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Multi-point Multi-hand Haptic Teleoperation of a Mobile Robot

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Abstract— **This paper introduces a novel approach to multi-point multi-hand haptic teleoperation of a mobile robot. The work extends upon existing approaches to provide the teleoperator with the ability to utilise one hand to achieve intuitive haptic control of the mobile robot while utilising the other hand to intuitively control the orientation (and corresponding visual information) of the robot's onboard camera. This work begins with the introduction of the Intuitive Haptic Conical Control Surface which extends upon existing approaches to provide the teleoperator with an intuitive method for issuing robot motion commands whilst simultaneously displaying real-time task-dependent haptic augmentation. A novel multi-point haptic gripper prototype is then introduced providing the basis for the teleoperator to haptically utilise the camera-in-hand metaphor for intuitive control of the visual information provided by the robot's onboard camera. The distinct advantages justifying the individual approaches are discussed and it is suggested that using dual haptic modalities the teleoperator can utilise both approaches simultaneously for intuitive haptic mobile robotic teleoperation. This work represents the first stage of a continuing research project and provides innovative contributions facilitating the presented approach to mobile robotic teleoperation. The realisation of this capability enables future research to fully investigate the human factors and efficacy of the approach.**

I. Introduction

Teleoperated mobile robots offer a valuable solution in many real-world applications including hazardous materials handling [1], Urban Search and Rescue (USAR) [2] and explosive ordnance handling and disposal [3]. In these types of applications the terrain is often harsh, task requirements are dynamic and successful task execution is highly critical. As such, fully autonomous mobile robotic systems are not likely to provide a feasible solution. Teleoperation, however, can facilitate human-level cognitive capabilities offering significant operational advantages. In order to realise these capabilities, the provision of adequate environment and task immersion is required to overcome the teleoperator's physical displacement from the robot's operating environment.

While some researchers focus on providing the operator with enhanced visual information [4, 5], others suggest that teleoperation can be improved through the integration of haptic Human-Robotic-Interaction (HRI) [6-8]. The haptic teleoperation of mobile robots has gained increasing research interest in recent years. The works by [8, 9] provide the teleoperator with a haptic indication of obstacles surrounding the mobile robot. The results presented in [8] quantitatively demonstrate the approach to significantly reduce the likelihood of mobile robot-obstacle collisions during teleoperation. The approach presented in [10] assists in mobile robotic teleoperation by providing the operator with haptic assistance to avoid robot rollover when traversing rough terrain. Such approaches haptically assist the teleoperator in performing a *particular task*, i.e. obstacle avoidance and the prevention of robot rollover respectively. As the basis for formulating a conceptual framework for haptic mobile robotic teleoperation, this work classifies such approaches as *task-dependent haptic augmentation*.

In contrast, the work by [11] proposes a haptic hybrid control strategy aiming to assist the teleoperator in *general* motion and positioning control. The work provides the teleoperator with a haptic method to control the motion and position of the mobile robot. Such an approach can be considered to offer generality across potential tasks, and this work classifies such an approach as *haptic motion control.*

This work argues that the existing approaches to haptic mobile robotic teleoperation primarily focus on either *haptic motion control* or *task-dependent haptic augmentation*. These two components of haptic mobile robotic teleoperation are depicted in the lower section of Figure 1.

The first contribution of this work is the Intuitive Haptic Conical Control Surface (IHCCS) which provides the teleoperator with an intuitive indication of the velocities being commanded to the mobile robot while simultaneously facilitating *task-dependent haptic augmentation,* such as the indication of surrounding obstacles. In this work, it is suggested that the teleoperator can utilise one hand to interact with the IHCCS to control the mobile robot.

The IHCCS simultaneously addresses both of the abovementioned components, ensuring that *task-dependent haptic augmentation* does not diminish the teleoperator's motion control process and similarly, that *intuitive haptic motion control* does not adversely affect the delivery of *task-dependent haptic augmentation*. Our earlier work [12] presents preliminary results demonstrating the ability of the IHCCS to allow the teleoperator to intuitively control the motion of the mobile robot.

