Fuzzy Haptic Augmentation for Telerobotic Stair Climbing

B. Horan, S. Nahavandi, D. Creighton and E. Tunstel

Abstract—**Teleoperated robotic systems provide a valuable solution for the exploration of hazardous environments. The ability to explore dangerous environments from the safety of a remote location represents an important progression towards the preservation of human safety in the inevitable response to such a threat. While the benefits of removing physical human presence are clear, challenges associated with remote operation of a robotic system need to be addressed. Removing direct human presence from the robot's operating environment introduces telepresence as an important consideration in achieving the desired objective. The introduction of the haptic modality represents one approach towards improving operator performance subject to reduced telepresence. When operating in an urban environment, teleoperative stair climbing is not an uncommon scenario. This work investigates the operation of an articulated track mobile robot designed for ascending stairs under teleoperative control. In order to assist the teleoperator in improved navigational capabilities, a fuzzy expert system is utilised to provide the teleoperator with intelligent haptic augmentation with the aim of improving task performance.**

I. 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]. Operating environments have included unstructured outdoor terrain, damaged urban terrain, such as construction debris fields, and otherwise challenging man-made terrain such as stairs. The capability of these systems to displace human presence from hazardous environments represents an important progression towards the use of robotic technology to preserve human safety. Whilst physical displacement removes the teleoperator from immediate threat, it is likely to decrease the operator's immersion in the remote operating environment. Any 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 for a system to recreate the sense of touch to the user. Several researchers have addressed different approaches to improving teleoperative capabilities utilising haptic technology to increase task relevant immersion [2,4-9].

Teleoperated mobile robots represent an important class of telerobotic systems, providing the ability to explore a diversity of remote environments. Therefore it is essential that the mobile robot is capable of safely reaching target locations within the environment in order to perform any critical task. When operating in an urban environment, the ability to achieve safe teleoperative navigation of stairs is an important requirement. While the articulated track method of locomotion has a proven mechanical aptitude for the stair climbing task [10,11], stable teleoperative control is more difficult to achieve.

Subjected to reduced telepresence due to 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. This research, however, values the superior ability of the teleoperator to utilise human-level judgement and intuition in total control of the mobile robot. As such, the *absolute human control* approach to teleoperation is presented and provides the basis for the proposed teleoperation scheme.

This work presents a haptic approach for executing a teleoperative stair climbing task using a purpose-built teleoperated mobile robot. The rover is equipped with appropriate application-specific sensory systems for acquiring and transmitting information regarding its operating environment in the form of haptic, or tactile, information. Important experimental data of the rover ascending stairs under teleoperative control was obtained, providing a basis for the development of a fuzzy haptic augmentation solution designed to improve task performance. Haptic augmentation refers to the provision of additional tactile senses that enhance perception or telepresence for the human teleoperator. The haptic contribution to the teleoperation system is two-fold. Firstly, the introduction of the haptic element provides the teleoperator with the capacity to intuitively determine the velocities they are commanding the robot. Secondly, the teleoperator is provided with real-time, task-relevant haptic augmentation indicating suggestive actions concerning the task at hand. The appropriate haptic augmentation is determined by approximate human-like reasoning derived from a fuzzy expert system designed to determine an appropriate suggestive action in order to

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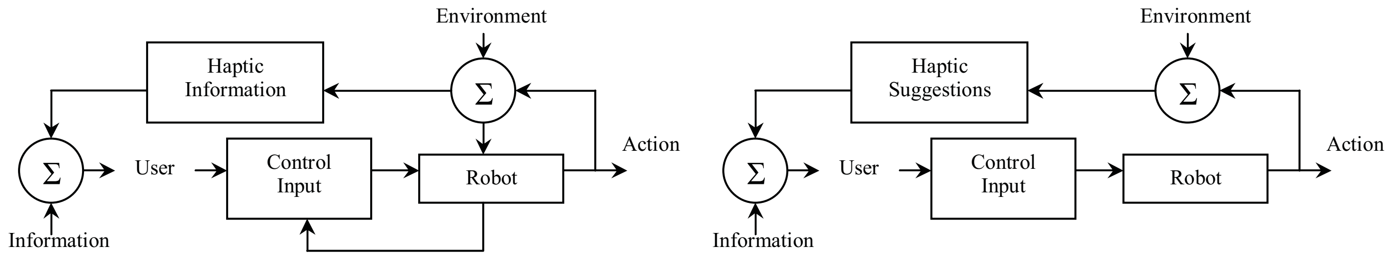

Fig. 1. a) Shared autonomy control strategy, b) Absolute human control

increase performance.

