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Trigger-Assisted Ambidextrous Control Framework for Teleoperation of Two Legged Manipulators

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Abstract— **This paper presents a motion-capture based control framework for the purpose of effectively teleoperating two legged manipulators without significant delays caused by the switching of controllers. The control framework generates high-level trajectories in 6 degrees-of-freedom and uses finger gesture detection to act as triggers in selecting which robot to control as well as toggling various aspects of control such as yaw rotation of the quadruped platform. The functionality and ease of use of the control framework is demonstrated through a real life experiment where the operator controls two quadrupedal manipulator robots to open a spray can. The experiment was successfully accomplished by the proposed teleoperation framework.**

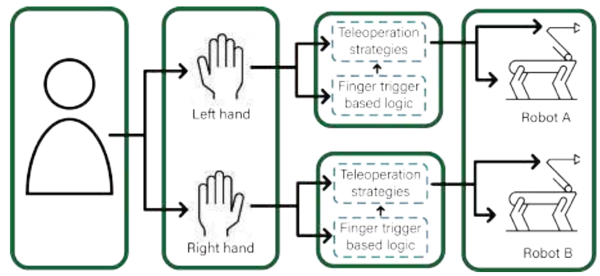

Fig. 1. Overview of the proposed teleoperation framework.

I. Introduction

Teleoperation has become an important part of robotic control, as an increasing number of robotic systems are being used for operations in locations that would be considered hazardous or remote. In the past, robots were merely used as platforms for collecting data in these environments, but more recently, an ever-increasing number of robotic systems are beginning to implement additional manipulation devices to allow them to also undertake physical manipulation tasks in the field [1]. However, if the robot becomes more complex, the teleoperation system must also improve and provide the teleoperator the capabilities to control the robot effectively. With the increasing number of hybrid robots, namely robots consisting of multiple systems that would typically require their own controller [2], current teleoperation control systems lack the capability to control both aspects of these robots simultaneously, allowing for a wider range of motions and intuitive and natural control.

Traditionally, joystick control has been the most common method of high level command generation for robots, however as presented in [3], it is seen that via this method, only one system could be controlled at once. Joysticks have been used to successfully teleoperate hybrid robotic systems, such as in that presented by [4] where an aerial manipulator was teleoperated through the use of a whole body controller and a joystick. However, the teleoperation is limited by the joystick having only 2 degrees of freedom (DoF) and consequently the trajectory generated by the joystick is only within a 2-dimensional plane.

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Through implementing a generic whole-body controller (WBC) [5] in these systems, it would enable the teleoperator to utilise the full redundancy of the robot while only providing one input reference trajectory. This is achieved in [6] through the development of a WBC-teleoperation framework, however, this framework neither realises locomotion tasks nor offers the ability to control multiple robots. Furthermore, this also requires a teleoperation controller to generate feasible input trajectories. Alternative methods of teleoperation have thus been developed, such as the use of haptic controllers alongside whole body control [7] as well as semi-autonomous systems [8]. Many of these haptic controllers employ bilateral control through the use of a compliant master device, but the range of movement is limited to the hardware workspace, which may interfere in some teleoperative tasks [9]. Target-object-orientated methods such as that presented by [10] illustrate the use of physical devices to assist in teleoperation. However, when compared to a wearable motion capture suit, the hardware used in this study does not allow for manipulation of compliant objects nor does it enable accurate manipulation of objects of different geometry than a cuboid. Others utilised motion as a method of high level command generation for hybrid manipulator systems, for example, [11] presents a method using body tilt to generate acceleration and velocity commands for a bipedal wheeled robot. The manipulator in this case is controlled via an arm mounted motion capture linkage [12]. However, the hardware limits the freedom of the teleoperator in this case.