In many real-world telerobotic applications it is common for the operator to be provided with a single camera view of the remote environment. This work supports this common practise, however, as the second contribution of this work, introduces an approach enabling the teleoperator to use their other hand to intuitively interact with the robot mounted camera using a new multi-point haptic gripper and the camera-in-hand metaphor [13, 14].

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The camera-in-hand metaphor was introduced in the work by [13, 14]. In their work the Phantom Desktop haptic device provides the operator with a method to control the perspective of the visual information when navigating within a virtual environment. The haptic device's stylus is aligned with the viewing angle of the virtual camera and haptic rendering is proposed to improve the operator's interaction.

In the approach presented by this work, the teleoperator is able to haptically grasp and orientate a virtual camera in order to control the orientation of the real robot-mounted camera. The virtual camera can also be grasped in different configurations depending on the teleoperator's preference. It is suggested that the teleoperator can utilise the proprioceptive haptic information from grasping the virtual camera to infer the real camera's visual perspective of the remote environment. In order to facilitate this approach, the necessary kinematic analysis of the robot-mounted camera and haptic gripper are presented and discussed.

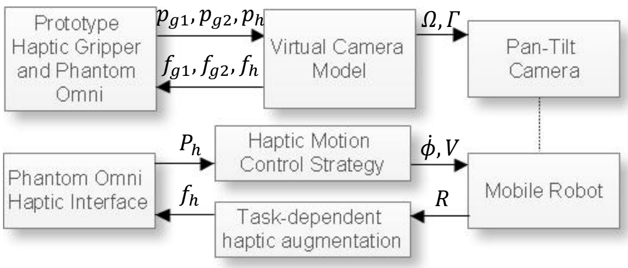

Figure 1 Architecture of the multi-point multi-hand haptic mobile robotic teleoperation.
p is the position of the corresponding Haptic Interaction Point (HIP), f is the rendered haptic force at the corresponding HIP, R is robot state feedback, Ω and Γ are the pan and tilt of the camera and $\dot{\phi}, V$ are the mobile robot's velocities.

This work proposes that the teleoperator can utilise one hand to intuitively control the mobile robot (using the IHCCS) while using their other hand to manipulate the virtual camera to control the visual perspective of the remote environment. As the first stage of a continuing research project, this work focuses on the novel contributions facilitating the proposed approach. The realisation of this capability enables future research to fully investigate the human factors and efficacy of the approach.

II. Intuitive Haptic Conical Control Surface

In the works by [8-10], the *car-driving metaphor* provides the basis for the teleoperator to use a haptic device to command velocities to the mobile robot. The *car-driving metaphor* utilises position-velocity kinematic mapping, where the displacement of the HIP (P_h) across a horizontal plane, h_x-h_y, is mapped to the linear and angular velocities of the mobile robot. As depicted by Figure 2, *task-dependent haptic augmentation* (F_β) acts across the planar surface in order to assist the teleoperator in a particular task. Under normal conditions, that is, in the absence of haptic augmentation ($F_\beta = 0$), the teleoperator can move the haptic device freely across the haptically rendered 2-D plane commanding motions to the mobile robot.

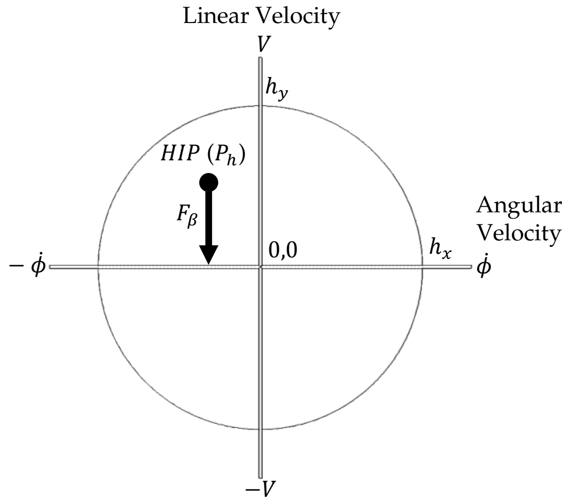

Figure 2 2-D position-to-velocity mapping of the car-driving metaphor.
F_β indicates a haptic suggestion provided to the teleoperator as to an appropriate action, $+V$ is forward robot motion and $+\dot{\phi}$ is CW (from above) turning robot motion. Note: The shown position of the *HIP* corresponds to the robot moving forward while turning left.

