Mixed Reality Interface for Improving Mobile Manipulator Teleoperation in Contamination Critical Applications

Bozyil, Rohat; Bejczy, Bence; Vaičekauskas, Evaldas; Petersen, Sune Baagø Krogh; Bøgh, Simon; Hjorth, Sebastian; Hansen, Emil Blixt

Published in:
Procedia Manufacturing

DOI (link to publication from Publisher):
10.1016/j.promfg.2020.10.087

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 51 (2020) 620–626

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021)
14-17 September 2021, Athens, Greece.

Mixed Reality Interface for Improving Mobile Manipulator Teleoperation in Contamination Critical Applications

Bence Bejczy[b], Rohat Bozyil[b], Evaldas Vaičekauskas[b], Sune Baagø Krogh Petersen[b], Simon Bøgh[b], Sebastian Schleisner Hjorth[b], Emil Blixt Hansen[b]

[a]*Department of Electronic Systems, Aalborg University, Aalborg, Denmark*
[b]*Department of Materials and Production, Aalborg University, Aalborg, Denmark*

Abstract

This paper presents a mixed reality teleoperation interface for mobile manipulation tasks in contamination critical production environments, where human presence is undesirable. This is achieved by using an intuitive control approach and providing the operator with a sense of depth through various visual feedback modalities. The different visual feeds from a mono- and stereoscopic multi-camera setup are displayed for the operator, in a mixed reality control room developed in Unity. The control interface employs the differentiation of the VR controller's pose, interpolated into a trajectory for the end-effector. The communication between the operator and the robot is facilitated through ROS for control commands and visual feedback. Speed of operation is typically not crucial in current use cases, while task safety, accuracy, and perception are paramount. The paper presents the latest research developments of a mixed reality interface designed and tested for a mobile manipulator.

Keywords: Human-Robot Interaction; Teleoperation; Cleanroom Environments; Robotics; Mixed Reality; Mobile Manipulator

1. Introduction

In pharmaceutical manufacturing regulation, authorities assess and designate the required cleanliness of the production environment, based on the microbial risk faced by the patient administered with the product [1]. Production environment cleanliness can be assessed in terms of concentration of airborne particles [2], these environments are commonly referred to as *cleanrooms*. Cleanrooms are used when there is a need for reducing the risk of product contamination, like in aseptic pharmaceutical manufacturing [3]. As humans are the primary source of contamination in cleanroom environments [4], it is highly desirable to reduce human presence or remove the human from the environment entirely to reduce the risk of contamination.

The tasks of the human worker need to be fulfilled by a system, such as a mobile manipulator, able to navigate and manipulate objects in a cleanroom environment. Humans in automated production environments need to handle both expected and unexpected failures and maintenance, meaning an autonomous robot system would have to account for all possible outcomes. Due to the complexity of the task pool, autonomy is not yet a viable option for every task in cleanroom manufacturing, as it can only deal with reoccurring and well-defined tasks. Teleoperation is seen as a mean to deal with the remaining cases, eliminating the need for the human presence inside the cleanroom in the form of a remotely controlled mobile manipulator [5].

Teleoperation of mobile manipulators necessitates the transmission of visual feedback to a remotely located operator. The use of stereoscopic visual feedback for robotic teleoperation systems has been a topic of research for over 20 years, with the desire of simulating a more natural vision system for depth perception [6]. The use of stereoscopic cameras also turned the focus towards immersive display technologies like augmented reality (AR) or virtual reality (VR) [7, 8].

In this work, an end-to-end framework for a remote control approach of an industrial mobile manipulator for cleanroom environments is presented. This paper contributes to the work in the area of cleanroom robotic applications by a mixed reality (MR) teleoperation interface, which provides the opera-

2351-9789 © 2020 The Authors. Published by Elsevier Ltd.

10.1016/j.promfg.2020.10.087

tor with a sense of depth regarding the visual feedback from the workspace and natural hand-guided motion control, using consumer-grade VR hardware. The use of mixed reality for teleoperation of a mobile manipulator is a novel solution for cleanroom maintenance, repair and operations (MRO).

In section 3 the system framework and the implementation of the visual interface and control are described. The demonstration of the feasibility of the approach and results of the system performance test are presented in section 4 and section 7. Finally, the findings from the results and the reflections on the research on the developed teleoperation system are detailed in section 5, section 6 and section 7.

