude for the stair traversal task [10,11], however stable teleoperative control is often far more difficult to achieve.

Subjected to reduced telepresence given the assumed limited environmental immersion, safe open-loop control of the robot is likely to prove challenging to the teleoperator. Approaches have been presented providing autonomous [11] or semiautonomous solutions [12] for the telerobotic stair-climbing task. The work presented here, however, values the teleoperator's superior ability to utilise human-level judgment and intuition in total control of the mobile robot. This is not to say that the robot's intelligence should be neglected. As such, the *absolute human control* approach to teleoperation is presented and provides the premise for the proposed teleoperation scheme. This article presents a haptic approach for executing a teleoperative stair traversal task using a purpose-built teleoperated mobile robot. The robot is equipped with appropriate sensory systems for acquiring and transmitting information regarding its operating environment in the form of haptic, or tactile, information.

The haptic contributions to the presented teleoperation system are two-fold. Firstly, the haptic cone control surface provides the teleoperator with a means to intuitively determine the velocities he/she is commanding the robot with. Secondly, the teleoperator is provided with real-time, task-relevant haptic augmentation indicating suggestive actions concerning the desired objective in the stair-traversal task. Importantly, the haptic cone control surface operates hand-in-hand with the implemented haptic augmentation. The appropriate haptic augmentation is provided by the robot's onboard intelligence, determined by approximate human-like reasoning derived from a fuzzy expert system.

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2. TELEOPERATION CONTROL ARCHITECTURE

The teleoperated articulated track mobile robot presented in this work demonstrates the *absolute human control* approach to teleoperation. This work defines absolute *human control* as the ultimate human-in-the-loop control of the robot's actions. While the semi-autonomous approach to teleoperation is achieved through combined human-robot control, the teleoperator does not necessarily control all of the robot's actions. As depicted by Fig. 1.a, this arrangement can result in a conflict of control whereby the user is commanding one action and the robot performs an action undesirable to the operator. This is possible because the robot has the capability to directly control it's actions; therefore, should the robot make an inappropriate decision, it can be executed independent of the teleoperator's control. The approach presented by this work differs in that the teleoperator ultimately controls all of the robot's actions. The teleoperator, however, still receives real-time information regarding the robot's desired (or suggested) action. In this scenario, depicted by Fig. 1.b, the teleoperator relies on his/her advanced intelligence and intuition to determine what action or combination of actions is conducive to successful task execution.

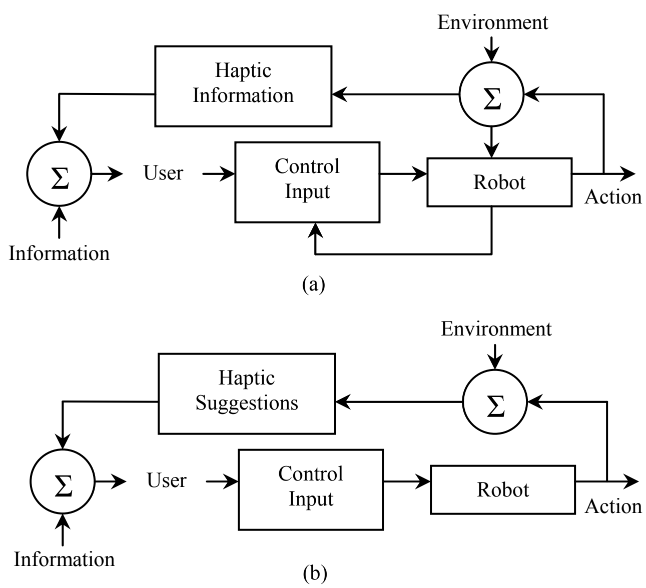


Fig. 1. (a) Shared autonomy control strategy; (b) Absolute human control

In the context of a haptically teleoperated robotic system, the absolute control approach provides haptic suggestions to the teleoperator concerning what the robot perceives to be a suitable action. The bilateral nature of the implemented haptic interface enables the teleoperator to provide a motion command to the robot, whilst simultaneously receiving the haptic suggestions from the robot. This real-time bidirectional flow of information is achieved through simultaneous human-robot force (haptic) interaction with the single-point haptic interface. This single point of human-haptic interaction, represented in 3-D space ensures that the intentions of both the operator and the robot are coincidental, thus overcoming any conflict in control. As such, the haptic control interface is designed so that the teleoperator can easily overpower the maximum exertable haptic force, thereby facilitating ultimate teleoperator control of the robot's actions. The control architecture of the haptically teleoperated robotic system is presented in Fig. 2.

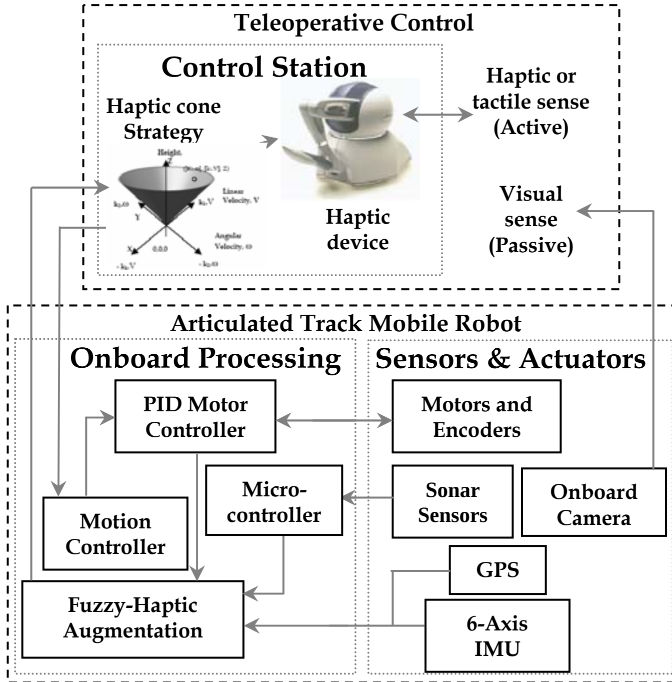


Fig. 2. Robot System Control Architecture.

