Cartesian Robot Controlling with Sense Gloves and Virtual Control Buttons: Development of a 3D Mixed Reality Application

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Abstract: In this paper, we present a cartesian robot controlled by a mixed reality interface that includes virtual buttons, virtual gloves, and a drill. The mixed reality interface, into which the virtual reality input/output devices and sense gloves have been integrated, enables the control of the cartesian robot. The data transfer between the mixed reality interface and the cartesian robot is implemented via Arduino kit. The cartesian robot moves in 6 axes simultaneously with the movement of the sense gloves and the touch of the virtual buttons. This study aims to perform remote-controlled and task-oriented screwing and unscrewing of a bolt using a cartesian robot with a mixed reality interfaces.

1 INTRODUCTION

Designing robots that interact with humans through virtual, augmented, and mixed reality (MR) environments, designing augmented reality (AR) interfaces that mediate this communication and achieving optimal design practices are one of the most important issues in the field of human robot interaction (HRI). Robotics studies are aimed at fully autonomous robots that cooperate with humans. Although significant work has been done in this field recently, the areas where autonomous robots are used are limited (Xu et al., 2022). In this case, robots controlled by remote devices as a joystick are used as a solution. Some studies in the literature show that robots are controlled by sensor data on screens and other input and output devices used for video games (Tanaka et al., 2018; Klamt et al., 2018).

While traditionally controlled robots have their advantages, MR, AR, and virtual reality (VR) offer a promising alternative as immersive interfaces that allow three-dimensional work and an alternative method of mediating HRIs that enable communication between them (Gruenbaum et al., 1997; Sato and Sakane, 2000).

Programming and simulation of industrial robots in large-scale manufacturing facilities are time-consuming and costly. Therefore, the focus is on programming and simulation of MR-based collaborative robots to improve the experience of robot control (RC) and HRI. While augmented reality can be used for data visualization, MR is more comprehensive and can be used for interactivity (Gallala et al., 2019) and is a one-dimensional arrangement between real and virtual environments (Skarbez et al., 2021; Gallala et al., 2021). In particular, MR, AR ,and, VR interfaces have significant advantages over conventional techniques in terms of the user's spatial awareness and immersion, and the improved performance, lower cost, and usability of the input/output (I/O) devices used with these interfaces encourage their use in RC and HRI (Stotko et al., 2019; Whitney et al., 2019). MR, AR and, VR interfaces also provide unique experiences that were not possible with previous technologies (LeMasurier et al., 2021; Hetrick et al., 2020).

Studies on HRI with MR, AR ,and, VR interfaces have focused on topics such as picking up and placing an object (Xu et al., 2022), novel control methods (Bustamante et al., 2021), eye-tracking interaction for object search and tracking, and head-motion interaction for selection and manipulation, deep-learning-based object recognition for initial position estimation (Park et al., 2021), object identification based on head pose (Higgins et al., 2022), analysis of user perception of robot motion during assembly of a gearbox (Höcherl et al., 2020), and picking up and placing an object using eye and head movements of the robot (Park et al., 2022). The focus of these studies is on MR, AR, and VR interfaces, robotic arms, and HRI.

In recent years, haptic devices have been used in VR environments. Haptic or force feedback interfaces

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used with force sensor systems allow users to touch, grasp, feel, and manipulate virtual objects (Shor et al., 2018). In addition, the user's actual hand and finger movements when touching, grasping, and lifting objects are mimicked by their virtual hand and fingers in the virtual environment (Espinoza et al., 2020). These devices allow people to interact with virtual objects in VR or remote environments and transfer force to the arm (Park et al., 2016). Force feedback is important for effective and productive manipulations in confined spaces. The operator can recognize more states of the operation through force feedback, improving task performance (Nakajima et al., 2014; Pacchierotti et al., 2016; Li et al., 2016).

Cartesian robots are widely used in the industry due to their high payload and speed, repeatability and accurate positioning (Rui et al., 2017) capabilities. To improve the accuracy and efficiency of the cartesian robot manipulation tasks, an HRI with non-contact electromagnetic force feedback (Du et al., 2020) and a machine vision-based calibration method have been proposed to satisfy the automatic and intelligent motion control of cartesian Robot (Rui et al., 2017). Control of cartesian robots with virtual interfaces has been proposed in some studies (Palmero et al., 2005; Martínez et al., 2021). Studies on HRI focus on the control of MR, AR, and VR interfaces which mostly concentrate on robotic arms. The proliferation of studies on MR interfaces and control of cartesian robots, which are widely used in the industry, will enable them to be profitably and efficiently used like other robots. Adding haptic devices such as sense gloves to these interfaces will enable more realistic immersion by integrating physical interactions with virtual objects into these interfaces.