II. ROVER 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. This arrangement, as depicted by Fig. 1.a, can result in a conflict of control whereby the user is commanding one action and the robot elects to perform a different action. This is possible because the robot has the capability to directly control it's actions and therefore, should the robot make an incorrect 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 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.

In the context of a haptically teleoperated robotic system, the absolute control approach provides force-based 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 interaction with the single-point haptic interface. This single point of 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. As previously mentioned, the teleoperator's control of the robot is bilateral, where motion command inputs and display of task-relevant haptic augmentation occur simultaneously on the same point in haptic space.

III. HAPTIC MOTION CONTROL

The haptic capabilities of this system are represented by two distinct contributions to achieving improved teleoperative performance. The first contribution is the methodology facilitating the kinematic mapping between the manipulator-style haptic interface (Fig. 2) and the mobile robot [6]. In order to provide the teleoperator the ability to control the motion of the rover, the haptic cone strategy was developed. Unlike a 2-D approach to controlling the linear and angular velocities of the mobile robot [5], the operator's control of the single point in haptic space is constrained to the conic surface. As the probe of the haptic device is moved across the virtually rendered conic surface, the robot is commanded with

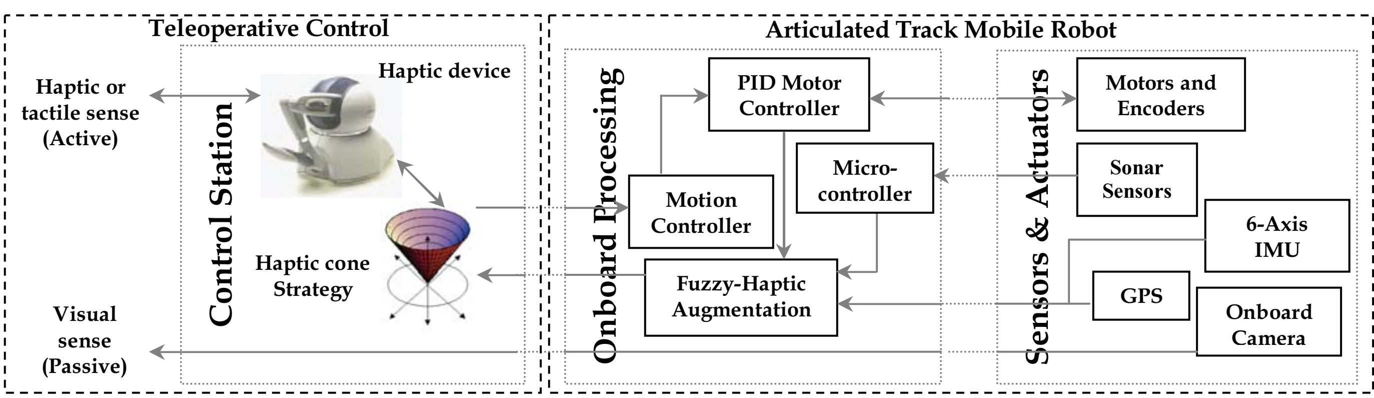

Fig. 2. Robot Control Architecture

corresponding linear (V) and angular (ω) velocities, as depicted by Fig. 3. This provides the operator with the ability to control the motion of the robot. This approach exploits the haptic attributes of the system utilising a vertical (Z) displacement, providing the operator with an intuitive indication of the current velocity being commanded. As such, a haptic interface capable of providing grounded force feedback and an adequate 3-D workspace is required. This approach also provides the teleoperator with the ability to determine the zero velocity position, dictated by (0,0,0), using only their haptic senses. Importantly, by using the haptic cone strategy, the user can infer the current velocity 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 without interfering 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 conic surface as an intuitive indication of the current velocity commanded to the robot.