2. Background

Since the Oculus Rift's Kickstarter launch in 2012, the market for consumer VR has expanded. This has also led to an increase in academic research surrounding the use of AR/VR in robotics. Lipton et al. showed how their Virtual Reality Control Room was successfully used for teleoperation of manufacturing-related tasks over wired and wireless networks [9]. Similar research in mixed reality manipulator teleoperation has been conducted at Brown University [10, 11]. They have shown how many daily tasks, like folding clothes, can be successfully teleoperated through what they call a virtual gantry system. However, their control and visual feedback differ in that Lipton et al. uses an egocentric approach by having the operator inhabit the robot, virtually positioned inside the head of the robot. While, the researchers from Brown university took the robocentric approach of having the operator around an interactive 3D model of the robot with a superimposed point cloud of the robot and its surrounding environment, where the operator acts as a puppeteer. Both research groups use virtual reality and the Baxter dual-armed manipulators.

The use of AR/VR has also been appearing in research surrounding teleoperation of mobile manipulators. However, these systems are focused on military and construction applications. All of them make use of an egocentric approach, however, their controller approaches vary from haptic-controller [12], proprietary-controller [13], to VR-controller [14]. The use of mobile manipulator platforms for automation in industrial environments has been extensively investigated throughout the last decade [15, 16, 17]. However, these systems are either usually programmed for a specific sequence of operation or unsuitable for the context of a cleanroom application.

3. System framework

To complete the tasks of a human worker inside a cleanroom, three functional guidelines have to be tackled:

- The operator has to be able to manipulate the environment remotely
- Receive sensory feedback as a reference of the operated environment
- Moving between distinct areas of the cleanroom

To make the fulfillment of these guidelines possible, the design includes a robotic manipulator, multiple mono- and stereoscopic camera systems for providing visual feedback to the operator through the graphical user interface (GUI) and a mobile robot base for providing mobility. As the wiring of such a system would hinder the mobility, the communication has to be wireless between the operator's interface and the mobile manipulator.

The design is focused on an intuitive interfacing approach, both for manipulating and visualizing the teleoperated workspace. Based on the background research, commercially available VR equipment is considered to be suitable to create such an implementation.

The designed system (see Figure 1) is interpolating the VR controller's 6D pose into a trajectory for the end-effector of the manipulator. The MR interface incorporates multiple camera feeds from the mobile manipulator and also includes VR elements, such as buttons. These buttons provide the operator with additional functionalities, which are further detailed in subsection 3.3. Each of the individual stations has a dedicated webcam streamed to the GUI and optional control presets to choose from. The end-effector speed can also be limited by respective scaling factors, described in subsection 3.2.

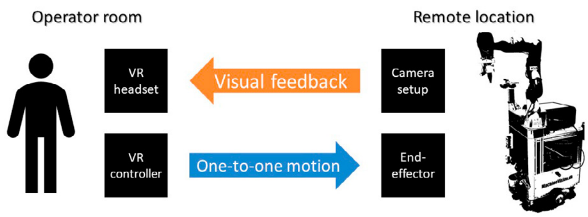

Fig. 1. Case scenario described, regarding the control (blue) pipeline and the visual feedback (orange) pipeline. The wireless feature allows for the mobile manipulator to be situated in a remote location (such as the sealed cleanroom production environment), meanwhile the operator is using the VR equipment in the dedicated control room.

3.1. System architecture

The framework for the hardware (see Figure 2) describes a slave-master relation between the operator's interface and the mobile manipulator. The solution is developed using a mobile manipulator platform (see Figure 3). The platform consists of a KUKA LBR iiwa 7 R800 manipulator, a Neobotix differential drive base MP655, a Schunk WSG 50-110 gripper, and the respective computers to control them. The Valve Index VR headset, the HTC VIVE controller and two HTC Base Station 1.0, are supported by a computer on the operator's side. This specific VR setup is capable of pose estimation with sub-millimeter precision [18]. The master computer is receiving wired camera inputs from the Logitech C922 webcams, one for each workstation, and three of them mounted onto the wireless mobile manipulator.