In this context, a cartesian robot with stepper motors and motor control units that can move in six axes, and a virtual environment in which this robot is controlled, including direction virtual control buttons and virtual hands representing sensory gloves, has been developed. The Unity 3D application development platform was used to develop the virtual environment. Arduino unit was used to communicate between the Cartesian robot and this virtual environment. In addition, the Arduino software development platform was used to program the Arduino. The Cartesian robot is moved simultaneously in the six axes by touching the direction virtual buttons on the control panel or without touching the virtual buttons with sense gloves. During touching, the force and vibration are transferred to the actual hand through the sense gloves. Through this transfer, the user gets a more realistic feeling when interacting with virtual objects. With the designed system, the screwing and unscrewing of bolts was realized without touching the cartesian robot.

This paper is organized as follows: Related Work section contains the literature on human-robot interaction and MR, AR and, VR, Preliminary Study section contains the hardware and software tools of the designed Cartesian robot system, their intended use, design and implementation of the system Discussion and Conclusion section contains a summary of the content of the paper, the limitations encountered during the design, the proposed solutions and the final application areas.

2 RELATED WORKS

Recent advances in interactive handheld, MR, and VR systems for controlling a robot significantly increase the applicability of this approach. VR environments have also been developed to visualize the trajectories of mobile wheelchairs and robots (Chadalavada et al., 2015; Schiavi et al., 2009). Developments in AR and VR are advancing rapidly and are being usefully integrated into HRI (Andersen et al., 2016; Chakraborti et al., 2017; Diaz et al., 2017). Alternative control methods such as brain-computer interfaces for robots, graphical predictive interfaces for RC, eye sensors for eye control, VR simulators and simulations to improve medical skills, and robots for teleoperation are being used in various disciplines (Zhang and Hansen, 2019; Pérez et al., 2019; MacCraith et al., 2019; Watson et al., 2016; Walker et al., 2019). In addition, real-time RC requires a secure physical connection between human and robotic operators and manipulators (Schiavi et al., 2009). In the context of these developments, the design of appropriate interfaces for HRI, delivery windows, manual guidance, collaborative work, and control issues are at the forefront (ANSI/RIA and ANSI, 2012). In the manufacturing industry, designing and testing machines and their interfaces is often a costly and long process. These long processes can be overcome by designing and actively using machine interfaces in VR environments and combining these environments with the haptic experiences of physical interfaces (Murcia-López and Steed, 2018a; Ucar et al., 2017; van Deurzen et al., 2021).

Haptic and force feedback during interaction with virtual objects can be less distracting in environments with rich visual and auditory data in many VR applications. Haptic and force feedback in VR applications can greatly enhance user immersion and embedding (Jones and Sarter, 2008; Zhou et al., 2020). The literature suggests that haptic applications with individual finger force generation can play a role in education as well as in industry and healthcare (Civelek et al., 2014; Civelek and Fuhrmann, 2022; Murcia-López and Steed, 2018b; Richards et al., 2019; Vergara et al., 2019; Grajewski et al., 2015; Christensen et al., 2018; Civelek and Vidinli, 2018).

Stepper motors are one of the preferred motor types for cartesian robot motion. It is a control motor widely used in model (Kołota and Stępień, 2017). The control system of a conventional stepper motor usually controls a single stepper motor, but later various solutions of multiple control systems for stepper motors have been proposed (Wang et al., 2020; Chen et al., 2012; WANG et al., 2020; Zhang et al., 2021; Slater et al., 2010). These studies have enabled the control system to control multiple stepper motors simultaneously and to control and adjust the operating state of stepper motors in real time.

3 PRELIMINARY STUDY

A cartesian robot and a virtual environment in which the cartesian robot is controlled have been developed for collaboration between machines and humans.