Haptically controlled mobile robotics has been discussed by several researchers in recent years [4-9,15]. Our previous work [6] 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. This provides the teleoperator with a method by which to control the motion of the robot. This component is addressed by the haptic cone control strategy. The second component is the relevant methodology for providing appropriate haptic augmentation to assist the operator in the performance of a particular task. This is addressed by the fuzzy-haptic augmentation for the stair-traversal scenario. Consideration of both components is integral to the haptic control of a mobile robot as they occur simultaneously on the same point in haptic space. Fig. 3 graphically depicts these two components.

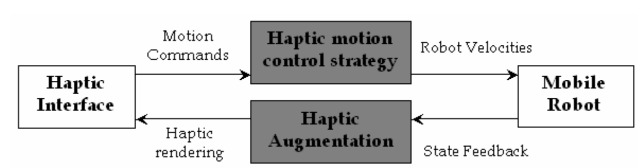


Fig. 3. Main components of the haptic teleoperation.

The design of both the haptic motion control strategy and the haptic augmentation cannot impede one another's operation. This design constraint was also discussed by [5-

7], who noted that task-relevant haptic augmentation must not diminish the teleoperator's motion control process and similarly, motion control cannot adversely affect the augmentation process.

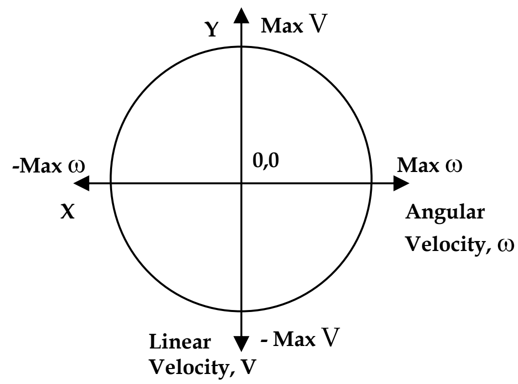
3. Haptic Cone Motion Control

In the work presented by [4,5,7], motion control is achieved through 2-D kinematic mapping of the X, Y displacements of the haptic device across a horizontal plane 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 across the 2-D plane whilst 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?

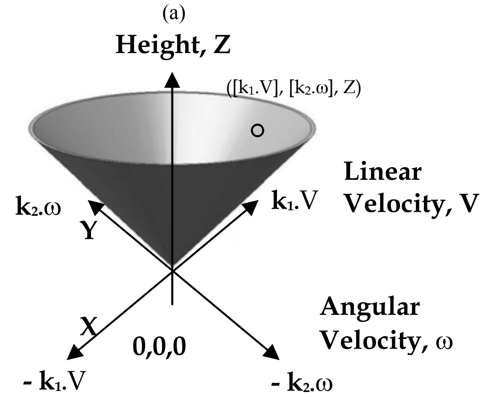
Given a 2-D approach, in order for the teleoperator to perform a zero motion command to the robot, the teleoperator must rely on their visual sense to infer the motion being commanded to the mobile robot. This may impede on the teleoperator's ability to concentrate on other aspects of the task at hand. It becomes apparent that this may prove contradictory since the haptic component is introduced to utilise the teleoperator's tactual sensory modality, however the operator is relying heavily on their 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 on one another. As such, when considered independently, the haptic cone motion control capability is required to allow free motion across 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. Unlike a 2-D approach to controlling the motion of the mobile robot, the operator's control of the single point in haptic space is constrained to a 3-D *conical* surface. As the probe of the haptic device is moved across the virtually rendered surface, the robot is commanded with corresponding linear (V) and angular (ω) velocities, as depicted by Fig. 4b. 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.

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 3-D virtual haptic cone control surface, the user can infer the current velocities being commanded to the robot, while still having unimpeded motion across 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.



(a)



(b)

Fig 4. (a) 2-D kinematic mapping [4,5,7], (b) 3-D haptic cone control surface.

The circular geometry of the 2-D control surface in the X-Y plane (Fig. 4a) defines the limits of the allowed velocity commands which were chosen empirically. 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 3-D virtual haptic cone control surface overcomes this limitation by introducing a third dimension to the kinematic mapping between the grounded haptic display and the mobile robot. Functionally, the 2-D and 3-D approaches 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 graphically depicted above in Fig. 4b with its 3-D virtual control surface given by

$$(k_1.V)^2 + (k_2.\omega)^2 = (k_3.Z)^2 \tag{1}$$

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 (see Fig. 4b)

$$([k_1.V],[k_2.\omega],Z) \tag{2}$$

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.

3.1 Haptic Cone Design Considerations

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 the (0.00, 0.00, 0.00) (ω,V,Z) position at the origin of the cone. As such a dead-zone (corresponding to near-zero Z values) 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.

The introduced dead-zone is depicted by Fig. 5, where v_{dz} and ω_{dz} denote the dead-zone thresholds and r_{dz} the radius of the deadzone, chosen empirically as 3mm. 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.