In contrast, motion capture suits are being used at an increasing rate due to being a light-weight and cost-effective method to extract human joint data. In addition, many motion capture suits are wireless, meaning that the teleoperator is not constrained to the hardware space. Body tilt is also used by [13], in a scenario where a teleoperator uses a motion capture suit to detect the pitch of the human, this method however lacks the force feedback implemented by [14]. This method employs a mode switching trigger used to determine whether commands are sent to the base or the manipulator [13]. This issue of being unable to control both base and manipulator simultaneously is answered through the use of a whole body controller to couple the two systems, however this method lacks control in specific DoFs [14]. As many motion capture applications in robot teleoperation focus on using the operator's upper-body motion, there are limited studies that utilise the human operator's lower-body motion. Although one of which is [15] which is also an example of precise mapping from the user's movement to the robot's pose.

To improve the dynamic performance of humanoid robots, Ishiguro et al. introduced a real-time dynamic control method to both the upper and lower body of a humanoid robot [16]. The methods could implement dynamic whole-body movements, including kicking and hitting a ball. However, it still has difficulties in applying to complex movements, for example, running and rough terrain locomotion. [17] presented a method using whole body control as well as joint mapping to control a humanoid robot. This method would however only work with robots that are kinematically similar to a human, and could not be applied to any robot that is not a biped. Motion capture suits have been paired with joystick controllers to achieve both low level joint mapping and high level motion commands, however the joint mapping is limited to a robot of humanoid structure [18]. Furthermore, although the joystick suits this method as using motion tracking to generate high level commands would interfere with the joint mapping [18]. The combination of joystick and motion capture suit works particularly well when the joystick is used to control a 2-DoF system, such as a quadruped, and the motion capture suit is used for higher-DoF systems such as robotic arms [19]. Motion capture suits have also been used in motion imitation control, where a wheeled manipulator would mimic the teleoperator's movements [20]. However, this work only utilises the use of one of the teleoperator's arms and only works for robots who have similar kinematic structure to a human, limiting the potential for a highly functional control framework.

In this paper, we propose a teleoperation control framework, based upon our previous work [21], that uses a wireless inertia-based motion capture suit to generate high level commands for simultaneous control of two legged manipulators. With the use of finger-detection, gesture controls are implemented to allow the teleoperator to enable and disable certain axis of movement for ease of control and switch between control of the robot's manipulator and quadrupedal base seamlessly.

The paper is structured as follows: Section 2 contains an overview of the control system as well as its formulation. Section 3 covers the experiment design, Section 4 analyses the results obtained from the experiment, and Section 5 discusses the conclusions and future work.

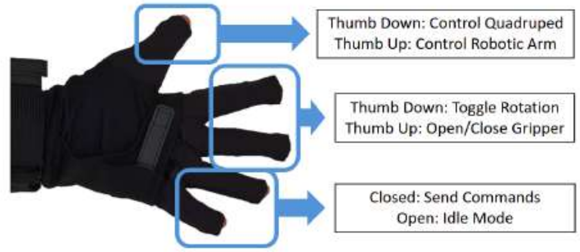

Fig. 2. Triggers and their functions assigned to each group of fingers, the triggers on the respective fingers are the same for both hands.

II. Control Framework Overview

In the control framework, coordinate frames are obtained from the inertia-based motion capture suit, Perception Neuron. In our previous work, we showcased a framework using the entirety of the motion capture suit, however, due to this framework only making use of the upper body, the lower half of the motion capture suit is not used and therefore not necessary for the teleoperator to wear [21]. This decision comes from multiple factors, from the ability to prepare to teleoperate faster as there is less preparation and to focus more on where humans are more naturally dexterous, their hands and arms rather than their legs.

Thus, in the control framework, a single hand is used to control several parts of a single robot system, in this example, the framework is used to control a quadruped platform and a robotic arm. As this is implemented on both hands, the total number of systems that are able to be controlled increases as well as enabling the possibility of controlling two separate systems simultaneously. In order to select which system to control, finger triggers are utilised allowing for the teleoperator to close and open specific fingers to send commands to a selected system.