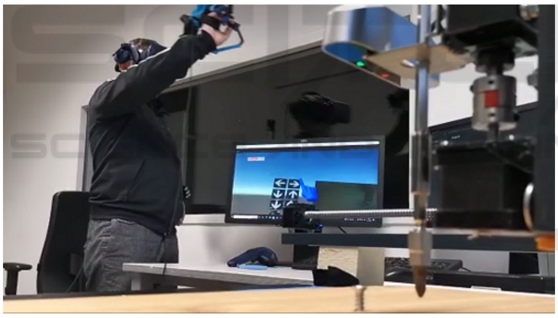

Figure 1: Interaction of virtual hand and virtual buttons during implementation.

Figure 2: Interaction of the virtual hand with the drill during execution.

As shown in Figures 1 and 2, the cartesian robot is equipped with stepper motors, stepper motor controllers, a web camera, an Arduino unit, and appropriate tools for movement in 6 axes. The designed VR environment includes the virtual hands representing the sensory gloves, virtual control buttons and a virtual display. In addition, HMD, HTC Vive tracker, sensory gloves, etc. are used to capture and immerse the real hand position and head movements.

3.1 Cartesian Robot Design

Cartesian robots are designed as linear industrial robots (i.e. they move in a straight line and do not rotate) and have three main control axes that are perpendicular to each other. They move in 6 axes on 3 rails. They are reliable and precise in 3D space. As a robotic coordinate system, it is also suitable for horizontal movements and stacking boxes.

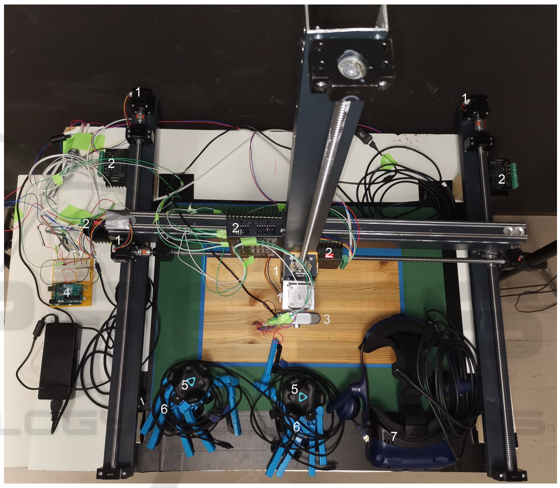

Figure 3: Top view of the designed cartesian robot. 1. Stepper Motors, 2. Stepper Motor Control Units, 3. Webcam, 4. Arduino, 5. HTC Vive Trackers, 6. Sense Gloves, 7. HMD.

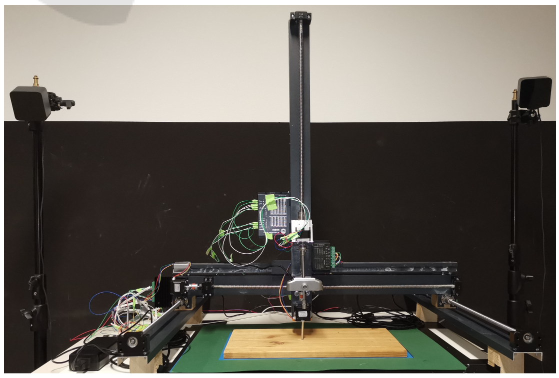

Figure 4: A front view of the designed cartesian robot.

As shown in Figures 3 and 4, a Cartesian robot was developed that screws and unscrews a bolt in this work. The frame of the system is designed to allow movements in 6 axes and is made of rigid aluminum material due to its light weight. Next, the bolt, floating bearing block and bracket parts were assembled, and the system was connected to the stepper motors via a claw coupling. Finally, cable connections were made between the motors and the motor controllers, and among the motors, Arduino, and the computer. The robot was equipped with a camera to determine the boundaries of the movement, and the motor was placed in an area bounded by the colors, which consisted of two different colors. The reason for placing it in the colored area is to determine the limits of the robot's movements and to prevent the moving part of robot from bumping against the fixed skeleton.

3.2 Design of the Virtual Environment

As shown in Figure 5, a virtual environment was designed for the Cartesian robot control. The virtual environment includes control buttons, virtual hands representing sense gloves, a virtual screen to which the image of the colored surface is transferred, and a virtual drilling machine. The control buttons send the data defined under certain conditions when touched by the virtual hands to a C program interface, which is used to control the Arduino through the serial interface to allow the Cartesian robot to move in six axes (right, left, front, back, up, and down).

