The Design and Performance of Low Cost Haptic Interfaces to Control Precision Nuclear Robotic System

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Abstract

Nuclear decommissioning environments are challenging and hazardous, typically involving high temperatures, pressures and extreme radiation. Robotic devices are commonly used to complete tasks within challenging environments, which would otherwise pose a risk to human health, however remotely operating robots without full three-dimensional vision is challenging, and operators of robotic systems require extensive training to enable precise navigation through three-dimensional environments using multiple two-dimensional views for feedback. This project explores the possibility of using a human arm as a master device for controlling a variety of low-cost slave robots, with the aim of reducing training times whilst providing a cheaper, more intuitive control system. Virtual Reality (VR) and haptics are used as an aid for navigation of the remote environment, whilst also providing a digital twin for the operator to enable real-time feedback from the slave robot.

Introduction

Robotic systems are often used where the task is not accessible by humans, or where robots are quicker and more efficient; applications include nuclear, automation and manufacturing. Master-slave systems are commonly used to control robots remotely. In most cases, the master station will have a similar or identical kinematic layout to the slave, simplifying control systems. Two-dimensional camera views of the slave robot's environment are typically provided as feedback to the master station, requiring the operator to navigate a three-dimensional environment using multiple two-dimensional images. Varying levels of haptic feedback are used to provide the user with a sense of touch and depth-perception. Master-slave systems require extensive operator training programmes. To master the dual-perception technique for navigation, operators must first learn how to use two-dimensional images and gain a sense of depth and position before having the capability to complete complex tasks with the slave robot. Master-slave systems are used in environments where there is a desire to locate the operator away from the point of work; examples include decommissioning [1].

Modern VR technology is powerful, cheap and readily available, and is increasingly being used in industry to aid design and development of components and plants; collaborative design reviews, where each participant of the review is provided with a Head-Mounted Display (HMD) and can examine and explode three-dimensional CAD models, is now a real, cheap possibility. The complexity of VR has grown due to enhanced open-source software and commercialisation of VR HMD's, which has enabled beta testing of devices to be amplified. VR can be used with varying levels of functionality – the simplest form of VR is an animated three-dimensional CAD model, which can be manipulated by PC software to demonstrate events, tasks or projected moves of a robot. More complicated, fully-representative VR enables images to be projected in three-dimensions (through HMD's), whilst also providing tactility to give the user a complete sense of the virtual environment.

Training times and costs can be reduced by implementing simpler, more intuitive control schemes. A single, dominant master would have the capability to control many types of robot and robotic devices, whilst reducing the hardware cost of the master-slave systems it inhibits. Using VR development software and COTS HMD's and controllers, it is possible to create a digital-twin of a tele-operable robot, providing the user with a fully-representative virtual model of the robot rather than a digital representation. Reducing the training cycle enables a wider variety of people to become competent in remote tele-operation of robots.

This paper presents a system which integrates low-cost virtual reality technology with haptics in order to create an intuitive, cost-effective interface for remotely operating robotic devices. We demonstrate the feasibility of the techniques as well as benefits to the quality of human-robot interaction.

Background

In nuclear decommissioning [2], master-slave systems are utilised for completing tasks which require varying levels of precision. The risk involved in demolition and extreme radiation creates a need for cheap and simple hardware and control systems. Second-hand diggers and bulldozers are often used where the tool and control system have been separated, allowing remote operations in the radiated environment at a minimal cost.

To aid human visual perception of remote environments, mixed reality (Virtual and Augmented) platforms are being utilised. Surgical training tools [3] utilise Virtual Reality to aid training, development and teaching for Minimally Invasive Surgery (MIS), and explore in detail the true value of haptic feedback in the control loop. Augmented Reality is also used as a training aid for haptic dental training [4]. The difficulties and psychological effects of remote teleoperation with high cognitive loads, such as maintenance robots, are aided by the immersiveness of Augmented Reality [5]. This application utilises master-slave systems mixed with virtual interfaces and mappings.

Robot tele-operation requires a significant level of concentration from operators, who are expected to use multiple sources of information to complete delicate tasks in remote environments. This can create a high level of cognitive-load on operators. Two-dimensional views for feedback are commonly used to aid navigation through three-dimensional environments, presenting a need for high concentration. High cognitive-loads can negatively impact the performance and concentration of operators, affecting spatial-awareness and depth-perception within the robot’s environment. Dual-perception techniques required by operators present a need for extensive training, typically involving dummy tasks to allow the operator to become accustomed with the control scheme and manipulating the robot as desired.

The high cognitive-load and required spatial reasoning skill creates a gulf between those who are capable of remote tele-manipulator operation and those who are not. Operators are required to can use a viewport, such as that provided by a camera, with a viewing angle different to that of their natural viewport, i.e. their eyes. An in-experienced operator’s natural inclination will be to attempt to operate within the camera viewport using the same orientation as their current space. However, this does not consider the viewing angle, which will cause perceived movement to be disorientated. Experienced operators mentally adjust for this, having spent many hours performing training exercises, such as manipulating complex objects without line-of-site.