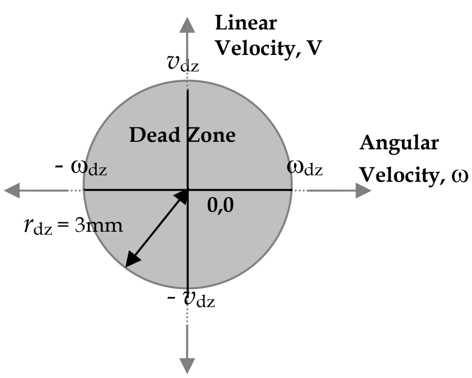


Fig. 5. Dead-zone around origin

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. The 3-D virtual haptic cone control surface is defined by Eq. (1) 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. If k_3 is too small, then there is little difference to a 2-D control surface and finding the zero velocity command position, that is the origin of the cone may be difficult, and in contrast if k_3 is too large, then it may be hard for the operator to infer the robot velocity commands that they are providing. Given the physical limitations of the implemented haptic device, the possible geometries of the 3-D virtual haptic cone control surface are considered with respect to the device's workspace restrictions.

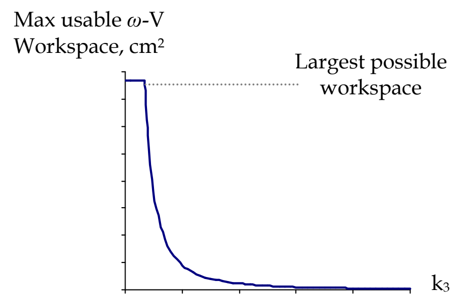


Fig. 6. Workspace versus k_3 given the physical limitations of the implemented haptic device.

The Phantom Omni from SensAble Technologies [14] offers a workspace of 160 W x 120 H x 70 D mm. Given the desire to use the largest possible workspace of the relatively small device, the maximum usable ω-V workspace becomes dependant on k_3. As demonstrated by Fig. 6, as k_3 increases, the maximum usable workspace decreases. Whilst the slope defined by 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 Fig. 6, 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.

3.2 Haptic Cone Rendering

In order to haptically render the 3-D virtual haptic cone control surface and to also render any required haptic augmentation, a suitable methodology is required. Fig. 7 illustrates how the 3-D virtual haptic cone control surface is rendered. F_α is the 3-D force vector for rendering the 3-D virtual haptic cone control surface (F_α is normal to the conic surface), d is the distance of the point in 3-D 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

$$F_\alpha = K_p.e(t) \tag{3}$$

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

$$e(t) = \gamma_{cone} - \gamma_{current} \tag{4}$$

The units of the error e are millimetres and K_p = 0.5N.

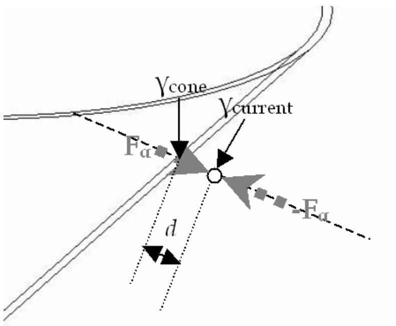


Fig. 7. Haptic cone rendering proportional control for *normal-to-cone force.*

In a scenario where no haptic augmentation is necessary and the teleoperator's manipulation of the haptic probe is unopposed across the 3-D 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.

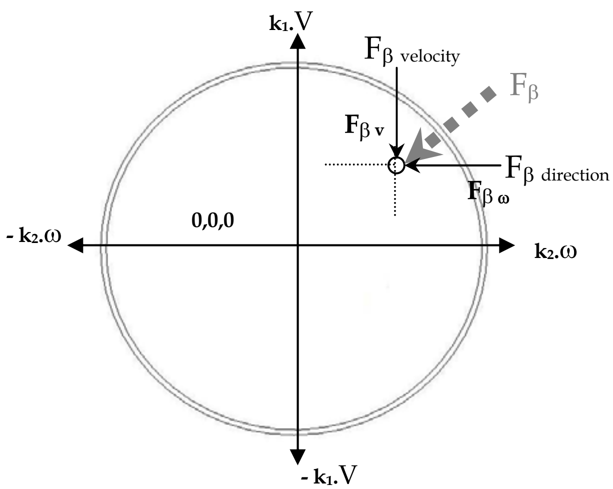


Fig.8. Haptic augmentation rendering across 3-D conical control surface.

Depicted from above, Fig. 8 demonstrates how F_β provides suggestions to the operator regarding the robot's suggested action. As such, when F_β is required to haptically augment the operator's control across the haptic cone control surface, the overall haptic force *f* is given by Eq. (5). The haptic force rendering is maintained at a rate of 1 KHz.

$$f = F_\alpha + F_\beta \tag{5}$$

3.3 Validation on a Mobile Reconnaissance Platform

The OzBot MkVI articulated track mobile robot is considered in this work. 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 [13] is utilised and is formulated in a world co-ordinate system as follows

$$\dot{x} = \frac{r}{2}\left[\omega_o(1-i_o) + \omega_i(1-i_i)\right]\left[\cos\theta(t)\right] \tag{6}$$

$$\theta = \frac{r\left[\omega_o - \omega_i\right]t}{B} \tag{7}$$

$$\dot{\phi} = \frac{r\left[\omega_i(1-i_i) - \omega_o(1-i_o)\right]}{B} \tag{8}$$

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 left and right tracks, θ 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

$$\omega_o = \frac{2V - \omega B}{2r} \qquad \omega_i = \frac{\omega B}{r} + \omega_o \tag{9}$$

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

The coefficients of slip, i_o and i_i, account for the slip between the robot's tracks and the terrain. Appropriate coefficients of slip enable the kinematic model to remain consistent across various terrains, and in this application this corresponds to achieving the desired robot velocities. As accurate coefficients of slip are going to vary on a case-by-case basis, the coefficients of slip i_o and i_i were chosen as 0. The assumption was made that the human operator is an adequate compensator for any inaccuracies in the kinematic model when operating on various terrains. The kinematic parameter values for the OzBot MkVI platform are presented in Table 1.