Figure 5: The virtual control panel.

The sense gloves were equipped with HTC Vive trackers that transmitted their position from the real world to the virtual world. The position data from the trackers attached to the sense gloves is transmitted to the gloves in the virtual environment via base stations, allowing the virtual gloves to move simultaneously with the real hand. When the virtual drill is gripped by the virtual gloves, the data from the virtual hand, which contains the information required to move the Cartesian robot, is transmitted through the serial port to the C programming interface to drive the motors. When the button of the drill is touched with the index finger, the necessary data to turn the motor to the right is transmitted, and when the same motor is touched with the middle finger to turn it to the left. Therefore, the motor is rotated in two axes to turn. By this, the motor can be rotated clockwise or counterclockwise in order to tighten or to loosen the bolt. When the position of the bolt and the position of the drill tip used to screw or unscrew the bolt match, touching the drill button screw or unscrew the bolt.

In order to ensure that the Cartesian robot does not collide with its own skeleton during operation, the motion boundaries are defined with colored paper. These boundaries are transmitted to the virtual screen via the webcam and help the user decide whether to continue or stop the movement in one axis.

3.3 Implementation

As shown in Figure 6, during the application, the HMD position, the position of the sense glove, and the finger positions of sense glove are transmitted to the virtual control panel framework. The updated VR environment is transmitted to the HMD. The updated force feedback during virtual touch is transmitted to the sense glove. The position data during the touch of the virtual buttons and the position data of the hand movement after gripping the drill are transmitted to the Arduino framework. The motor rotation data defined according to the incoming data is recorded in Arduino kit and transmitted to the motor control units through the Arduino kit. The control units drive the motors according to the transmitted data. The image of the surface on which the cartesian robot is moving is transmitted to the virtual control panel via the webcam.

The virtual environment was created using the C# programming language on the Unity 3D platform. The necessary algorithms were coded for the simultaneous movement of the virtual hands representing the sense gloves, the transfer of the position information of the sense gloves to the virtual hand. The information about the events that occur when the virtual buttons are touched with the virtual hands, the position information of the virtual hands when the virtual object is grasped and moved with the virtual hand, and the transfer of the image of the moving area of the robot to the virtual screen during the movement of the robot. In addition, the virtual environment is programmed to provide force feedback to the user's hand via the sensory glove motors when the virtual buttons are touched with the sensory gloves and the drill is gripped. This increases the user's perception of reality when grasping and touching objects and gives the user the feeling of being in a real world. The Ports module (System.IO.Ports;) in the C# language was used for the data flow, and the data flow between Unity and the Arduino is through the