Using the *car-driving metaphor*, *task-dependent haptic augmentation* is achieved by applying haptic forces across the 2-D planar surface. Denoted by F_β, these haptic forces provide the relevant haptic suggestions to the teleoperator. In the example depicted by Figure 2, F_β suggests for the teleoperator to reduce the commanded forward velocity. While it is apparent that the *car-driving metaphor* supports *task-dependent haptic augmentation*, there is no method for the teleoperator to *haptically* infer the velocities they are currently commanding to the mobile robot.

Using this approach, even if the teleoperator was provided with a haptic aid indicating the current displacement of the HIP from the zero velocity position, such as a spring-type system, this would clearly interfere with the provided *task-dependent haptic augmentation*. In such an arrangement, it would be unclear to the teleoperator as to whether the *task-dependent haptic augmentation* or spring-type haptic aid was suggesting to move the HIP in a certain direction.

Using this 2-D approach, in order for the teleoperator to perform a zero motion robot command, i.e. $h_x = h_y = 0$, the teleoperator relies on visual feedback of the mobile robot's motion. Haptic interaction is introduced to utilise the teleoperator's haptic sensory modality, however the teleoperator is limited to their visual sense in order to provide such motion commands.

The IHCCS overcomes this limitation and provides intuitive *haptic motion control* without diminishing the necessary *task-dependent haptic augmentation*. Unlike the 2-D *car-driving metaphor*, the IHCCS constrains the teleoperator's movement of the *HIP* to a 3-D parametric surface as depicted by Figure 3.

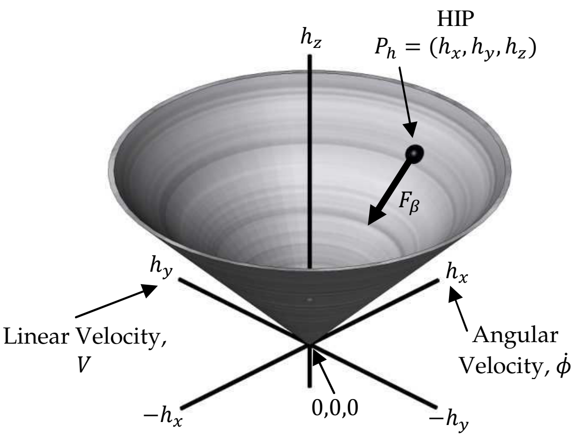

Figure 3 3D Intuitive Haptic Conical Control Surface (IHCCS)

The geometry of the IHCCS provides the teleoperator with a deterministic method to position the HIP at $P_h = (0,0,0)$ in order to stop the robot's motion. It is also suggested that the IHCCS provides an intuitive haptic indication of the current commanded velocities. As with the 2-D approach, F_β provides the teleoperator with a haptic suggestion as to an appropriate action.

The IHCCS is defined by the following parametric expression

$$h_x{}^2 + h_y{}^2 = (k_3 h_z)^2 \quad (1)$$

where the h_x and h_y parameters are mapped to linear, V, and angular, $\dot{\phi}$, robot velocities, k_3 is a constant related to the slope of the cone, and the HIP is constrained to the parametric surface.

The IHCCS extends upon the *car-driving metaphor* by providing a h_z displacement for the commanded mobile robot velocities. Any haptic interface capable of providing grounded force feedback and an adequate 3-D workspace can be utilised. This approach provides the teleoperator with a deterministic method to locate the HIP to $P_h = (0,0,0)$ (corresponding to zero robot motion) independent of visual information. It is also suggested that an experienced user would be able to use the current vertical displacement for any point on the conical surface as an indication of the current velocities being commanded to the robot. Using the IHCCS, the operator can infer the current velocities being commanded to the robot, while still having unimpeded motion across the conical surface. This is an essential requirement, as it facilitates the display of *task-dependent haptic augmentation*. The haptic augmentation acts across the IHCCS so as not to impede in the motion control process. The actual *task-dependent haptic augmentation* may constitute approaches such as those introduced in [8-10].