Using the fingers as triggers is made possible with the motion capture suit being able to output co-ordinate frames of each of the fingers. This allows for the linking of each finger to a function, however, to make it easier for the teleoperator, a trigger is activated when either both the index and middle finger or the ring and pinky finger are closed. Trajectories are generated by the framework by first setting a reference point in the world frame by closing a hand. Cartesian positions and Euler angles of each hand are calculated, of which are then translated into high level commands for the end effector of the robot arm or base of the platform.

A. Finger-based Trigger System

Firstly, when both hands are open, no commands are sent to the robots and the teleoperator can move freely without controlling either robot. To begin controlling the robot, the teleoperator must close either hand, the trigger used to detect this is the closure of the ring and pinky finger. As the goal is to control multiple robots with a distinct platform and manipulator, each hand controls a different robot, in this scenario the left hand controls the A1 system and the right controls the Aliengo system.

The thumb is used to toggle control between either the quadruped base or the robotic arm. Another trigger, the index and middle finger, is used to determine whether the teleoperator controls linear movement in the Cartesian x or y axis or rotational movement in the yaw axis for the quadruped platform, if used when the thumb trigger is not active. If the thumb trigger is active, this trigger then determines the closure state of the end-effector gripper. These triggers and their respective functions are outlined in Fig.2.

B. Teleoperation Algorithm

Whilst the Cartesian position of the hand is taken with respect to the world frame, the orientation cannot as it would also incorporate aspects of the human body tilt into the output. Therefore, to avoid this, the relative orientation of the hand is instead taken with respect to the fore arm link origin, located at the elbow.

To generate trajectories, an origin point in the world frame is created when the hand is closed and the relative position of the hand in the world frame to this origin point is used to determine the direction and magnitude of motion of the respective device. This is formulated as:

$$\boldsymbol{x}_{sd}^{t} = \boldsymbol{x}_{sd}^{0} + \boldsymbol{\mu}(\boldsymbol{x}_{m}^{t} - \boldsymbol{x}_{m}^{0}), \quad (1)$$

where $\boldsymbol{x}$ refers to the vector $\boldsymbol{x} = [x, y, z, \theta_{\text{roll}}, \theta_{\text{pitch}}, \theta_{\text{yaw}}]$ of which represents displacements in the Cartesian and rotations in the Euler axes respectively. Subscripts "m" refers to the master device, "s" refers to the slave device, and "d" to the desired value. Superscript "0" refers to the initial time when the hand is closed. μ are the gains used to scale motion between the operator and robot.

Due to the motion capture suit not being constrained to a set location, the human teleoperator is free to rotate and move around their environment. However, if the relative position of the hand to the world frame is not corrected for the yaw of the teleoperator in the world frame, then the output trajectories are orientated towards the location that the motion capture suit was first initialised. Therefore, the yaw from the central back link is used to determine the direction the operator is facing and offset the yaw generated from turning. This is formulated as

$$\boldsymbol{h}_{\text{local}} = \boldsymbol{R}_{\text{yaw}}^{-1} \cdot \boldsymbol{h}, \quad (2)$$

where $\boldsymbol{h} \in \mathbb{R}^{3\times1}$ represents the position vector of the hand link with respect to the world frame. $\boldsymbol{h}_{\text{local}}$ refers to the position vector where the yaw of the operator's body has been offset. $\boldsymbol{R}_{\text{yaw}} \in \mathbb{R}^{3\times3}$ is a rotation matrix constructed using the yaw orientation of the central spine line.

Multiple triggers are used in the framework through the action of opening and closing the thumb and fingers. To detect finger closure, the framework checks the distances between the end of each finger to the link in the centre of the hand. Once each distance is below a tuned threshold, the finger is considered closed. This is formulated as

$$\boldsymbol{r}_{\text{finger}} \geq \boldsymbol{s}_{\text{finger threshold}}, \quad (3)$$