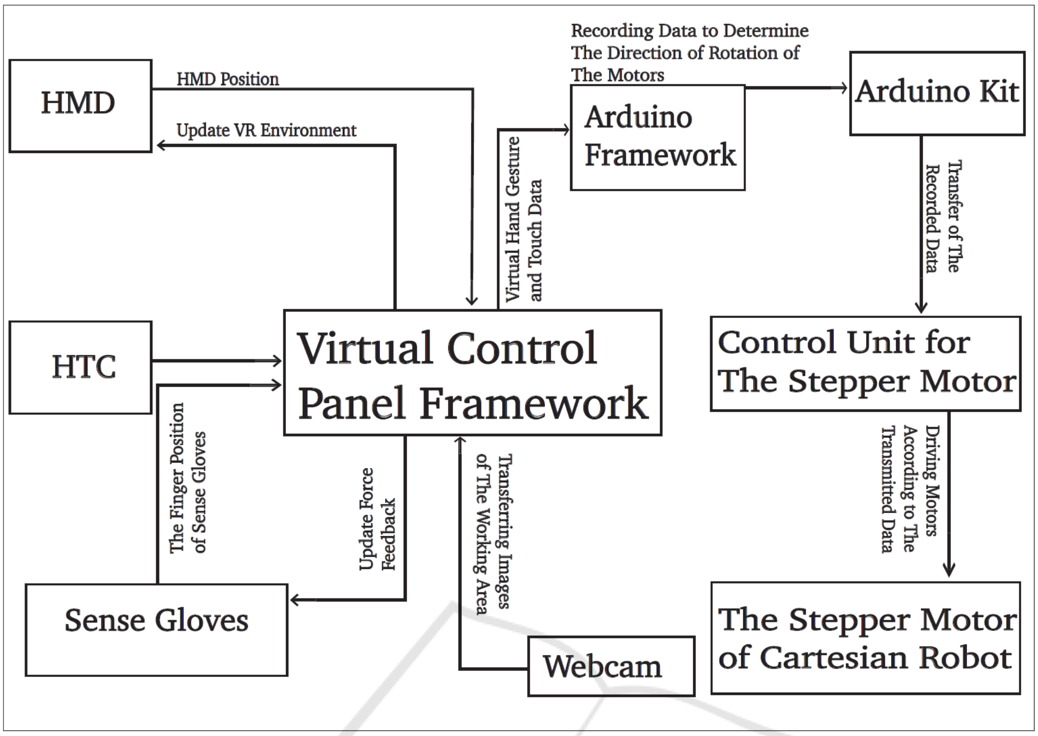

Figure 6: Input and output devices, virtual control panel framework, the Arduino framework, the Arduino, the stepper motor control unit, the stepper motors of the Cartesian robot and the events that take place between them.

SerialPort COM4.

```
public SerialPort serial = new SerialPort
("COM4", 115200, Parity.None,
8, StopBits.One);
```

The processes required to receive the data sent by Unity to the Arduino and to send the necessary commands to the control units of the motors that move the robot under certain conditions according to the received data are coded in the C programming language.

Events that occur when a button is touched with the virtual hand are transmitted as string data to the Arduino programming tool via the serial port. If the virtual drill is gripped with the virtual hand, the end position of the virtual hand is compared with the start position. The string data is transferred to the Arduino programming tool according to the size and smallness of the comparison. Here, the incoming data at Arduino is interpreted and information is sent to the stepper motor controllers depending on the type of incoming data. Based on the information received, the direction of rotation of the stepper motors is determined. When the bolt and the drill meet in the same position, the motor to which the bolt mounting tip is attached is rotated and the bolt is screwed or unscrewed.

4 DISCUSSION AND CONCLUSION

Mixed reality and robot control, supported by Sense gloves to control a Cartesian robot, combines the capabilities of communication and interaction between input and output hardware tools, virtual environment, controls, and machine components with the experience of performing a task without touching the machines. During this interaction, motors on the sensor gloves transmit force to the hand and the image received from the workspace where the task is being performed to the virtual screen, giving the user a more realistic sense of being in a more real world. The image transmission is done through a two-dimensional virtual screen. Matching the positions of the bolt and drill bit to remove the bolt is done using these images, either by pressing the virtual control buttons with the virtual hand or by moving the drill bit with the virtual hand.

During the application, both by touching the buttons with the fingers of the virtual hand and by moving the gripped drill with the virtual hand, the movement of the machine in six axes was realized simultaneously. When the position of tip of the drill coincided with the position of the bolt, the task of screw and unscrew the bolt was realized.

In the literature, studies on the development of mixed reality robot control interfaces have mainly focused on robotic arms. In this work on remote control of Cartesian robots, we believe that the use of MR control interfaces will help the improvement of control interfaces for Cartesian robots. In addition, to cost-efficient hardware and software tools, the designed system is highly reproducible and perfectly configurable by the user.

There are several ways to improve the implementation. For example, more powerful motors could be used to improve performance. To increase realism, the workspace of the Cartesian robot can be virtualized in 3D and transferred to the virtual environment, and the motion boundaries can be determined by encoding. Future studies in this area, including assembly and disassembly of machine parts, machine repair, construction and maintenance, as well as virtual surgical procedures can be performed through virtual environments and force feedback devices without being in the environments where these processes take place.

REFERENCES

Andersen, R. S., Madsen, O., Moeslund, T. B., and Amor, H. B. (2016). Projecting robot intentions into human environments. In *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, pages 294–301.

ANSI/RIA and ANSI (2012). American national standard for industrial robots and robot systems – safety requirements. In *American National Standard for Industrial Robots and Robot Systems – Safety Requirements*. American National Standards Institute/Robotics Industry Association.