Table 1. OzBot MkVI Kinematic Parameters

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 coefficient)*	0.00
i_o *(outer slip coefficient)*	0.00

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 [4,5,7], as depicted in Fig. 4a. This 2-D approach provides a benchmark for analysis of the presented 3-D cone methodology. An experiment was conducted to investigate the ability of the presented approach to improve operator performance when attempting to achieve a zero motion command state. Several human operators were used as subjects in the experiment. The validation of this approach is considered with respect 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 [16]. Webot's utilises the ODE (Open Dynamic Engine) for the simulation's physics and for the purposes of this experimentation provided an adequate evaluation environment.

3.3.1. Experimental evaluation

Fig. 9 (left) illustrates the OzBot MkVI in the virtual environment. The virtual world was modeled as a planar surface with four bounding walls. The premise is that the operator is provided with limited visual information in the robot's operating environment. As such, the subjects were only provided with a view of the remote environment via the robot's 60˚ field of view colour camera, which was mounted onboard and facing forward. Fig. 9 (right) depicts a snapshot of the view ahead of the robot provided to the subjects during the experimentation. The following experimental procedure was completed for both the 2-D planar and 3-D virtual cone control approaches to haptic mobile robotic motion control.

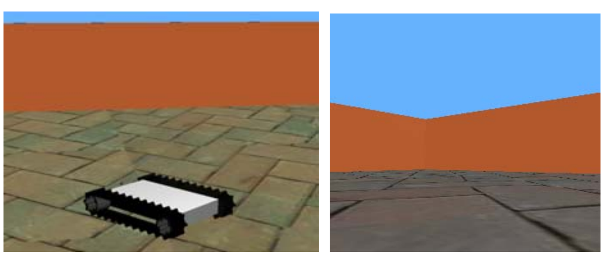


Fig. 9. OzBot MkVI within the virtual environment (left) and operator's view from the onboard camera (right).

Experimental Procedure

Firstly, the operator was instructed to provide a velocity command to the OzBot MkVI mobile platform with a magnitude and duration specified by Eq. (10-12) below.

$$0.75 \cdot (MaxV) \le V \le 1.0 \cdot (MaxV) \qquad (10)$$

$$\omega \le -0.20 \cdot (Max\omega) \ OR \qquad (11)$$

$$\omega \ge 0.20 \cdot (Max\omega)$$

for $t \ge 3$ seconds. (12)

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 Eqs. (10)-(12) and to wait a random duration, satisfying the below constraint (13), at which point they are informed visually that they need to achieve a zero motion state (stop the robot) as quickly as possible.

$$2 \le t \le 5 \sec \qquad (13)$$

Once the operator achieves the motion state satisfying the below constraint, (14), according the dead-zone (Fig. 5), for the required duration (15) the teleoperator is informed visually that the task is completed.

$$(\omega^2 + V^2) \le r_{dz}^{\ 2} \qquad (14)$$

$$t \ge 1 \sec \qquad (15)$$

As a preliminary presentation of the operator responses to the 2-D planar and 3-D virtual cone control approaches their control behaviours were recorded with the aim of obtaining a typical representative teleoperator response as presented by Figures 10 and 11. As can be observed in Fig. 11, the 2-D planar control 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 = 0.12 m/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 2-D approach relies heavily upon visual information provided to the teleoperator. Utilising the 3-D haptic cone methodology, a single representative teleoperator response is presented below in Fig. 11. While the decreasing velocity commands are similar to that of the typical response of the 2-D planar approach (Fig. 10), it can be observed that no overshoot of the desired ω, V occurred.

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

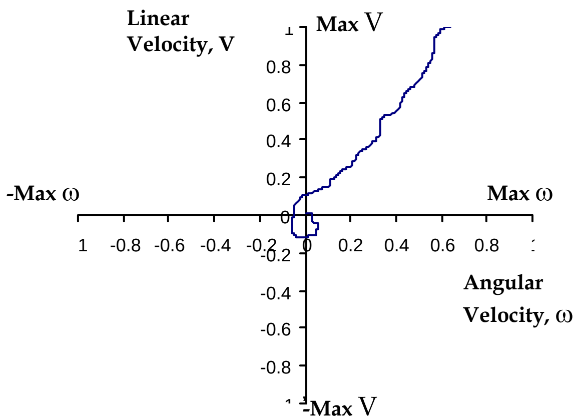


Fig. 10. Typical response for 2-D kinematic mapping.

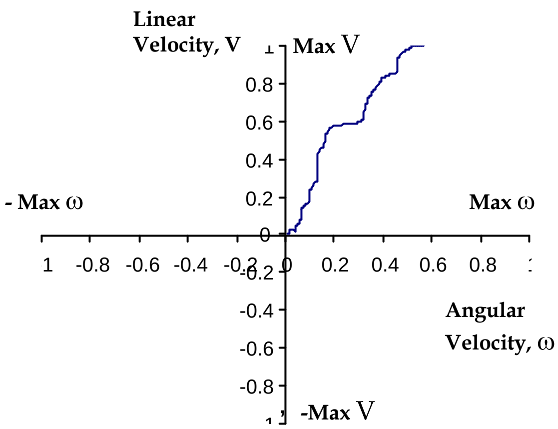


Fig. 11. Typical response utilizing haptic conical control surface.