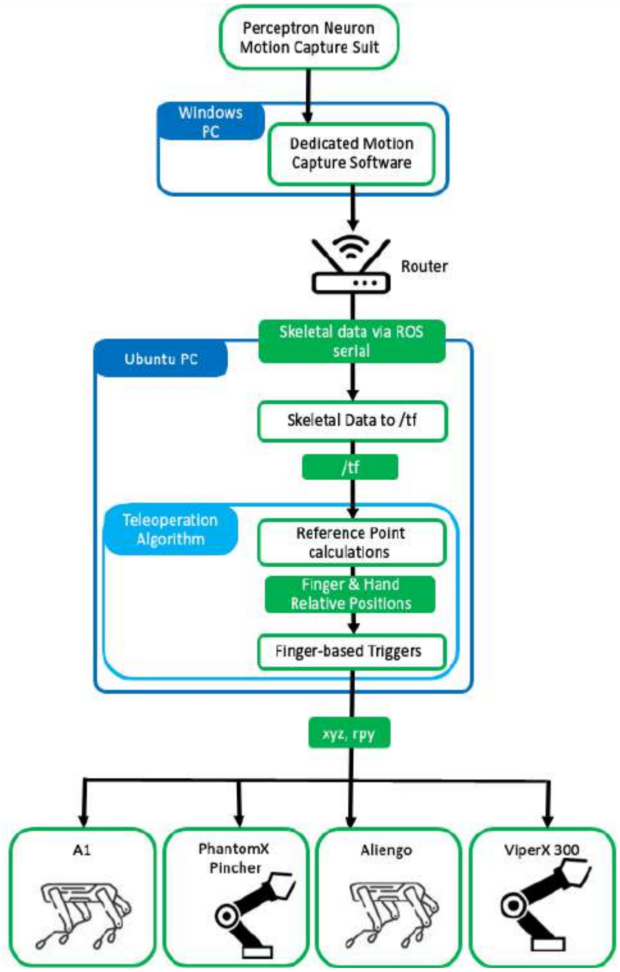

Fig. 3. A complete system diagram of the teleoperation framework, illustrating the flow of information from the motion capture suit to the robots.

where $\boldsymbol{r} \in \mathbb{R}^{4\times1}$ represents the distance of each finger to the central hand link and $\boldsymbol{s} \in \mathbb{R}^{4\times1}$ represents the threshold distance values for each finger set to detect the closure of each finger. Subscripts "f" and "h" refer to the finger end link and hand link respectively. Where the finger triggers could be detected through gauging the distance between two points, the thumb however is different as there as many locations that could be considered a closed thumb, however, a "thumbs up" position is discreet with little ambiguity, therefore the trigger is based around whether the thumb is in this position. The formulation for this is

$$\boldsymbol{w}_{\text{thumb}} \geq \boldsymbol{s}_{\text{thumb threshold}}, \quad (4)$$

where $\boldsymbol{w} \in \mathbb{R}^{3\times1}$ represents the Euler angles in the of the end link of the thumb with respect to the base link of the thumb and $\boldsymbol{b} \in \mathbb{R}^{3\times1}$ represents the threshold values in each rotational axis set to detect the thumb closure.

C. Hardware Implementation

The quadrupeds used are the Unitree Aliengo and A1, each with a mounted robotic arm on top. They each carry a ViperX 300 5-DoF robotic arm and a PhantomX Pincher 4-DoF robotic arm respectively. Each robotic arm is mounted on the top side of the trunk of the quadruped. Robot Operating System (ROS) is used to connect the two robots over a 5 GHz wireless network to a Ubuntu computer, which acts as the ROS master. The motion capture suit data is retrieved from the suit via the Perceptron Neuron dedicated software on a Windows computer, which is then sent to the Ubuntu computer via ROS serial. This data is then converted into standard ROS TF format, which is then input into the teleoperation algorithm that allows for the high level commands for either robot to be computed. A flag is used in the command message to differentiate which command goes to which robot. A complete system diagram is presented in Fig.3.