Bustamante, S., Peters, J., Schölkopf, B., Grosse-Wentrup, M., and Jayaram, V. (2021). Armsym: A virtual human–robot interaction laboratory for assistive robotics. *IEEE Transactions on Human-Machine Systems*, 51(6):568–577.

Chadalavada, R. T., Andreasson, H., Krug, R., and Lilienthal, A. J. (2015). That's on my mind! robot to human intention communication through on-board projection on shared floor space. In *2015 European Conference on Mobile Robots (ECMR)*, pages 1–6.

Chakraborti, T., Sreedharan, S., Kulkarni, A., and Kambhampati, S. (2017). Alternative modes of interaction in proximal human-in-the-loop operation of robots. *CoRR*, abs/1703.08930.

Chen, H., Duan, Z., Lian, X., and Zhang, X. (2012). The design of stepper motor system based on can bus. In *2012 2nd International Conference on Consumer Electronics, Communications and Networks (CECNet)*, pages 3262–3265.

Christensen, N. H., Hjermitslev, O. G., Stjernholm, N. H., Falk, F., Nikolov, A., Kraus, M., Poulsen, J., and Petersson, J. (2018). Feasibility of team training in virtual reality for robot-assisted minimally invasive surgery. In *Proceedings of the Virtual Reality International Conference - Laval Virtual*, VRIC '18, New York, NY, USA. Association for Computing Machinery.

Civelek, T. and Fuhrmann, A. (2022). Virtual reality learning environment with haptic gloves. In *2022 3rd International Conference on Education Development and Studies*, ICEDS'22, page 32–36, New York, NY, USA. Association for Computing Machinery.

Civelek, T., Ucar, E., Ustunel, H., and Aydın, M. (2014). Effects of a haptic augmented simulation on k-12 students' achievement and their attitudes towards physics. *Eurasia Journal of Mathematics, Science and Technology Education*, 10:565–574.

Civelek, T. and Vidinli, B. (2018). Resection of benign tumor in tibia with a high speed burr by haptic devices in virtual reality environments. In *Proceedings of the Virtual Reality International Conference - Laval Virtual*. International Institute of Informatics and Systemics.

Diaz, C., Walker, M., Szafir, D. A., and Szafir, D. (2017). Designing for depth perceptions in augmented reality. In *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 111–122.

Du, G., Zhang, B., Li, C., Gao, B., and Liu, P. X. (2020). Natural human–machine interface with gesture tracking and cartesian platform for contactless electromagnetic force feedback. *IEEE Transactions on Industrial Informatics*, 16(11):6868–6879.

Espinoza, J., Malubay, S. A., Alipio, M., Abad, A., Asares, V., Joven, M. J., and Domingo, G. F. (2020). Design and evaluation of a human-controlled haptic-based robotic hand for object grasping and lifting. In *2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, pages 0068–0075.

Gallala, A., Hichri, B., and Plapper, P. (2019). Survey: The evolution of the usage of augmented reality in industry 4.0. *IOP Conference Series: Materials Science and Engineering*, 521:012017.

Gallala, A., Hichri, B., and Plapper, P. (2021). Human-robot interaction using mixed reality. In *2021 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, pages 1–6.

Grajewski, D., Górski, F., Hamrol, A., and Zawadzki, P. (2015). Immersive and haptic educational simulations of assembly workplace conditions. *Procedia Computer Science*, 75:359–368.

Gruenbaum, P. E., McNeely, W. A., Sowizral, H. A., Overman, T. L., and Knutson, B. W. (1997). Implementation of Dynamic Robotic Graphics For a Virtual Control Panel. *Presence: Teleoperators and Virtual Environments*, 6(1):118–126.

Hetrick, R., Amerson, N., Kim, B., Rosen, E., Visser, E. J. d., and Phillips, E. (2020). Comparing virtual reality interfaces for the teleoperation of robots. In *2020*

Systems and Information Engineering Design Symposium (SIEDS), pages 1–7.

Higgins, P., Barron, R., and Matuszek, C. (2022). Head pose for object deixis in vr-based human-robot interaction. In *2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pages 610–617.

Höcherl, J., Adam, A., Schlegl, T., and Wrede, B. (2020). Human-robot assembly: Methodical design and assessment of an immersive virtual environment for real-world significance. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 549–556.

Jones, L. and Sarter, N. (2008). Tactile displays: Guidance for their design and application. *Human factors*, 50:90–111.