Under normal conditions, that is, in the absence of *task-dependent haptic augmentation*, the teleoperator moves the HIP freely across the IHCCS. When *task-dependent haptic augmentation* is required, F_β acts across the conical surface as depicted in Figure 3. The IHCCS allows the teleoperator to control the motion of the mobile robot with an intuitive indication of the current commanded velocities, whilst supporting the ability to provide *task-dependent haptic augmentation.*

The mapping of the current position of the HIP to mobile robot velocities is expressed by the following

$$V = k_1 h_y \ m/sec \quad (2)$$

$$\dot{\phi} = k_2 h_x \ rads/sec \quad (3)$$

where $\dot{\phi}$ and V are the commanded angular and linear velocities of the robot respectively, h_x and h_y are the displacements from $P_h = (0,0,0)$, and $k_1$and k_2 are scaling coefficients.

The geometry of the IHCCS provides the teleoperator with an intuitive indication of the current commanded velocities, while permitting *task-dependent haptic augmentation* to act across the conical surface. The IHCCS is defined by expression (1), where k_3 specifies the relative slope of the surface. As depicted by Figure 4, different values of k_3 will influence the ability of the IHCCS to provide an indication of the current commanded velocity.

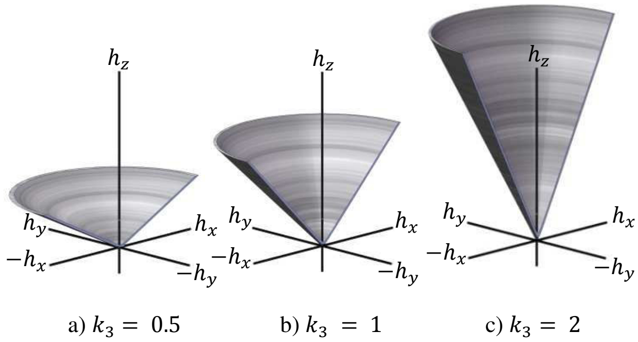

Figure 4 IHCCS for various values of k_3

Figure 4 illustrates the IHCCS in three scenarios; $k_3 = 0.5$, 1 and 2. If k_3 is too small (e.g. Figure 4 a), then there is little difference to a 2-D control surface and it may prove difficult for the teleoperator to locate the HIP to the origin of the IHCCS. In contrast, if k_3 is too large (e.g. Figure 4 c), then it may be difficult for the teleoperator to infer the commanded robot velocities.

In determination of the appropriate slope of the IHCCS it is pertinent to also consider the physical limitations of the implemented haptic device. The Phantom Omni offers a relatively small usable haptic workspace of ≈ 160 W x 120 H x 70 D mm, and, as such, it is desirable to provide the teleoperator with the largest possible h_x, h_y workspace. As k_3 increases however, the maximum usable h_x, h_y workspace decreases accordingly. The relationship of the usable h_x, h_y workspace to k_3 was considered and k_3 specified as $k_3 = 0.7$ corresponding to the largest possible h_x, h_y workspace.

Other important considerations of the IHCCS are not discussed here, however can be found in [15]. The IHCCS is introduced as the first contribution of this work, allowing the teleoperator to haptically control the motion of the mobile robot using one hand. The second contribution of this work is our approach to the camera-in-hand metaphor using a new multi-point haptic gripper.

III. GRASPING THE CAMERA-IN-HAND METAPHOR

The second contribution of this work provides the teleoperator with intuitive control of the robot mounted camera using a novel haptic gripper and the camera-in-hand metaphor. The camera-in-hand metaphor was introduced in the work by [13, 14]. In their work the Phantom Desktop haptic device provides the operator with a method to control the perspective of the visual information provided when navigating within a virtual environment.

The approach presented herein allows the teleoperator to haptically *grasp* a virtual camera using a multi-point haptic gripper. The virtual camera can be grasped in different configurations depending on the teleoperator's preference. This approach allows the teleoperator to orientate the virtual camera using a similar process to the manual orientation of a pan-tilt camera. The corresponding orientation of the virtual camera is kinematically mapped to the real-camera, allowing the teleoperator to control the perspective of the provided visual information.