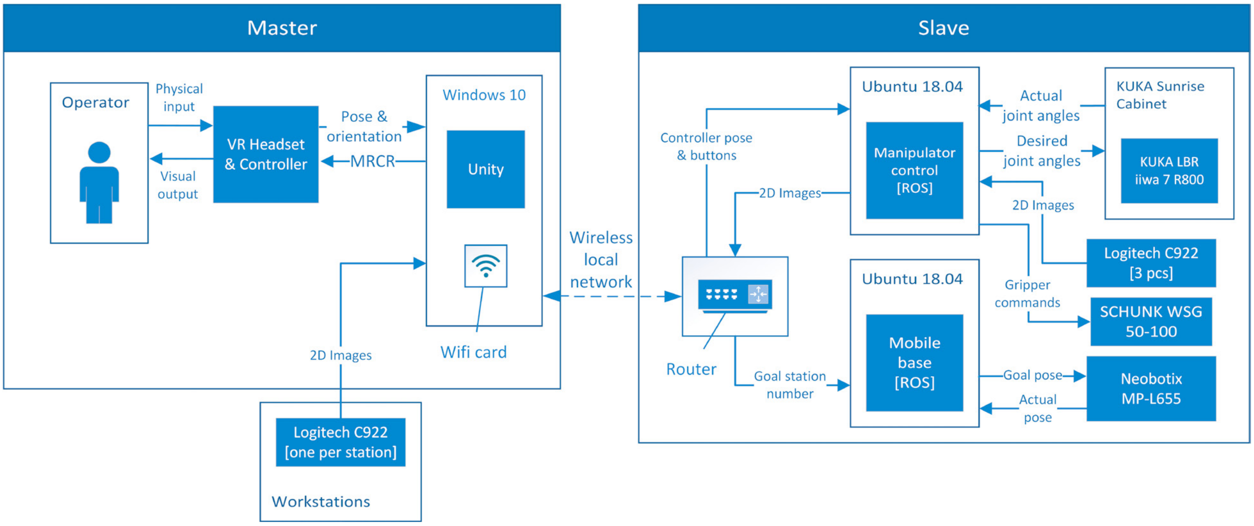

Fig. 2. System architecture design, separated into the two operational spaces, one facilitating the operator's control room and the other representing the remote workspace. The dash lines indicate wireless, the solid indicate wired connection. The lines linking the hardware components detail the information sent over the specific channel.

ROS (Robot Operating System) handles the majority of the data flow between the systems (see Figure 2), sending the controller inputs from Unity to the mobile base, the gripper, and the manipulator. The Unity project runs on the master Windows 10 computer and receives position and orientation data from the VR headset and controller. The controller's pose and button inputs are published to the slave computer, which translates these values to Cartesian coordinates for the end-effector and uses the button values for additional functionalities. These coordinates get processed by a MATLAB script, which sends the desired joint angles to the KUKA Sunrise Cabinet, which then actuates the motors. The webcam streams are transmitted with ROS topics to the GUI, over the wireless network. The workspace cameras are wired to the Windows 10 computer, as they are not required to be mobile. The Neobotix base is controlled through the GUI, where the operator can select the desired station, where the base autonomously navigates upon the choice.

Fig. 3. Hardware components of the system: Mobile manipulator platform (*left*), one instance of the Logitech C922 webcam (*top-right*), Valve Index VR headset and the HTC VIVE VR controller (*bottom-right*).

3.2. System control

To accommodate the desired functionality raised for the manipulator, namely to interpolate the VR controller's pose to the end-effector's trajectory, a control program is developed. The overall goal is to develop the real-time generation of the end-effector's trajectory based on the interpolation of the operator's hand pose. The solution results in one-to-one hand to end-effector motion, which is found to be an intuitive way of controlling the manipulator in this application.

The end-effector's trajectory is created by adding the accumulative difference of the VR controller's pose to the initial state of the end-effector. For both position and orientation, the difference between the consecutive VR controller pose readings is calculated and summed to the overall difference, which is then added to the initial pose to find the desired pose. The desired pose then, by the execution of inverse kinematics, provided by KST (Kuka Sunrise Toolbox) [19], sets the array of corresponding joint values for the manipulator.

For manipulation tasks requiring precision, motion scaling factor is introduced, since providing space for error is required, due to the inconsistency in hand motion. To deal with the inconsistencies in the motion of the hand, the trajectory is smoothed by filtering. Additionally, a *dead man's* switch is implemented to disassociate hand motion from the end-effector's trajectory and set it to stay still until the control is initiated again by pressing the trigger on the VR controller. This feature is considered to be useful for reconfiguring the hand when needed, or in the cases where it is required for the manipulator to stay static. Since the manipulator trajectory is fully reliant on the operator's hand motion, it is not prevented from damaging the surrounding objects. To reduce the forces that the manipulator would apply when in contact, spring-mass-damper behavior is imposed, resulting in a reduced initial force. The applied force grows with the increase of the offset, generated from the difference between desired and actual poses, according to Hooke's law. Kuka Sunrise OS provides an impedance controller to accommodate the mentioned spring-like behavior.