The time taken to achieve the zero motion command state, Eqs. (14-15), and % of Max ω and V overshoot represent significant performance metrics. The results of the experimentation are presented in Fig. 12. The average time taken to achieve the zero motion command state Eqs. (14-15), using the 3-D virtual haptic cone was 2.1 seconds, while for the 2-D planar approach the average time was far greater at 7.1 seconds. It becomes obvious that the 3-D approach is of great benefit in reducing the time taken to achieve a zero motion command state.

Using the 2-D approach, the maximum overshoot in the V direction was 15.9% of Max V and the maximum overshoot in the ω direction was 13.1% of Max ω. Using the 3-D virtual haptic cone the maximum overshoots were significantly lower in the V direction at 5.7% of Max V and in the ω direction at 5.2% of Max ω. Using the 2-D planar approach the average % Max overshoot in the V and ω directions was 1.84% and 0.29%, respectively. Again, the 3-D approach achieved an average % Max overshoot performance in the V and ω directions of 0.67% and -0.56%, respectively, indicating that on average the operator did not overshoot at all in the ω direction.

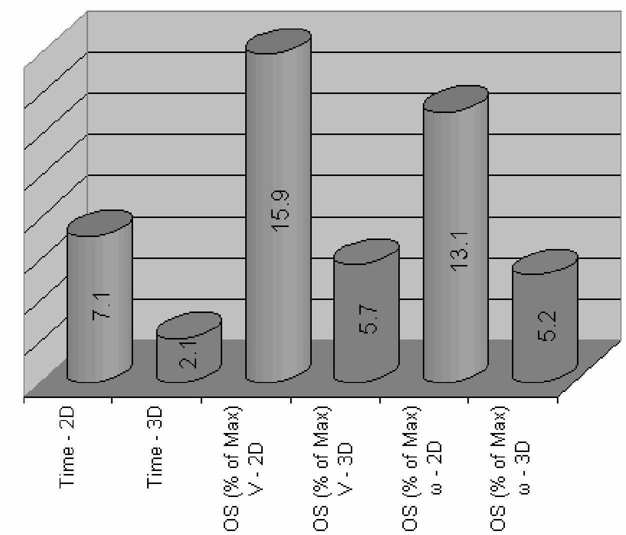


Fig 12. Experimental Results for the 2-D vs 3-D approach.

From the results presented in Fig. 12, it can be observed that for the given experiment the introduced 3-D approach achieved better performance than the 2-D approach. As mentioned earlier the effects of the slope of the cone surface defined by k_3 will impact the effectiveness of the approach in achieving its aims. As such, this needs to be addressed in future work to determine a method for obtaining the optimal slope.

4. Fuzzy-Haptic Augmentation for Stair Traversal

The haptic cone control surface facilitating 3-D haptic motion control of an articulated tracked mobile robot has been presented above. In order to develop the collaborating haptic augmentation, investigation of the stair-traversal task was performed. The work by other researchers investigates the utility of a mobile robot for climbing stairs [11]. In our previous work [15], data representing roll and pitch angles were obtained for OzBot MkVI while performing stair climbing under teleoperative control. Their findings, combined with our first hand experience in teleoperative stair traversal, led to two important observations. Firstly, it was noticed that due to inconsistent track-terrain interaction, the teleoperated robot was likely to yaw, or deviate, from a straight path while climbing the stairs. Given the inclination of the stairs, deviation from a straight-line path, parallel to the direction of the stairs, is causal to an increased amount of roll of the robot body. This increase in body roll obviously increases the likelihood of the robot tumbling down the stairs. In order to avoid the above situation, it is desirable for the robot to minimise the amount of roll undertaken. The second important observation noted was that as the pitch angle of the robot increased, so did the likelihood of the robot tumbling down the stairs. It was also observed that as the forward velocity of the robot increased, an increase in the resulting pitch angle followed.

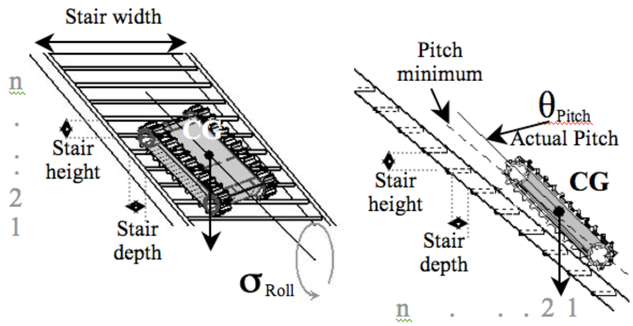


Fig. 13. Pitch and roll as task objectives to be minimized.

These observations establish roll and pitch as two significant performance metrics utilised for the presented task-relevant haptic augmentation. The robot's roll and pitch angles during the stair-climbing task can be determined in real-time by the Inertial Measurement Unit (IMU). The robot's sensory systems are presented in Fig. 2. Fig. 13 illustrates these metrics in the context of the stair climbing task wherein the objective is to minimise pitch and roll.

4.1 Generation of Haptic Information

For the purpose of developing an appropriate haptic augmentation methodology, the two objectives can be represented by the following objective function where σ_{Roll} represents the roll angle and θ_{Pitch} represents the pitch angle of the robot.

$$\Lambda = \sigma_{Roll} \cdot \theta_{Pitch} \tag{16}$$

The objective of the augmentation methodology is to provide appropriate haptic assistance to the teleoperator in order to minimise Λ. Minimisation of the objective function, Λ, represents the desired behaviour of the robotic system while traversing the stairs. In general, the minimum pitch will be governed by the stair height and depth (see Fig. 13); the objective to minimize pitch whilst ascending the stairs holds regardless. Minimisation of Λ provides the basis for the intelligent augmentation methodology as presented below. In order to provide the teleoperator with task-relevant haptic augmentation according to the objective function Λ, a suitable methodology is required. Firstly, a technique for haptically displaying the appropriate information is required. In order to provide the user with haptic suggestions on how to minimise the amount of robot roll, the technique depicted by Fig. 14 is utilised, where τ represents the magnitude of the haptic augmentation force. If the robot is undergoing a roll motion, then the haptic augmentation suggests that the user varies the robot's angular velocity in order to steer in the appropriate direction to correct the action. That is, if the robot is rolling right, then the operator is advised to turn left.