As the basis to facilitate this approach, the kinematic analysis of the robot mounted pan-tilt camera and haptic gripper are presented in the following sections. The functionality of the approach is then discussed in Section C.

A. *MOBILE ROBOT PAN-TILT CAMERA*

In order to achieve mobile robotic teleoperation the provision of adequate environment and task immersion is required to overcome the teleoperator's physical displacement from the robot's operating environment. The above section discusses the IHCCS, introduced to improve the teleoperator's control of the mobile robot using haptic interaction. Despite the benefits of the approach, it is apparent that the teleoperator still requires visual information of the remote operating environment.

In the work by [16], stereoscopic cameras provide the teleoperator with 3-D views of the remote environment. While such a capability is beneficial to teleoperation, the visual information provided to the operator is limited by the camera's finite field-of-view (FOV).

The work by [17] overcomes this limitation by proposing an omni-directional vision system providing the teleoperator with a super-wide FOV. The approach, however, requires substantial image processing. In addition, even when the teleoperator can be provided with complete visual information from the robot's operating environment, operator loading can prove a significant limitation.

Given the above considerations, it proves logical that many real-world teleoperated robots utilise single camera views of the remote environment. The approach taken by this work is to maintain this common practise but to provide the teleoperator with the ability to achieve real-time intuitive haptic control of the robot mounted camera. This ability is facilitated through the camera-in-hand metaphor and our prototype multi-point haptic gripper.

The appropriate orientation of the robot's pan-tilt camera is essential to successful teleoperation. This is evident when considering the situation where the camera is facing directly skywards. In such a scenario, it is highly likely that the teleoperator will be unable to adequately perceive the terrain in front of the robot. The presented approach addresses this issue by allowing the teleoperator to control (and have a haptic indication of) the perspective of the pan-tilt camera.

The robot-mounted pan-tilt camera can be considered as a two degree-of-freedom manipulator with its base attached to the mobile robot. The camera, $\{C\}$, and robot, $\{R\}$, reference frames are assigned as shown in Figure 5 and are specified as right-hand coordinate systems. As the camera undergoes pan and tilt motions, the perspective of the visual information provided to the teleoperator can be expressed by the location and orientation of the camera's reference frame, $\{C\}$, with respect to the robot fixed reference frame, $\{R\}$.

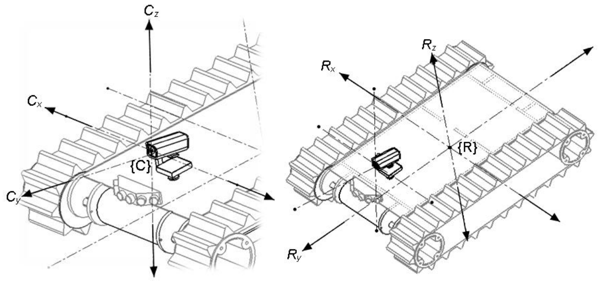

Figure 5 The camera and mobile robot reference frames $\{R\}$ is the robot fixed frame and $\{C\}$ is the camera fixed frame where the C_Y axis is aligned with centre of the camera's FOV.

Denoting Ω and Γ as pan and tilt respectively, the Denavit-Hartenberg (D-H) convention [18, 19] is utilised to provide the forward kinematic model of the camera's current *pose* (position and location) relative to the mobile robot.

Table 1 D-H (modified) parameters [19] for the camera's current pose

Joint i	A_{i-1} (mm)	α_{i-1} (rad)	D_i (mm)	θ_i(rad)
1	219	0	43.96	$\pi/2$
2	0	$\pi/2$	60	Ω
3	35.45	$-\pi/2$	0	Γ
4	0	0	0	$-\pi/2$