The solution developed is meant to change the station to accomplish different tasks that vary in complexity and characteristics. A seven degrees-of-freedom manipulator is capable of providing all of the three dimensional translational and rotational movement for the object it manipulates. However, it is be argued that it is more difficult to control for the operator, than a manipulator with fewer degrees of freedom [20]. The approach of the solution developed is to define the task-specific settings for the minimum necessary degrees of freedom that the operator needs to accomplish the task (e.g. total 3 degrees of freedom: X, Y, Z translation, with the orientation fixed perpendicular to the XY plane). This task-specific setting can be toggled 'on' and 'off' through the GUI, and it is different for each respective station. For switching between the stations, the Neobotix mobile base is utilized. The mobile base runs the `move_base` package in ROS. When Unity sends a new desired station for the mobile base to be at, its desired coordinate is set to the station's corresponding predefined coordinate in the map of the work environment. The mobile base uses AMCL (Adaptive Monte Carlo Localization) to position itself on the map. The `global_planer` package is used, which is based on the local minimap-free navigation function NF1. The local planner is based on the TEB (Timed-Elastic-Band) algorithm.

3.3. Visual interface

By using a Valve Index virtual reality headset, HTC Vive controller, and two base station 1.0 trackers, the operator remotely interacts with the production environment by controlling the robot using a MR interface developed in the Unity game engine. It is an operating environment with 3 virtual screen objects used for displaying different visual feeds, both 2D and 3D, from the robot and the workspace.

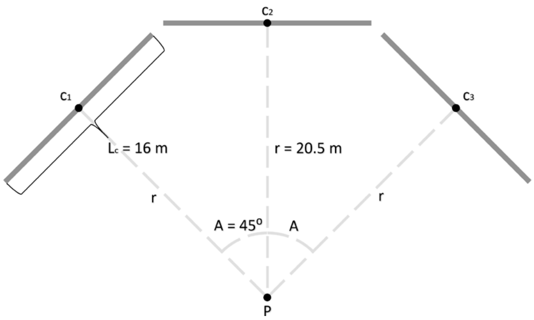

Fig. 4. The operators position P, is centered at an equal distance r, from the center of the three virtual screens c_1, c_2 and c_3.

Within the mixed reality control room, the operator is positioned with an equal distance to the center of each of the virtual screens. The dimensions of the screens are 16 x 9 meters in virtual space, as shown in Figure 4. The left screen displays the video feed from a single camera placed on the gripper. The right screen dynamically switches between displaying the video feed from the different workspace cameras, depending on the robot's current station. The middle screen displays the superimposed video feed from a stereoscopic camera setup, such that the left and right camera feed is displayed to their respective eye. The operator can interact with GUI elements positioned above the middle screen, shown in Figure 5. The GUI elements are interacted with through a virtual laser pointer controlled by the VR-controller. Specific functions are activated, when the laser and an interactive GUI button have contact for 2 seconds. The GUI elements consist of:

- **Speed**: displays the motion scaling factor, which can be changed using the VR-controller.
- **Station**: displays the current station ID. The station can be shifted by using the two adjacent interactive arrow buttons, transmitting a command for the mobile base to move to the new station.
- **Free/Func**: interactive buttons to switch between free movement and the task-specific setting for the given station.

Precise object manipulation requires a sense of depth of the environment since monocular depth estimations are inaccurate [21]. The camera setup of the mobile manipulator itself consists of 3 Logitech C922 webcams with a horizontal field-of-view of 70.42^o. A single webcam is attached to the gripper, while the remaining two webcams form a stereoscopic pair installed on the Neobotix base, which can be seen in Figure 6. Their optical axes are parallelly aligned 96 mm apart, which is 32 mm more than the average interpupillary distance of a human [22]. The larger interpupillary distance displaces the point of convergence slightly further away from the cameras' baseline, by approximately 23 mm. The difference is insignificant, as there is a distance of a minimum 400 mm between the baseline of the stereoscopic camera setup and the workspace.