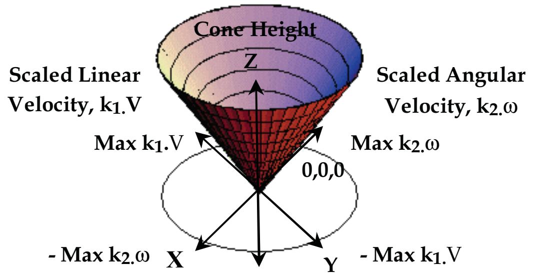

Fig. 3. 3-D Cone kinematic mapping

The second haptic contribution to this system is the task-relevant haptic augmentation provided to the teleoperator. The application-specific haptic augmentation acquires the relevant sensory data and employs a fuzzy expert system to provide the teleoperator with haptic suggestions regarding the current task. This is discussed in a later section.

IV. Task Evaluation

The cone strategy facilitating haptic motion control of an articulated tracked mobile robot has been presented above. In order to introduce the collaborating haptic augmentation, investigation of the stair climbing task was performed. The work by other researchers investigates the utility of a mobile robot for climbing stairs [11]. Their findings, combined with first hand experience in teleoperative stair climbing, led to two important observations. Firstly, it was noticed that due to inconsistent track-terrain interaction, the teleoperated robot was likely to 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 rover increased, an increase in the resulting pitch angle followed.

The data representing the rover's roll and pitch angles were obtained by the rover's sensory systems while performing stair climbing under teleoperative control. This data was obtained from a single representative run at a sampling rate of 5Hz over a nominal duration of 20 seconds and is presented by Fig. 4. These observations establish roll and pitch as the two significant performance metrics utilised for the task-relevant haptic augmentation presented in this work.

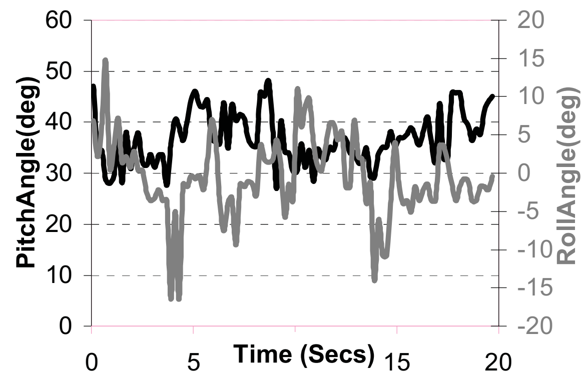

Fig. 4. Experimental data – Pitch and Roll angles of the robot climbing stairs

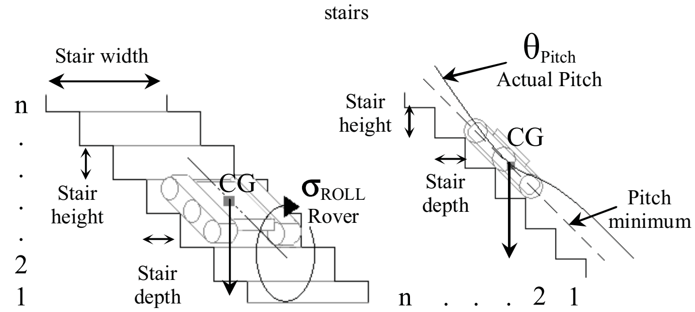

Fig. 5. Task objectives

The robot's roll and pitch angles during the stair climbing task are determined in real-time by the Inertial Measurement Unit (IMU). The robot's sensory systems are presented in Fig. 2. Fig. 5 illustrates the identified objectives for the stair climbing task. For the purpose of developing an appropriate haptic augmentation methodology, the two objectives can be represented by the following objective function

$$\Lambda = \sigma_{Roll} \cdot \theta_{Pitch} \qquad (1)$$

where σ_{Roll} represents the roll angle and θ_{Pitch} represents the pitch angle of the robot.