Klamt, T., Rodriguez, D., Schwarz, M., Lenz, C., Pavlichenko, D., Droeschel, D., and Behnke, S. (2018). Supervised autonomous locomotion and manipulation for disaster response with a centaur-like robot. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 1–8.

Kołota, J. and Stępień, S. (2017). Analysis of 3d model of reluctance stepper motor with a novel construction. In *2017 22 International Conference on Methods and Models in Automation and Robotics (MMAR)*, pages 955–958.

LeMasurier, G., Allspaw, J., and Yanco, H. A. (2021). Semi-autonomous planning and visualization in virtual reality. *CoRR*, abs/2104.11827.

Li, W., Gao, H., Ding, L., and Tavakoli, M. (2016). Trilateral predictor-mediated teleoperation of a wheeled mobile robot with slippage. *IEEE Robotics and Automation Letters*, 1(2):738–745.

MacCraith, E., Forde, J., and Davis, N. (2019). Robotic simulation training for urological trainees: a comprehensive review on cost, merits and challenges. *Journal of Robotic Surgery*, 13.

Martínez, M. A. G., Sanchez, I. Y., and Chávez, F. M. (2021). Development of automated virtual cnc router for application in a remote mechatronics laboratory. In *2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, pages 1–6.

Murcia-López, M. and Steed, A. (2018a). A comparison of virtual and physical training transfer of bimanual assembly tasks. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1574–1583.

Murcia-López, M. and Steed, A. (2018b). A comparison of virtual and physical training transfer of bimanual assembly tasks. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1574–1583.

Nakajima, Y., Nozaki, T., and Ohnishi, K. (2014). Heartbeat synchronization with haptic feedback for telesurgical robot. *IEEE Transactions on Industrial Electronics*, 61(7):3753–3764.

Pacchierotti, C., Prattichizzo, D., and Kuchenbecker, K. J. (2016). Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery. *IEEE Transactions on Biomedical Engineering*, 63(2):278–287.

Palmero, D., Perez, A., Ortiz, M., Amaro, F., and Henriquez, F. (2005). Object recognition and sorting by using a virtual cartesian robot with artificial vision. In *15th International Conference on Electronics, Communications and Computers (CONIELECOMP'05)*, pages 201–206.

Park, K.-B., Choi, S. H., Lee, J. Y., Ghasemi, Y., Mohammed, M., and Jeong, H. (2021). Hands-free human–robot interaction using multimodal gestures and deep learning in wearable mixed reality. *IEEE Access*, 9:55448–55464.

Park, K.-B., Choi, S. H., Moon, H., Lee, J. Y., Ghasemi, Y., and Jeong, H. (2022). Indirect robot manipulation using eye gazing and head movement for future of work in mixed reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 483–484.

Park, T. M., Won, S. Y., Lee, S. R., and Sziebig, G. (2016). Force feedback based gripper control on a robotic arm. In *2016 IEEE 20th Jubilee International Conference on Intelligent Engineering Systems (INES)*, pages 107–112.

Pérez, L., Diez, E., Usamentiaga, R., and García, D. F. (2019). Industrial robot control and operator training using virtual reality interfaces. *Computers in Industry*, 109:114–120.

Richards, K., Mahalanobis, N., Kim, K., Schubert, R., Lee, M., Daher, S., Norouzi, N., Hochreiter, J., Bruder, G., and Welch, G. (2019). Analysis of peripheral vision and vibrotactile feedback during proximal search tasks with dynamic virtual entities in augmented reality. In *Symposium on Spatial User Interaction*, SUI '19, New York, NY, USA. Association for Computing Machinery.

Rui, W., Huawei, Q., Yuyang, S., and Jianliang, L. (2017). Calibration of cartesian robot based on machine vision. In *2017 IEEE 3rd Information Technology and Mechatronics Engineering Conference (ITOEC)*, pages 1103–1108.

Sato, S. and Sakane, S. (2000). A human-robot interface using an interactive hand pointer that projects a mark in the real work space. In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*, volume 1, pages 589–595 vol.1.

Schiavi, R., Bicchi, A., and Flacco, F. (2009). Integration of active and passive compliance control for safe human-robot coexistence. In *2009 IEEE International Conference on Robotics and Automation*, pages 259–264.