III. Experiment Design

To demonstrate the capabilities of the control framework, a real life experiment was conducted through the use of two quadrupedal manipulators. In the experiment, the operator must control both robots to perform the task of removing the cap of a spray can. The cap removal task is split into several steps; firstly, the two robots are placed approximately 1.5 meters either side of the water bottle, which is located in the centre of the testing area. Secondly, the smaller robot with the lower DoF robotic arm, the A1 system, will travel forward, rotate as needed and pick up the spray can from a flat surface and then move into an open area. Next, the Aliengo system will approach the A1 system and then both robots will be orientated to allow the Aliengo's robotic arm to proceed in removing the cap of the spray can, at which point the experiment ends[1].

In the experiment, the PhantomX Pincher's end-effector is redesigned to be more effective at grasping cylindrical objects. The experiment is performed with the operator in line of sight of the robot however in the future, the possibilities of using two robots to act as a 3rd person view for teleoperation will be investigated.

IV. Experiment Results

In the experiment, the operator first closes their left hand to send linear velocities to the A1 quadruped in order to move it towards the spray can's location, which is achieved by having the operator move their left hand forward when in this state. Then, the index and middle finger of the operator is opened to initiate the yaw control state of the A1, due to this being a different trigger, the reference is generated again from the moment the index and middle fingers are opened. In this state, rolling the left hand will result is a corresponding yaw velocity in the A1. The operator then opens their left hand to reset the reference point and then closes their left hand excluding the thumb to activate arm control. The arm is then manoeuvred using the left hand to grasp the spray can with the teleoperator opening their index and middle finger to toggle the gripper closure state, picking up the spray can.

[1]The experiment video can be found at `https://youtu.be/TApk6XrgYhY`

Following this stage, the operator initiates yaw control of the A1 again and rotates it so that it is facing the Aliengo. The operator then closes their index and middle fingers in order to move the A1 sideways until within range of the ViperX 300 robotic arm that is mounted on the Aliengo. The operator now keeps their left-hand open to prevent any commands being sent to the A1 system, and the right-hand excluding thumb closes to control the ViperX 300. First, the right hand is moved in the y-axis to send a yaw position to the robot arm before guiding the end-effector around the cap of the spray can and opening the right hand's index and middle finger to close the end-effector. The operator then guides the robot arm to lift the cap away and opens their right hand before closing it again, thumb included, to generate a sideways velocity so the Aliengo moves out of the path of the A1. After this is complete, the right hand opens to prevent commands being sent to the Aliengo system and the left hand closes to move the A1 forward past the Aliengo, concluding the experiment.

A time-lapse of the experiment is illustrated in Fig.4. Figures 5, 6, 7, 8, 9 and 10, representing respectively (b), (c), (d), (f), (i) and (l) in Fig.4, illustrate the relationship between the references generated by the teleoperation framework and the finger-based trigger system with the velocity and position feedback of the quadrupeds and robotic arms. The references consist of the velocity and position commands generated by the teleoperation framework post-gain. The feedback values are obtained from the IMU of the quadruped and the joint positions of the robotic arm. As can be seen in Figures 5-10, the feedback values from the quadruped and robotic arms do no respond to the change in reference values unless the teleoperation trigger, represented by the shaded area, is active. Upon the release of the teleoperation trigger, represented by non-shaded areas, no further changes in the reference value will not be sent to the system until the respective teleoperation trigger is activated again.

Overall, the teleoperation framework proved to be successful as it completed the task outlined in the experiment. However, some difficulty came from the teleoperation being in line of sight, with the velocity references for the quadrupeds being respective to the orientation of the quadruped itself. This then required the teleoperator to decide the correct direction of travel based off the yaw rotation of the commanded robot. This issue could be tackled in the future by adding a camera to each of the robots.