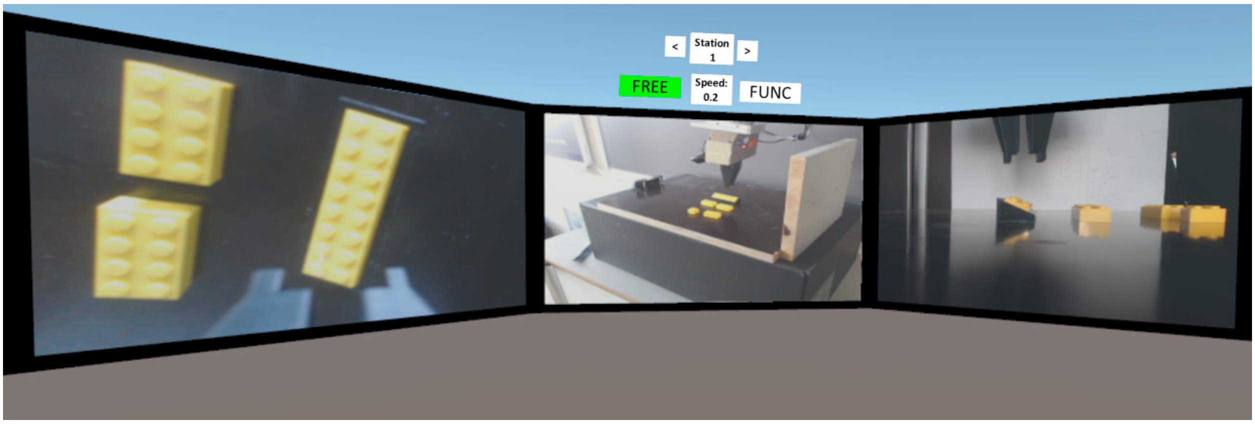

Fig. 5. The MR interface in Unity consists of: 2D display of gripper-view (*left*), 3D display of workspace-view from robot (*middle*), dynamic 2D display of workspace-view from current station (*right*) and GUI elements (*above middle*).

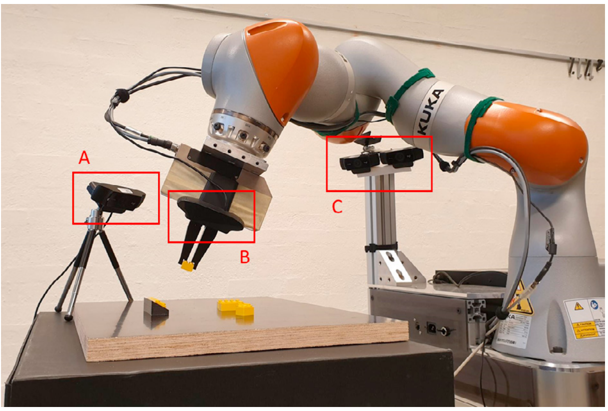

Fig. 6. Camera setup: (*A*) Workspace camera; (*B*) Gripper camera; (*C*) Stereoscopic camera setup. (*B, C*) are mounted onto the mobile manipulator.

4. Experiments and results

To prove the feasibility of the MR interface for teleoperation in a cleanroom environment, an experiment is conducted. The experiment consists of 3 steps:

1. Manipulation task at station 1
2. Navigation from station 1 to station 2
3. Manipulation task at station 2

The stations contain different manipulation tasks, that the operator accomplishes with the use of predefined task-specific settings. To accomplish the tasks, the operator is fully relying on the MR interface consisting of the GUI elements and various camera feedback. It is expected that the interface solution will provide the operator with a spatial understanding of each workspace and their respective components, allowing for unrestrained remote task fulfillment.

The simulated production process is the assembly of a simple LEGO structure, which is an analog of the task met at the

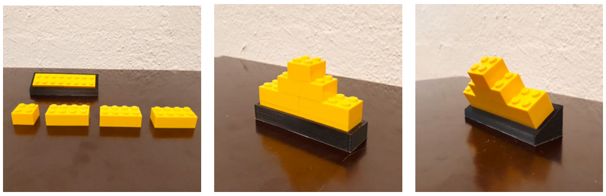

Fig. 7. Three BRICK2x4 and one BRICK2x2 used for test conduction (*left*), assembled structure for the horizontal fixture (*middle*) and assembled structure on a 30 degree slope (*right*).

cleanroom, for instance: disposing of glass shards, picking a fallen pill, or removing a stuck object. LEGO pieces are chosen for the uniformity, accessibility and they serve well for this test since the tolerance for imprecision to assemble the pieces is low. The LEGO structure consists of three BRICK2x4 and one BRICK2x2 shown in Figure 7. The structure needs to be built on both of the stations, for station 1 it is built perpendicular to the workspace surface, while for station 2 it is built on a 30^o slope. Fixtures are used for each of the workstations, as a base keeping the LEGO structure in a fixed pose. The operator is located outside of the simulated production environment.