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 climbing the stairs. In general, the minimum pitch will be governed by the stair height and depth (see Fig. 5); 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.

V. Fuzzy-Haptic Augmentation

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 displaying the appropriate information haptically is required. The previous section discusses two objectives associated with achieving improved task performance. In order to provide the user with haptic suggestions on how to minimise the amount of robot roll, the technique depicted by Fig. 6 is utilised, where τ represents the magnitude of the haptic augmentation force.

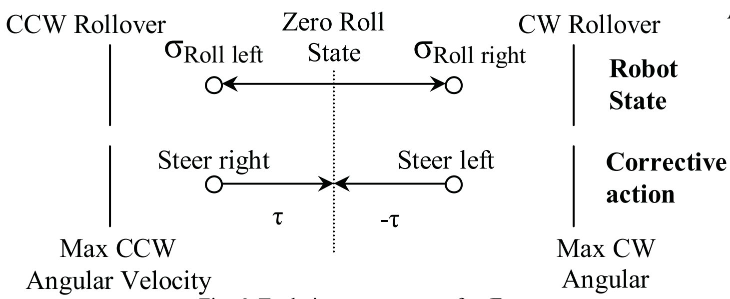

Fig. 6. Technique to augment for σ_{Roll}

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.

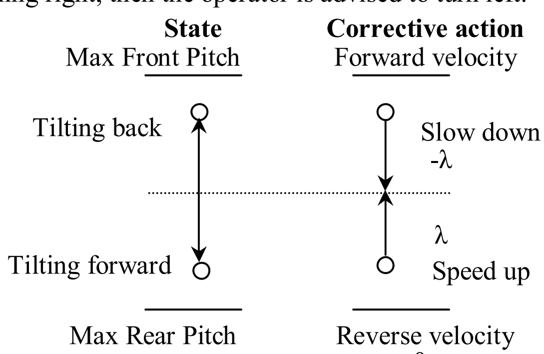

Fig. 7. Technique to augment for θ_{Pitch}

Similarly, in order to utilise haptic suggestions to minimise the robot's pitch angle, the technique depicted by Fig. 7 is utilised, where λ represents the magnitude of the haptic augmentation force.

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. 6 & 7. While these techniques specify how the operator receives the haptic information, determination of the appropriate force values for λ and τ requires additional investigation.

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. 6 and 7.

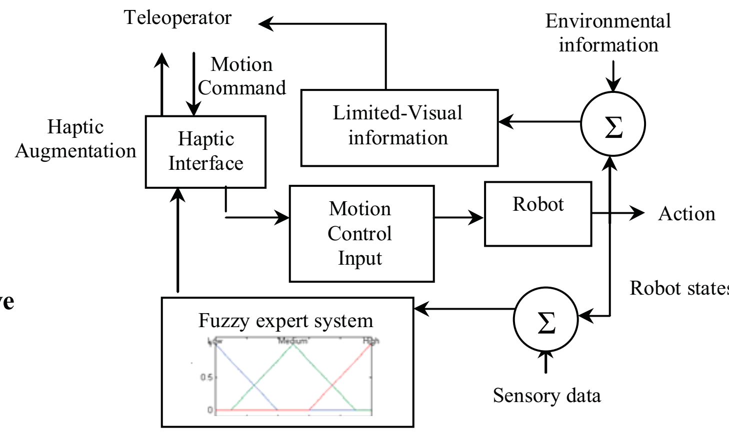

Fig. 8. Fuzzy-Haptic augmentation in the control loop

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. 8.

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 stability of the robot in fuzzy terms is presented below.

Firstly, the diagrams of Fig. 9 depict the four possible scenarios for two rover states, roll and pitch. Recall from Section IV that in the case of stair climbing, roll is related to the yaw heading of the robot, and similarly pitch to the rover's forward velocity. In these diagrams, the force vector (F=mg) resulting from the CG of the robot is considered in order to analyse the stability of the robot in the stair climbing task.