Given the above D-H parameters and the current states of Ω and Γ, the camera's current pose is given by homogeneous transformations resulting in

$$ {}^R_C T = \begin{bmatrix} nx & sx & ax & px \\ ny & sy & ay & py \\ nz & sz & az & pz \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where

$$nx = C\Omega \quad (5)$$
$$ny = S\Omega \quad (6)$$
$$nz = 0 \quad (7)$$
$$sx = -S\Omega C\Gamma \quad (8)$$
$$sy = C\Omega C\Gamma \quad (9)$$
$$sz = S\Gamma \quad (10)$$
$$ax = S\Omega S\Gamma \quad (11)$$
$$ay = -C\Omega S\Gamma \quad (12)$$
$$az = C\Gamma \quad (13)$$
$$px = 35.45 S\Omega C\Gamma \quad (14)$$
$$py = 35.45 C\Omega C\Gamma + 219 \quad (15)$$

$$pz = 103.96 + 35.45S\Gamma \tag{16}$$

and C represents $cos()$, S represents $sin()$, n,s,a represent the orientation of the C_X, C_Y and C_Z directions respectively (with respect to $\{R\}$) and $p_{x,y,z}$ is the relative position of $\{C\}$, with respect to $\{R\}$.

Figure 6 compares *detailed* and *robot camera* views of the mobile robot in the Webots simulation environment.

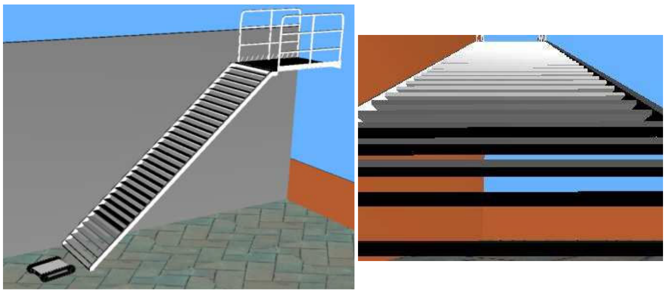

Figure 6 Views in a simulated robot operating environment. Left: Detailed visual information, Right: Limited visual information where $\Gamma = \Omega = 0$.

B. *MULTI-POINT HAPTIC GRIPPER*

As the basis for the teleoperator to haptically grasp the virtual camera a new multi-point haptic gripper is introduced. The prototype provides two additional Haptic Interaction Points to the Phantom Omni haptic device, facilitating the ability to haptically grasp virtual objects. Detailed information of the gripper design extends beyond the scope of this paper, however, can be found in [20]. The prototype device is depicted by Figure 7.

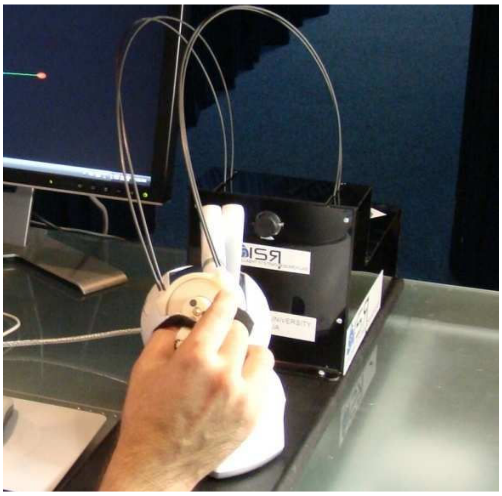

Figure 7 Haptic gripper prototype

The haptic gripper's end-effector and multiple Haptic Interaction Points are depicted in Figure 8.

In order to facilitate the haptic rendering of the virtual camera using the multi-point haptic gripper, the kinematics of the device need to be determined. Figure 9 presents the D-H (standard) kinematic notation for the Phantom Omni and coupled multi-point haptic gripper.

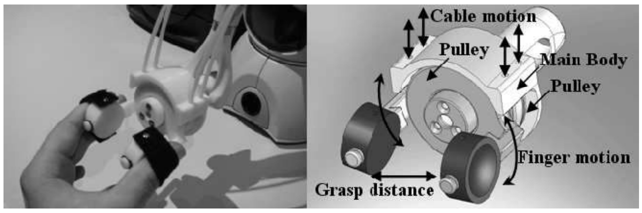

Figure 8 Phantom Omni and coupled haptic gripper

The D-H kinematic analysis for one of the gripper's two HIP's is presented below. Note: the modification of the presented model for the gripper's other HIP is straightforward.