DISSIMILAR MASTER-SLAVE SYSTEM OVERVIEW

Architecture

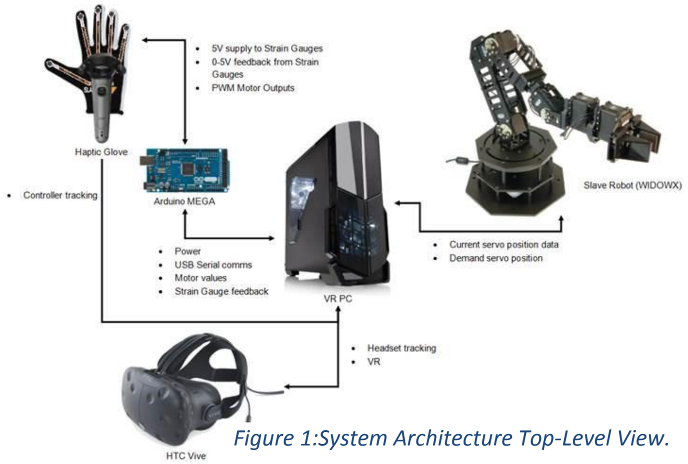

Figure 1:System Architecture Top-Level View.

The system architecture (see figure 3) consists of a custom made haptic glove, with a serial interface to a high-spec PC, an off-the-shelf VR headset, and a pair of hand-held controllers, all of which can be tracked within the physical workspace. These provide the input to a control system capable of manipulating a 5 degree-of-freedom robot arm. Within the haptic glove, strain gauges are mounted to the back of each finger. Bending a finger provides a change in resistance and therefore a change in voltage, which is measured using an Arduino MEGA and converted into an integer. The data is then sent into the virtual environment and translated into joint angles on the virtual hand model, with each strain gauge corresponding to a finger or thumb in the virtual model. As such, all the fingers can be individually measured, and actuated in VR. There are also small vibration motors mounted to each fingertip which are powered during a collision in the mixed-reality environment, providing a haptic feedback to the user. The Arduino communicates with the virtual environment over RS232.

A HMD and two VR controllers are used in this system. The first VR controller is used as a dead-man's switch to enable movements of the robot to begin, and the second controller is mounted to the back of the glove. This second controller is the primary source of position control, and provides a means for the user to create a displacement in position and orientation in 6 degrees of freedom. On triggering initiation of motion following, using a set of buttons on the controller, the initial position of the glove and robot are recorded, and displacements subsequently calculated from these respective origins. The tethered HMD allows the user to walk around in the virtual environment by walking within real-world spaces.

Master-Slave Relationship

Unlike the master-slave system used in JET [6], this system uses relative movements.; i.e. the relative movements of the master (the glove) are applied to the slave (the robot) relative to the slave's current position. This system has two major advantages - first, the master is not required to be in the same position as the slave when starting a move; and second, the work area of the master is capable of much smaller than that of the slave. Moreover, the lack of a one-to-one alignment allow the master to use novel configuration or even change its configuration mid movement to solve a problem.

During a move, the position and orientation of the glove is monitored and used to create a displacement from the initial start position. The new joint positions for the robot are derived using a custom inverse kinematic solution for the desired tool-tip position. The solution uses quaternion calculations to avoid gimbal-lock, and introduces limits to avoid damaging the robot hardware. These new joint positions are then sent to the robot to achieve the desired tool-tip position. This solution creates a relative mapping from the operator's hand to the robot's gripper. The movements are always relative to the hand's frame which creates a highly intuitive control method when the operator is orientated in such a way that the hand frame is close to that of the gripper frame. The operator moves their hand the gripper follows - left moves left, right moves right, up moves up, etc.

Experimentation

Within the purely virtual environment, a set of grasping tasks were used to assess usability of the system in terms of ability to navigate the environment, judge position of the robot in relation to objects, and perform simple grasping activities. Performance of the complete mixed-reality system was assessed qualitatively using a set of objects that could be manipulated using the robot in the real world. The system was found to be highly intuitive and users could become sufficiently familiar with the mappings to perform relatively natural manipulation and manual exploration of the remote objects within a few minutes.

Discussion

Low Cost Haptic Interfaces have a wide range of applications primarily enabling Control Precision Nuclear Robotic System where the cost and training required for a tele-robotics system had been prohibitively costly. Moreover, its asymmetric master-slave arrangement empowers the system to far greater flexibility, allowing the system to be applied to multiple slaves (e.g. quadcopters, or diggers) with little no adaptation or training required. Moreover, the level of information that can be rapid and intuitively presented to operators could (although not presented in this work) improve the quality and assurance of remote operations. Additionally, virtual systems can also be used for relatively in-expensive training of operators. This can be vital for applications such as JET, where a spare manipulator isn’t available for training purposes.

Future Work

Firstly, we intend to conduct thorough quantitative assessments of performance using the system, against standard benchmarks for comparison against other master user interfaces. The final goal is to implement this control system with a large-scale industrial robotic manipulator in an active environment, and complete simple remote handling tasks, such as bolt-tightening and component installations.

References

[1] Lee, Jong Kwang, et al. "Bridge-transported bilateral master–slave servo manipulator system for remote manipulation in spent nuclear fuel processing plant." *Journal of Field Robotics* 29.1 (2012): 138-160.

[2] Bogue, Robert. "Robots in the nuclear industry: a review of technologies and applications." *Industrial Robot: An International Journal* 38.2 (2011): 113-118.

[3] Okamura, Allison M. "Methods for haptic feedback in teleoperated robot-assisted surgery." *Industrial Robot: An International Journal* 31.6 (2004): 499-508

[4] Rhienmora, Phattanapon, et al. "Augmented reality haptics system for dental surgical skills training." *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology*. ACM, 2010.

[5] Yew, A. W. W., S. K. Ong, and A. Y. C. Nee. "Immersive Augmented Reality Environment for the Teleoperation of Maintenance Robots." *Procedia CIRP* 61 (2017): 305-310.

[6] Owen, Tom, et al. “Upgrading the JET Remote Handling System”. In proceeding of WM2018, Pheonix, Arizona (2018).

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