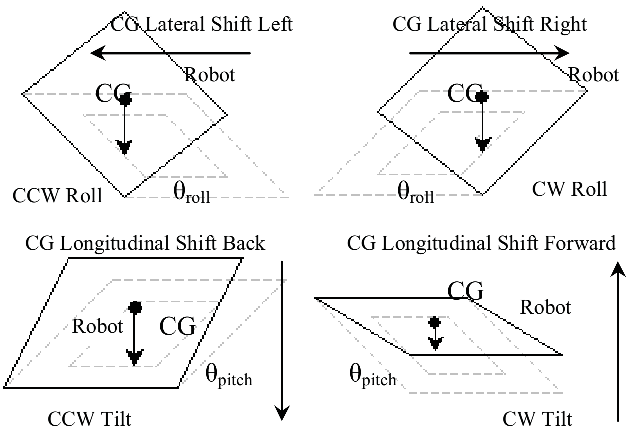

Fig. 9. Lateral and Longitudinal shifts of the CG force vector

The other dynamics of the rover such as acceleration and track-terrain interaction become a product of the human reasoning process and, in the case of a fuzzy system, do not necessarily require direct quantitative analysis. Rather, Fig. 9 qualitatively depicts how the centre of gravity of the robot shifts from its original position as the robot 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. 9. The deviation of the coincidental point of the vector and footprint is considered in both lateral (Fig. 9, upper) and longitudinal (Fig. 9, lower) directions for roll and pitch respectively.

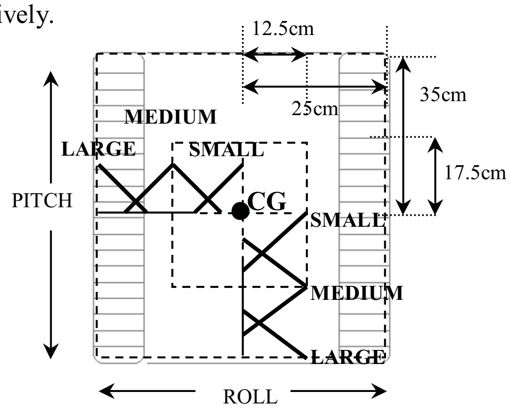

Fig. 10. Fuzzy stability diagram

The dashed lines of the footprint in Fig. 9 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 as shown in Fig. 10. 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. 11.

A simple, three-rule fuzzy rule base is used for each of the two single Input/Output fuzzy expert systems, illustrated by Fig. 11.c.

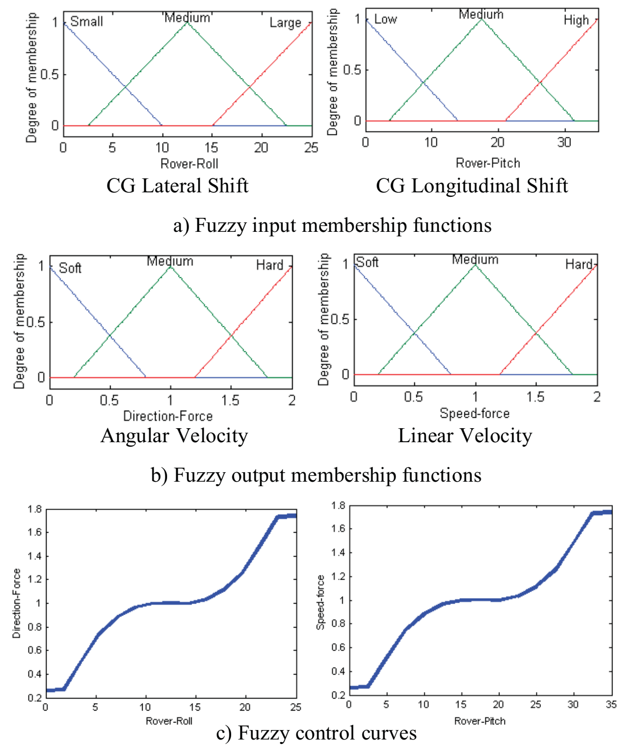

Fig. 11. Fuzzy membership functions and rule characteristic curves

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 modifiable. 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 rover velocity for both objectives, this could be easily achieved.