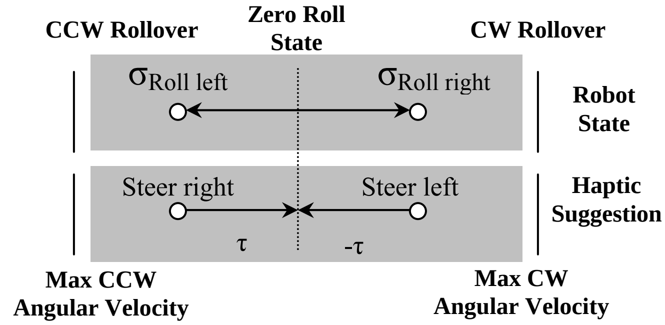


Fig. 14. Technique to augment for σ_{Roll}.

Similarly, in order to utilise haptic suggestions to minimise the robot's pitch angle, the technique depicted by Fig. 15 is utilised, where λ represents the magnitude of the haptic augmentation force.

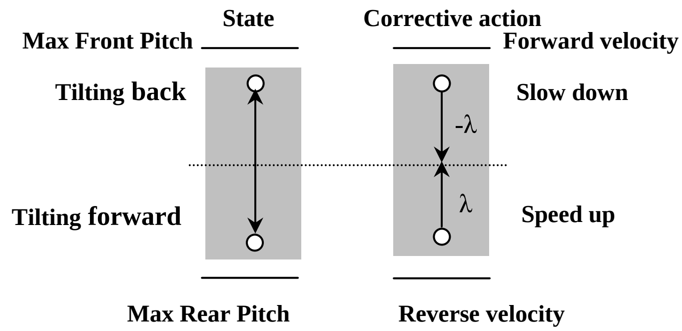


Fig. 15. Technique to augment for θ_{Pitch}.

If the robot's pitch angle is becoming too great, haptic augmentation allows the robot to suggest that the teleoperator varies its linear velocity. The philosophy governing the haptic augmentation received by the teleoperator is presented above and depicted by Fig. 14 & 15. While these techniques specify how the operator receives the haptic information, determination of the appropriate force values for λ and τ requires further investigation.

4.2 Determination of Haptic Augmentation Forces

While a model-based approach could potentially provide the user with suitable values of λ and τ in order to follow the specified objectives, a solution based on fuzzy logic offers the ability to easily represent and encode human-like expertise. Furthermore, model-based approaches cannot easily be changed should the user wish to update any part of the augmentation process, whereas a fuzzy system can be easily adjusted. In light of these considerations, this work presents a fuzzy approach to determining the appropriate haptic forces for the algorithm illustrated by Fig. 14 and 15. Fuzzy expert systems offer a mechanism for utilising human expertise without requiring a model of the system under control. The linguistic variables, fuzzy inference and a smooth transition between states make it possible for an artificial system to control a process in a manner similar to that of a human. The integration of the fuzzy expert system for augmentation in the *absolute control* approach to teleoperation is presented in Fig. 16.

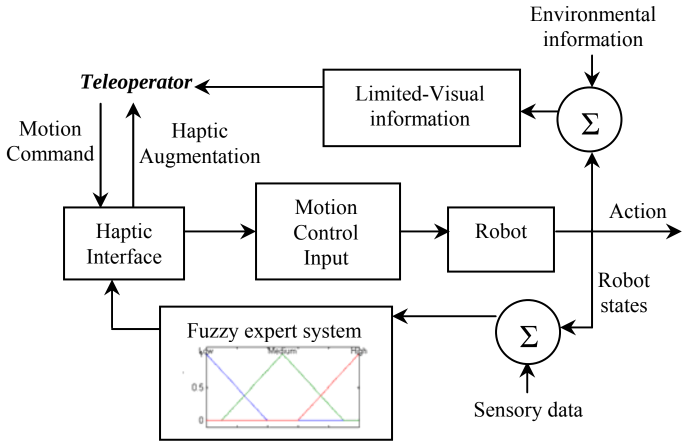


Fig. 16. Fuzzy-Haptic augmentation in the control loop.

The premise of this approach is that the human operator remains in absolute control [6] due to their superior intelligence, decision-making capabilities and human intuition. The haptic augmentation provides the teleoperator with information that may not be obvious due to physical displacement from the robot's operating environment. It appears logical, therefore, that the method used to process the appropriate sensory data and provide haptic suggestions to the operator is based on human-like approximate reasoning. In order to actually quantify appropriate membership functions for the development of a fuzzy expert system to provide the user with suitable values for λ and τ, the qualitative stability of the robot in fuzzy terms is presented below.

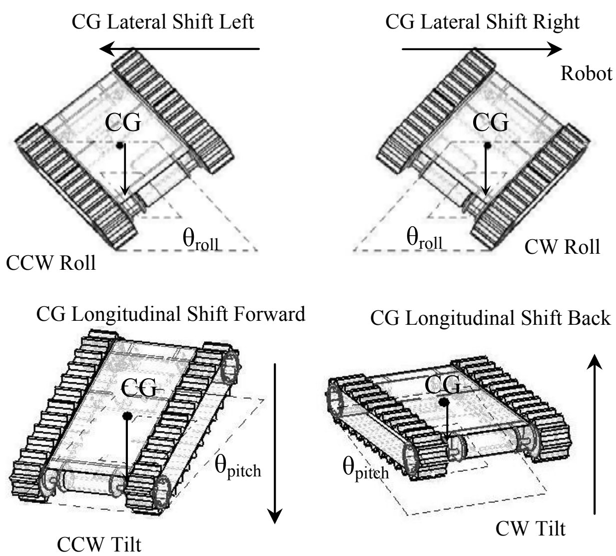


Fig. 17. Lateral and Longitudinal shifts of the CG force vector.