A case-specific gripper for the task has been designed. As it can be seen on Figure 8, the tips are flat and parallel respective to each other. There is also an 8 mm indent introduced, to accommodate the LEGO bricks, without letting them slip further up the gripper.

One of the developers of the system was chosen to test the feasibility of the setup. It is argued that the system in the real application should be operated by a trained individual, therefore the test was conducted by a person experienced with the system. Before the conduction, LEGO bricks are placed at the workstation and oriented in a manner, as they would be used for building the structure, as shown in Figure 7. The robot initiates at station 1, where the operator remotely assembles the structure perpendicular to the workspace surface. After the first assembly, the robot traverses to station 2, where the operator

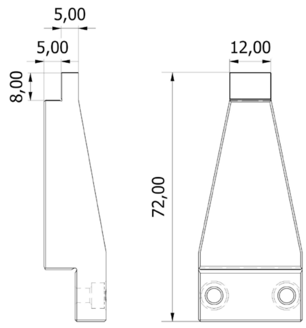

Fig. 8. Dimensions and design of the gripper.

assembles the structure on the sloped fixture, see Figure 7. The time to accomplish the individual assembly task is measured. The traveling time of the mobile base was considered irrelevant for the performance of this project, therefore it has been disregarded.

Over the course of 2 days, each of the respective tasks was conducted 15 times, resulting in a total of 30 timed assemblies. Each assembly was successfully carried out by the trained operator, without dropping or misplacing the LEGO pieces. The time spent for both assembly tasks during the particular runs is demonstrated in Figure 9. The average completion time for 3 degrees of freedom assembly in the perpendicular fixture reaches 1:10 minutes on average, meanwhile the more complex, by the required degrees of freedom, assembly task required 4:12 minutes on average.

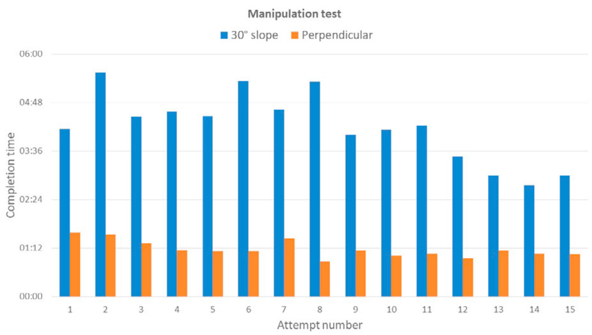

Fig. 9. Results of the test, (*orange*) executed on a fixture, perpendicular to the surface and (*blue*) on a fixture 30 degree slope. The fifteen attempts are in chronological order, and they represent the time required to complete the task.

5. Discussion

During the development of the system, the risk of failing the test by dropping the piece out of the workspace was identified. The situation could occur while imprecisely mounting pieces and applying too much force, which would result in the piece getting forced out of the gripper. However, the experiment shows the solution is feasible with no pieces dropped throughout the test runs.

The most difficult aspect for the trained operator was to orient the end-effector correctly. This was due to the VR controller's frame displacement away from the operator's palm. This means that for the operator to change the orientation of the end-effector without translating, it is needed to compensate for this misalignment. Another difficulty that the operator faced was the visual feedback's lack of detail. This was caused by the low resolution of the displayed camera feeds and inconsistent lighting, due to natural lighting.

The use of the VR controller gave the operator an intuitive sense of manipulator control. The proportional mapping from the precise pose estimation of the controller to the end-effector pose, made the trajectory generation seem cognitively undemanding. The motion scaling was crucial for the operator to perform the LEGO assembly since the one-to-one motion scaling did not provide a margin for motion error.

The virtually superimposed images (3D workspace-view from the robot) provided the operator with an understanding of the spatial relations between the gripper and the workspace, through the VR headset. However, the operator did not receive sufficient details of the LEGO bricks for the high precision moments of the assembly in the 6 degrees of freedom task. To compensate for the lack of detail, multiple cameras from different angles were used. A higher resolution for the 3D feed alone would provide the necessary visual feedback for the test, without the need for multiple cameras from different angles.