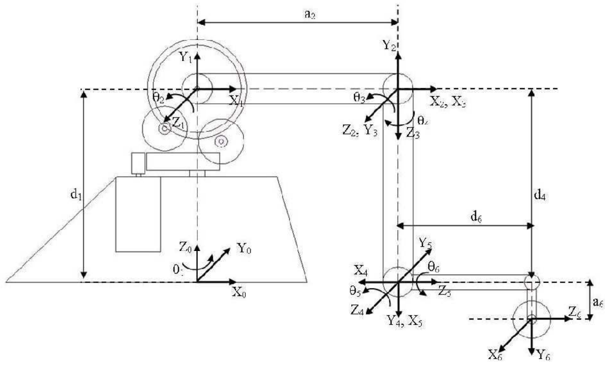

Figure 9 Forward kinematic analysis for the Phantom Omni and coupled haptic gripper

Table 2 Denavit-Hartenberg (standard) kinematic parameters for the haptic gripper coupled to the Phantom Omni

Joint i	θ_i	α_i	a_i(mm)	d_i(mm)
1	θ_1	$\pi/2$	0	133.35
2	θ_2	0	133.35	0
3	θ_3	$\pi/2$	0	0
4	θ_4	$\pi/2$	0	133.35
5	θ_5	$-\pi/2$	0	0
6	θ_6	0	25	88.5

Given the above D-H parameters and the current states of joints *1 to 6*, the position and orientation of one of gripper's HIP's ($g1$) is given by homogeneous transformations resulting in

$$ {}_6^1T = \begin{bmatrix} nx & sx & ax & px \\ ny & sy & ay & py \\ nz & sz & az & pz \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{17}$$

where

$$\begin{aligned} p_{g1x} &= a_6c_6c_5(c_4c_1c_{23} + s_1s_4) + (a_6c_6s_5c_1s_{23}) \\ &\quad -a_6s_6(s_4c_1c_{23} + s_1c_4) - d_6s_5(c_4c_1c_{23} - s_1s_4) \\ &\quad +d_6c_5c_1s_{23} + d_4c_1s_{23} + c_1a_2c_2 \end{aligned} \tag{18}$$

$$\begin{aligned} p_{g1y} &= a_6c_6c_5(c_4s_1c_{23} - c_1s_4) + a_6c_6s_5s_1s_{23} \\ &\quad +a_6s_6(s_4s_1c_{23} - c_1c_4) + d_6s_5(c_4s_1c_{23} + c_1s_4) \\ &\quad +d_6c_5s_1s_{23} + d_4s_1s_{23} + s_1a_2c_2 \end{aligned} \tag{19}$$

$$\begin{aligned} p_{g1z} &= a_6c_6c_4c_5s_{23} - a_6c_6s_5c_{23} + s_4a_6s_6s_{23} \\ &\quad +d_6c_4s_5s_{23} + d_6c_5c_{23} - d_4c_{23} + a_2s_2 + d_1 \end{aligned} \tag{20}$$

$$n_{g1x} = c_6c_5c_4c_1c_{23} + c_6c_5s_1s_4 + c_6s_5c_1s_{23} + s_6s_4c_1c_{23} + s_6s_1c_4 \quad (21)$$

$$n_{g1y} = c_6c_5c_4s_1c_{23} - c_6c_5c_1s_4 + c_6s_5s_1s_{23} + s_6s_4s_1c_{23} - s_6s_1c_4 \quad (22)$$

$$n_{g1z} = c_6c_4c_5s_{23} - c_6s_5c_{23} + s_6s_4s_{23} \quad (23)$$

$$s_{g1x} = s_6c_5c_4c_1c_{23} - s_6c_5s_1s_4 + s_6s_5c_1s_{23} + c_6s_4c_1c_{23} + c_6s_1c_4 \quad (24)$$

$$s_{g1y} = s_6c_5c_4s_1c_{23} - s_6c_5c_1s_4 + s_6s_5s_1s_{23} + c_6s_4s_1c_{23} - c_6c_1c_4 \quad (25)$$