Firstly, the diagrams of Fig. 17 depict the four possible scenarios for two robot states, roll and pitch. Recall that in the case of stair climbing, roll is related to the yaw heading of the robot, and similarly pitch to the robot's forward velocity. In these diagrams, the gravity force vector through the Centre of Gravity (CG) of the robot is considered in order to analyse the stability of the robot in the stair climbing task.

The other dynamics of the robot such as acceleration and track-terrain interaction are intuitively accounted for in the human reasoning process and, in the case of a fuzzy system, do not necessarily require direct quantitative analysis. Rather, Fig. 17 qualitatively depicts how the CG of the robot shifts from its original position within its polygon of support, or nominal footprint, as it undergoes roll and pitch motions.

In order for the robot to remain stable, the vertical force vector representing the CG (magnitude of F = mg) needs to stay within the footprint (fixed along the x, y plane), as demonstrated by the dashed lines in Fig. 17.

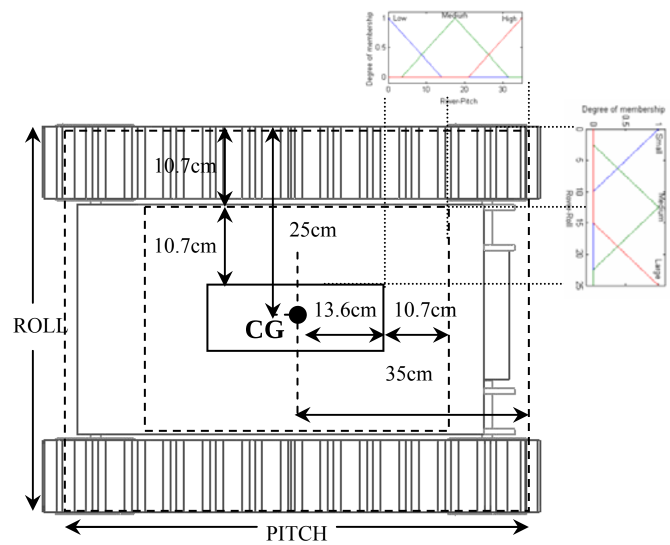


Fig. 18. Fuzzy stability diagram for the OzBot MkVI robot.

The deviation of the coincidental point of the vector and footprint is considered in both lateral (Fig. 17, upper) and longitudinal (Fig. 17, lower) directions for roll and pitch respectively. The dashed lines of the footprint in Fig. 17 are used to partition the lateral and longitudinal directions into fuzzy sets of the roll and pitch states. This partition is illustrated in the fuzzy stability diagram shown in Fig. 18. The framework quantifying the linguistic descriptions of the robot's motion has been developed, leading to the creation of the fuzzy expert system designed to provide the operator with task relevant augmentation. The membership functions and rule characteristic curves are presented in Fig. 19

. A simple, three-rule fuzzy rule base is used for each of the two single Input/Output fuzzy expert systems, illustrated by Fig. 19c. At this stage only a single fuzzy input is considered for both the roll and pitch, however the advantage of this control arrangement is that the system is easily extendable. It is extremely simple to include an additional fuzzy input for each expert system. For example, if it was deemed appropriate to also consider the robot velocity for both objectives, this could be easily achieved. The two fuzzy outputs are combined into a single vector acting along the conic surface as depicted by Fig. 8. As a result, the augmentation methodology will suggest an appropriate action to the teleoperator while he/she is performing the control process.

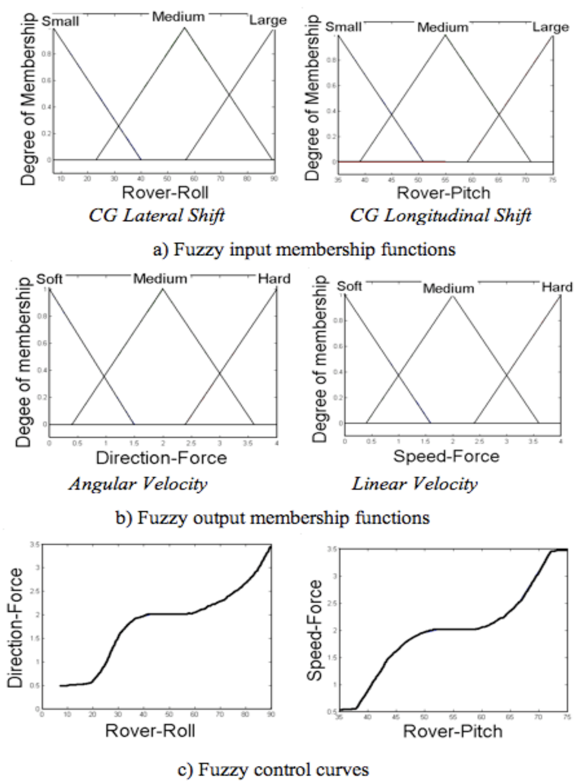


Fig. 19. Fuzzy membership functions and rule characteristic curves.