6. Future work

The system performance is highly dependent on visual feedback, as it is the main sensory input to the operator. The lighting of the environment was not accounted for during test performance, leading to varying illumination of the workspace. Future implementations will simulate the controlled lighting of cleanroom environments, to optimize for details of the workpiece. This will be valuable for both operator and computer vision applications. The implementation might also benefit from a decoupling of viewpoint, resulting in a *3rd person view*, where the user can interact with or move around the robot model and the workspace. The dynamic visualization of the working environment would provide different perspectives of the scene.

To create the ideal teleoperation interface for mobile manipulation, all sensory inputs expected by a healthy human sensory nervous system should be provided to the operator. Specifically, it would be beneficial to introduce haptic-, audio- and improved visual feedback. To alleviate the cognitive burden of controlling the system, some level of autonomy will be introduced. The instance of previous research to develop such implementation for mobile manipulators is the 'Skill-Based System' [23, 24], but it has not yet been used in a virtual reality environment. A mixed reality skill-based interface for programming would be a novel solution for handling unforeseen outcomes. With the expansion of possible tasks and outcomes, it might become necessary to investigate the possibility of using a dual-armed configuration for a mobile manipulator, which has been shown feasible for industrial settings [25].

7. Conclusion

This paper investigates and reports on the latest research in introducing a MR interface for mobile manipulators towards application in cleanroom applications. We report how a trained operator can employ a MR teleoperation interface for a mobile manipulator, to repeatedly succeed in high-precision assembly of a structure in different orientations. The test emulates an arbitrary manipulation task, within a production environment where human presence is undesirable. In the investigated cleanroom environments, safety, and precision outweighs speed-related performance. The test time might not be sufficiently fast to implement in a dynamic production environment, where swift interventions are crucial. However, the 100% success rate weighs higher than the average time of 1:10 and 4:12 minutes from the test, for the feasibility and reliability of multistation remote task handling in a cleanroom environment. Any future attempt on time reduction, should not have an adverse effect on the precision of the system.

The operator is provided with visual feeds from the gripper, robot, and the individual workspaces, giving an extensive spatial understanding of the workspace. The visual feedback in addition to the natural one-to-one trajectory control from the consumer-grade VR, allows the operator to freely assemble structures requiring high precision at multiple stations, from a remote location, without contaminating the environment. It is not only a novel teleoperation solution for cleanroom environments, but it also satisfies the requirement of reliable task completion.

References

[1] W. Whyte. "Assessing microbial risk to patients from aseptically manufactured pharmaceuticals", European Journal of Parenteral and Pharmaceutical Sciences, Volume 9, Number 3, Pages 71-77. 2004

[2] ISO 14644-1:2015. "Cleanrooms and associated controlled environments - Part 1: Classification of air cleanliness by particle concentration", International Organization for Standardization. 2015

[3] A. Quinto, J.C. Menezes. "Design, Validation, and Control of Sterile Manufacturing Facilities: A Brief Overview from the Perspective of Risk Management and Existing Regulations", Pharmaceutical Engineering, Volume 30, Number 2. 2010

[4] M.S. Favero, J.R. Puleo, J.H. Marshall, G.S. Oxborrow. "Comparative Levels and Types of Microbial Contamination Detected in Industrial Clean Rooms", Applied Microbiology, Volume 14, Number 4, Pages 539-551. 1966

[5] W.R. Hamel, P. Murray. "Observations concerning Internet-based teleoperations for hazardous environments", Proceedings 2001 IEEE International Conference on Robotics and Automation 2001, Pages 638-643 . 2001

[6] D. Drascic. "Skill Acquisition and task performance in teleoperation using monoscopic and stereoscopic video remote viewing", Proceedings of the Human Factors Society 35th Annual Meeting, Pages 1367-1371 . 1991

[7] A. Rastogi, P. Milgram, D. Drascic, J.J. Grodski. "Telerobotic control with stereoscopic augmented reality", SPIE Proceedings Volume 2653, Stereoscopic Displays and Virtual Reality Systems III, Pages 115-122 . 1996

[8] L.B. Rosenberg. "The Use of Virtual Fixtures as Perceptual Overlays to Enhance Operator Performance in Remote Environments", Technical Report AL-TR-1992-XXX, USAF Armstrong Laboratory, WPAFB OH. 1992