$$s_{g1z} = s_6c_4c_5c_{23} + s_6s_5c_{23} + c_6s_4s_{23} \quad (26)$$

$$a_{g1x} = s_5c_4c_1c_{23} - s_5s_1s_4 + c_5c_1s_{23} \quad (27)$$

$$a_{g1y} = s_5c_4s_1c_{23} + s_5c_1s_4 + c_5s_1s_{23} \quad (28)$$

$$a_{g1z} = s_5c_4s_{23} - c_5c_{23} \quad (29)$$

and $c_i = cos(\theta_i)$, $s_i = sin(\theta_i)$ and S_{ij} and C_{ij} refer to $sin(\theta_i + \theta_j)$ and $cos(\theta_i + \theta_j)$ respectively, $p_{g1x}, p_{g1y}, p_{g1z}$ correspond to the position of the HIP and n,s,a represent the orientation of the HIP's reference frame with respect to the allocated Phantom Omni reference frame.

This section presented the required kinematic analysis facilitating the control of the pan-tilt camera and haptic rendering of the virtual camera. The following section discusses the operator's ability to utilise the camera-in-hand metaphor to control (and haptically infer) the orientation of the robot mounted camera.

C. GRASPING THE CAMERA-IN-HAND

Given the necessary analysis of the robot mounted pan-tilt camera and the haptic gripper, the virtual environment facilitating the haptic grasping and orientation of the virtual camera (and control of the real camera) was developed.

In the developed environment the teleoperator is able to visualise the virtual camera (Figures 10 and 11). The virtual camera is modelled as a rigid object and can be haptically grasped using different configurations depending on teleoperator preference.

The teleoperator's manipulation of the virtual camera is constrained to the two-DOF motion of the physical camera's pan-tilt mechanism (expressions 4-16). The orientation of the virtual camera is then kinematically mapped to the physical camera using the formulations presented in the previous section. The haptic rendering was developed in Visual C++.

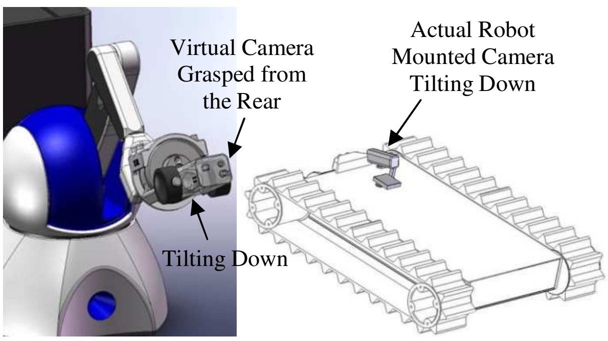

Figure 10 Haptically grasping the virtual camera from the rear

Figure 10 demonstrates the ability of the teleoperator to haptically grasp the virtual camera from the rear and to tilt the robot mounted camera slightly downward.

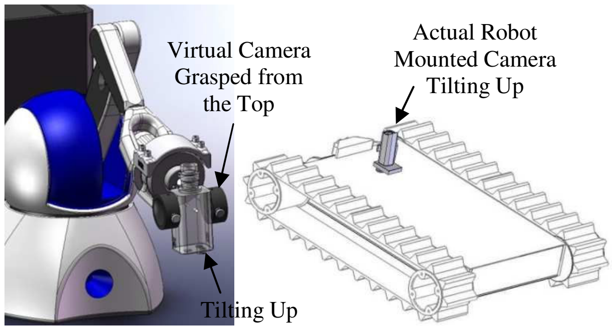

Figure 11 Haptically grasping the virtual camera from the top

Figure 11 demonstrates the teleoperator's ability to grasp the virtual camera from the top and to tilt the robot mounted camera skywards.

IV. CONCLUSION

This work proposes a new approach where the teleoperator can utilise one hand to haptically control the mobile robot (using the IHCCS) while using their other hand to haptically manipulate a virtual camera to control the visual perspective of the robot's operating environment. As the first stage of a continuing research project, this work focuses on the novel contributions facilitating the proposed approach. The realisation of this capability enables future research to fully investigate the human factors and efficacy of the approach.

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