4.3 Simulation Results

The fuzzy-haptic augmentation designed to provide the teleoperator with real-time haptic suggestions has been presented above. In order to demonstrate the performance of this approach in providing the teleoperator with appropriate haptic suggestions, the following simulation results are presented. In this scenario the teleoperator navigates the OzBot MkVI robot up the staircase while receiving the task-relevant fuzzy-haptic augmentation. The purpose of these results is to demonstrate how the operator is provided with task-relevant haptic suggestions. Whether the teleoperator decides to act based upon these haptic suggestions is up to the individual operator and as such is highly subjective.

Fig. 20 illustrates the OzBot performing the stair-traversal task under teleoperative control. The displacement of the robot along the inclined staircase, as projected on as X-Y plane beneath the staircase, is presented in Fig. 21. This corresponds to the view in Fig. 20 where X is in the direction of the width of the staircase and Y in the direction of the length.

Based on the robot traversing the stairs under teleoperative control, the behaviour of the fuzzy-based augmentation scheme is presented in Figs. 22 and 23, demonstrating the ability of the haptic augmentation strategy to provide the teleoperator with appropriate haptic suggestions based on the objective function, Λ.

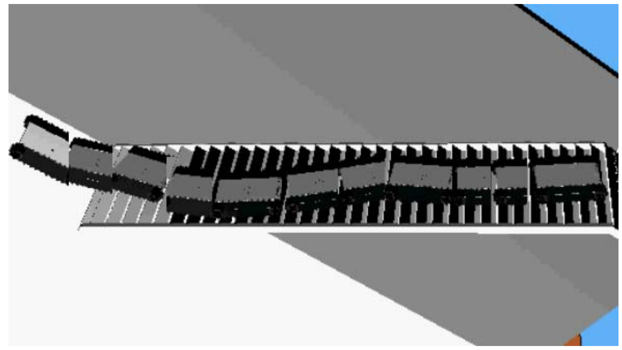


Fig. 20. Robot trajectory during the stair-climbing task.

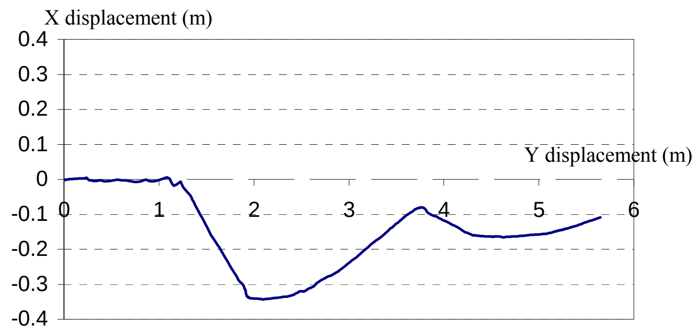


Fig. 21. X-Y displacements during the stair-climbing task.

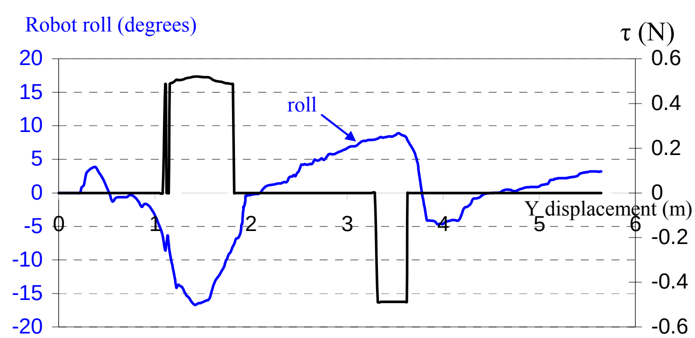


Fig. 22. Robot roll and corresponding haptic augmentation, τ.

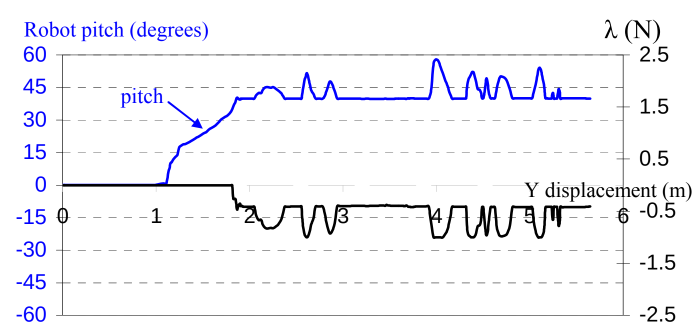


Fig. 23. Robot pitch and corresponding haptic augmentation, λ.

It can be observed that as the robot's CG shifts longitudinally (pitch) and laterally (roll), the haptic augmentation is consistent in providing the counter force suggesting an appropriate corrective action to the teleoperator. Furthermore, the magnitude of the haptic suggestive force is scaled by the implemented fuzzy expert system, representing human expertise in suggesting the importance of the appropriate actions. These results demonstrate the aptitude of the presented approach for providing the teleoperator with augmentation relevant to the stair-climbing task.

5. Conclusion

The haptic teleoperation system has been presented throughout this paper. The haptic cone strategy provides the teleoperator with a method for motion control whilst also giving an intuitive indication of the current commanded robot velocity. The fuzzy-haptic augmentation methodology has been presented, as well as simulation results demonstrating the predicted performance of the approach.

The 3-D virtual cone control surface has been presented with respect to the teleoperation of the OzBot MkVI mobile robot. It should be acknowledged, however, that this approach has 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 such systems whilst being able to simultaneously receive application-specific haptic augmentation, and as such the potential application domains are widespread.

6. Acknowledgement

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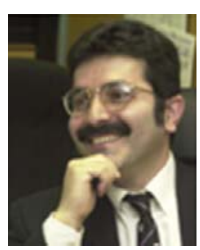

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