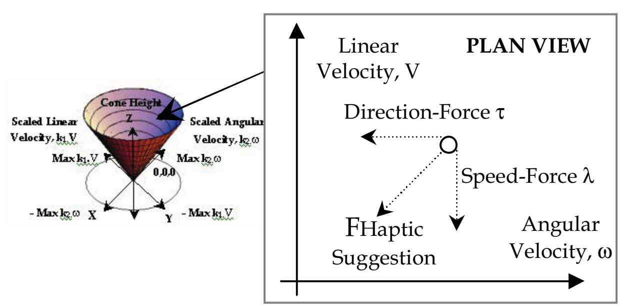

Fig.12. Fuzzy-Haptic augmentation

The two fuzzy outputs are combined into a single vector acting along the conic surface as depicted by Fig. 12. As a result, the augmentation methodology will suggest an appropriate action to the teleoperator while he/she is performing the control process.

VI. SIMULATION RESULTS

Based on the data of the robot climbing stairs gained through real-time experimentation, as shown in Fig. 4, the behaviour of the fuzzy-based augmentation scheme is presented below.

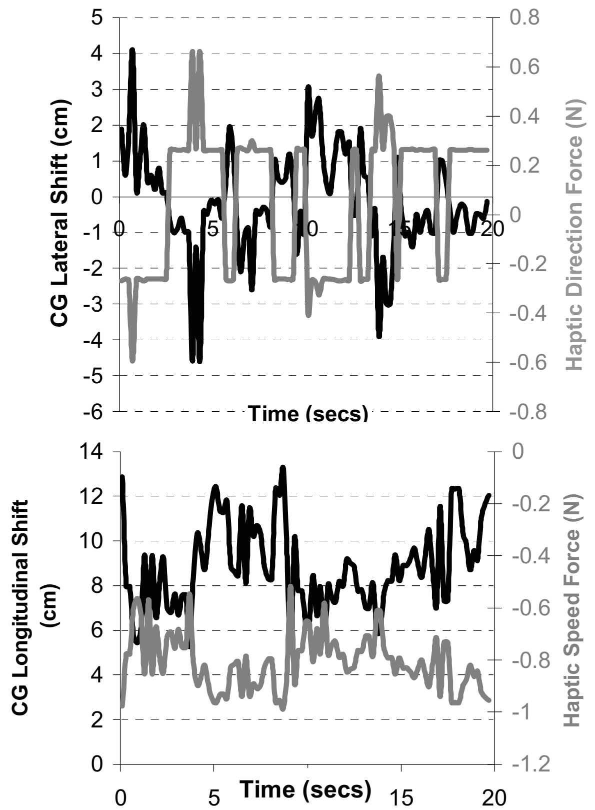

Fig. 13. Determination of the Lateral and Longitudinal Translations of the CG force vector based on data from Fig. 4 as well as the fuzzy haptic augmentation forces

The above results, as shown in Fig. 13, demonstrate the ability of the haptic augmentation strategy in providing the teleoperator with appropriate haptic suggestions based on the objective function, Λ. It can be observed that as the robot's CG shifts longitudinally and laterally, 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.

VII. 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 rover velocity. The fuzzy-haptic augmentation methodology has been presented, as well as simulation results demonstrating the expected performance of the approach.

The next stage in this research is the implementation of the presented approach for evaluation of teleoperator performance in the stair climbing task. With the aim of ease of experimentation and repeatability, a 3-D simulation environment representing the presented system will be developed. Given the subjective nature of the human operator, in order to quantify any changes in performance suitable quantitative analysis methodologies will be utilised.

VIII. ACKNOWLEDGEMENT

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