V. Conclusions

In this study, a teleoperation framework, that is highly versatile yet trivial to operate, has been developed. Through utilising both hands of the motion capture suit and a range of triggers bound to the fingers of the suit's gloves, two robots have been simultaneously controlled to complete a complex cooperative task, where two robots work together to remove a cap from a spray can. It is also postulated that this framework could be applied to a control a pair of a wide range of different robots, from wheeled manipulators to humanoids, due to its independence from the kinematic

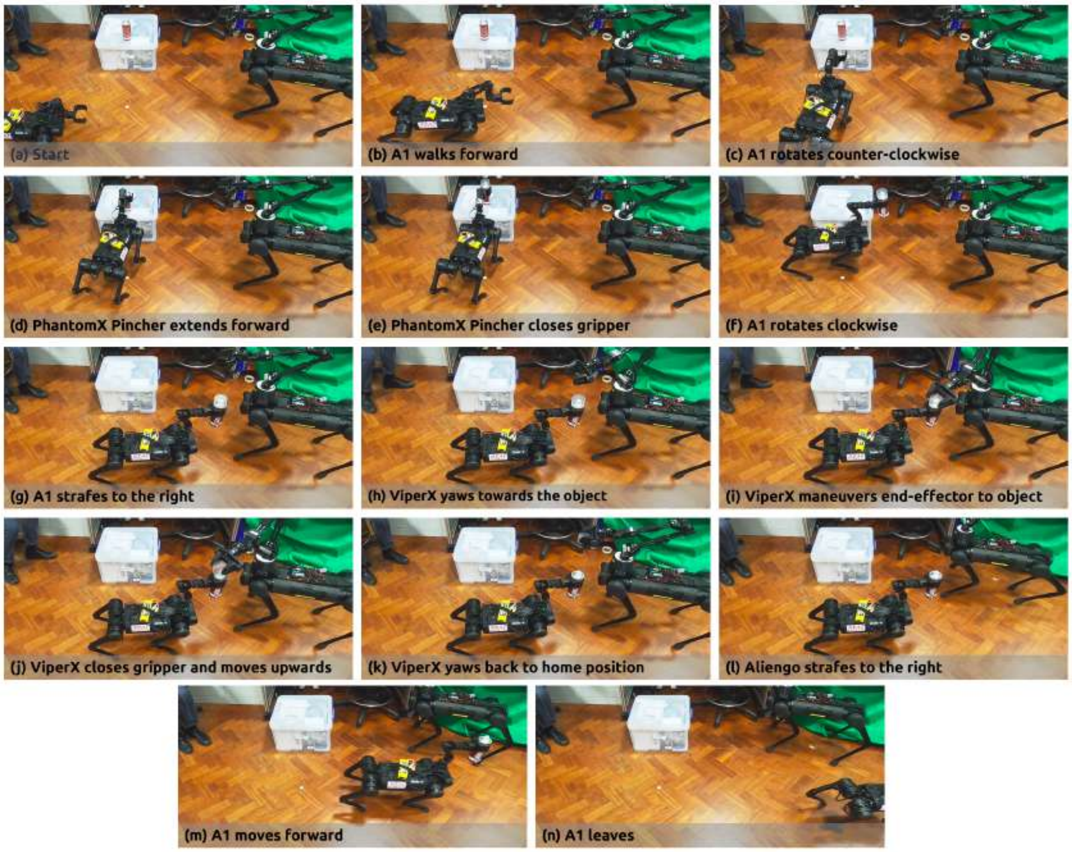

Fig. 4. Time-lapse showing each stage of the experiment. The experiment is performed in line of sight of the teleoperator.

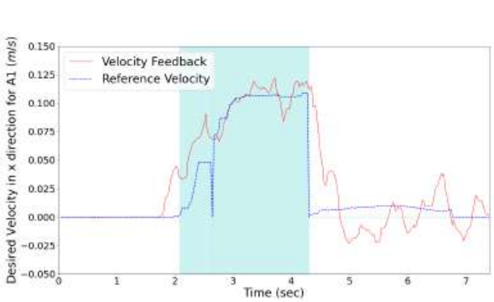

Fig. 5. Chart illustrating the forward velocity feedback of the A1 quadruped in reaction to the provided reference in the x-axis from the teleoperation framework. The shaded area represents when the teleoperation trigger for linear velocity control of the A1 is active.