Shor, D., Zaaijer, B., Ahsmann, L., Immerzeel, S., Weetzel, M., Eikelenboom, D., Hartcher-O'Brien, J., and Aschenbrenner, D. (2018). Designing haptics: Comparing two virtual reality gloves with respect to realism, performance and comfort. In *2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 318–323.

Skarbez, R., Smith, M., and Whitton, M. (2021). Revisiting milgram and kishino's reality-virtuality continuum. *Frontiers in Virtual Reality*, 2.

Slater, M., Spanlang, B., and Corominas, D. (2010). Simulating virtual environments within virtual environments as the basis for a psychophysics of presence. *ACM Trans. Graph.*, 29.

Stotko, P., Krumpen, S., Schwarz, M., Lenz, C., Behnke, S., Klein, R., and Weinmann, M. (2019). A vr system for immersive teleoperation and live exploration with a mobile robot. In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 3630–3637.

Tanaka, M., Nakajima, M., Suzuki, Y., and Tanaka, K. (2018). Development and control of articulated mobile robot for climbing steep stairs. *IEEE/ASME Transactions on Mechatronics*, 23(2):531–541.

Ucar, E., Ustunel, H., Civelek, T., and Umut, I. (2017). Effects of using a force feedback haptic augmented simulation on the attitudes of the gifted students towards studying chemical bonds in virtual reality environment. *Behaviour & Information Technology*, 36(5):540–547.

van Deurzen, B., Goorts, P., De Weyer, T., Vanacken, D., and Luyten, K. (2021). Hapticpanel: An open system to render haptic interfaces in virtual reality for manufacturing industry. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*, VRST '21, New York, NY, USA. Association for Computing Machinery.

Vergara, D., Extremera, J., Rubio, M., and Dávila, L. (2019). Meaningful learning through virtual reality learning environments: A case study in materials engineering. *Applied Sciences*, 9:1–14.

Walker, M. E., Hedayati, H., and Szafir, D. (2019). Robot teleoperation with augmented reality virtual surrogates. In *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pages 202–210.

Wang, X., Lu, S., and Zhang, S. (2020). Rotating angle estimation for hybrid stepper motors with application to bearing fault diagnosis. *IEEE Transactions on Instrumentation and Measurement*, 69(8):5556–5568.

WANG, Y., XU, J., LIU, Q., GOU, Y., LI, B., and ZHANG, Y. (2020). Design of can bus control motor based on stm32. In *2020 International Conference on Artificial Intelligence and Computer Engineering (ICAICE)*, pages 37–40.

Watson, G. S., Papelis, Y. E., and Hicks, K. C. (2016). Simulation-based environment for the eye-tracking control of tele-operated mobile robots. In *Proceedings of the Modeling and Simulation of Complexity in Intelligent, Adaptive and Autonomous Systems 2016 (MSCIAAS 2016) and Space Simulation for Planetary Space Exploration (SPACE 2016)*, MSCIAAS '16, San Diego, CA, USA. Society for Computer Simulation International.

Whitney, D., Rosen, E., Phillips, E., Konidaris, G., and Tellex, S. (2019). *Comparing Robot Grasping Teleoperation Across Desktop and Virtual Reality with ROS Reality*, pages 335–350. Springer International Publishing.

Xu, S., Moore, S., and Cosgun, A. (2022). Shared-control robotic manipulation in virtual reality. In *2022 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)*, pages 1–6.

Zhang, G. and Hansen, J. P. (2019). A virtual reality simulator for training gaze control of wheeled tele-robots. In *25th ACM Symposium on Virtual Reality Software and Technology*, VRST '19, New York, NY, USA. Association for Computing Machinery.

Zhang, L., Peng, H., Tang, L., Cao, X., and Yue, X.-G. (2021). A control system of multiple stepmotors based on stm32 and can bus. In *Proceedings of the 2020 2nd International Conference on Big Data and Artificial Intelligence*, ISBDAI '20, page 624–629, New York, NY, USA. Association for Computing Machinery.

Zhou, R., Wu, Y., and Sareen, H. (2020). Hextouch: Affective robot touch for complementary interactions to companion agents in virtual reality. In *26th ACM Symposium on Virtual Reality Software and Technology*, VRST '20, New York, NY, USA. Association for Computing Machinery.