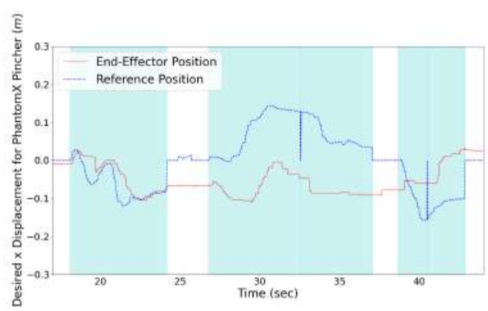

Fig. 7. Chart illustrating the end-effector location of the PhantomX Pincher in reaction to the provided reference in the x-axis from the teleoperation framework. The shaded area represents when the teleoperation trigger for controlling the robotic arm on the left hand is active.

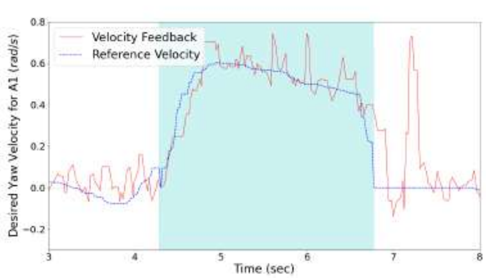

Fig. 6. Chart illustrating the yaw velocity feedback of the A1 quadruped in reaction to the provided reference in the roll-axis from the teleoperation framework. The shaded area represents when the teleoperation trigger for rotational control of the A1 quadruped is active.

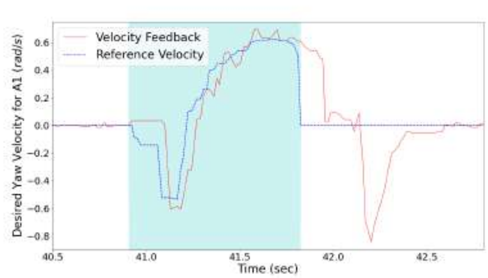

Fig. 8. Chart illustrating the yaw velocity feedback of the A1 quadruped in reaction to the provided reference in the roll-axis from the teleoperation framework. The shaded area represents when the teleoperation trigger for rotational control of the A1 quadruped is active.

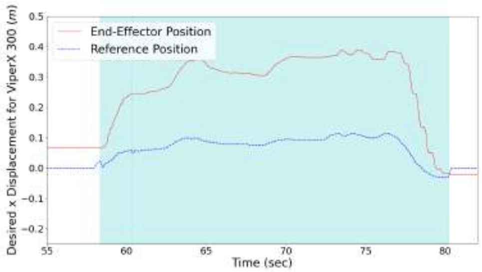

Fig. 9. Chart illustrating the end-effector location of the ViperX 300 robotic arm in reaction to the provided reference in the x-axis from the teleoperation framework. The shaded area represents when the teleoperation trigger for controlling the robotic arm on the right hand is active.

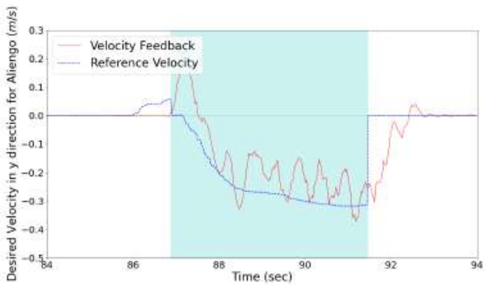

Fig. 10. Chart illustrating the sideways velocity feedback of the Aliengo quadruped in reaction to the provided reference in the y-axis from the teleoperation framework. The shaded area represents when the teleoperation trigger for linear velocity control of the Aliengo is active.

structure of the robots it is controlling. Future work to further develop this framework will be to integrate a whole-body controller within it and add a mobile third person camera, with gaze control [22], to allow for reliable visual feedback during teleoperation scenarios. In addition, to further enable the manipulation and control capabilities, sensors allowing the localisation of the two robots could be implemented.

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