[9] J.I. Lipton, A.J. Fay, D. Rus. "Baxter's Homunculus: Virtual Reality Spaces for Teleoperation in Manufacturing", IEEE Robotics and Automation Letters, Volume 3, Issue 1, Pages 179-186 . 2018

[10] D. Whitney, E. Rosen, E. Phillips, G. Konidaris, S. Tellex. "Comparing Robot Grasping Teleoperation Across Desktop and Virtual Reality with ROS Reality", Springer Proceedings in Advanced Robotics, Volume 10, Pages 335-350 . 2020

[11] D. Whitney, E. Rosen, D. Ullman, E. Phillips, S. Tellex. "ROS Reality: A Virtual Reality Framework Using Consumer-Grade Hardware for ROS-Enabled Robots", 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems, Pages 5018-5025 . 2018

[12] V.H. Andaluz, W.X. Quevedo, F.A. Chicaiza, J. Varela, C Gallardo, J.S. Sánchez, O. Arteaga. "Transparency of a Bilateral Tele-Operation Scheme of a Mobile Manipulator Robot", 3rd International Conference on Augmented Reality, Virtual Reality and Computer Graphics, Pages 228-245 . 2016

[13] P. Tripicchio, E. Ruffaldi, P. Gasparello, S. Eguchi, J. Kusuno, K. Kitano, M. Yamada, A. Argiolas, M. Niccolini, M. Ragaglia, C.A. Avizzano. "A Stereo-Panoramic Telepresence System for Construction Machines", 27th International Conference on Flexible Automation and Intelligent Manufacturing. Procedia Manufacturing, Volume 11, Pages 1552-1559 . 2017

[14] T. Kot, P. Novák. "Application of virtual reality in teleoperation of the military mobile robotic system TAROS", International Journal of Advanced Robotic Systems, Volume 15, Issue 1 . 2018

[15] C. Schou, R.S. Andersen, D. Chrysostomou, S. Bøgh, O. Madsen. "Skill Based Instruction of Collaborative Robots in Industrial Settings", Robotics and Computer-Integrated Manufacturing 2019, Volume 53, Pages 72-80 . 2018

[16] P.J. Koch, M.K van den Broek, P. Dębska, M.A Thormann, A.J. Tetzlaff, S. Bøgh, D. Chrysostomou. "A Skill-based Robot Co-worker for Industrial Maintenance Tasks", 27th International Conference on Flexible Automation and Intelligent Manufacturing. Procedia Manufacturing, Volume 11, Pages 83-90 . 2017

[17] R.E. Andersen, E.B. Hansen, D. Cerny, S. Madsen, B. Pulendralingam, S. Bøgh, D. Chrysostomou "Integration of a Skill-based Collaborative Mobile Robot in a Smart Cyber-Physical Environment", 27th International Conference on Flexible Automation and Intelligent Manufacturing. Procedia Manufacturing, Volume 11, Pages 114-123 . 2017

[18] M. Borges, A. Symington, B. Coltin, T. Smith, R. Ventura. "HTC Vive: Analysis and Accuracy Improvement", 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems.

[19] M. Safeea, P. Neto. "KUKA Sunrise Toolbox: Interfacing Collaborative Robots With MATLAB", IEEE Robotics Automation Magazine, Volume 26, Pages 91-96 . 2018

[20] C.E. Mower, W. Merkt, A. Davies, S. Vijayakumar. "Comparing Alternate Modes of Teleoperation for Constrained Tasks", 2019 arXiv:1905.04428

[21] S.P. McKee, D.G. Taylor. "The precision of binocular and monocular depth judgments in natural settings,"Journal of Vision, Volume 10, Issue 10

[22] C.C. Gordon, C.L. Blackwell, B. Bradtmiller, J.L. Parham, P. Barrientos, S.P. Paquette, B.D Corner, J.M. Carson, J.C. Venezia, B.M. Rockwell, M. Mucher, S. Kristensen. "2012 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics", United States Army Natick Soldier Research, Development and Engineering Center. 2012

[23] R.S. Andersen, S. Bøgh, T.B. Moeslund, O. Madsen. "Intuitive task programming of stud welding robots for ship construction", 2015 IEEE International Conference on Industrial Technology, Pages 3302-3307 . 2015

[24] R.S. Andersen, S. Bøgh, T.B. Moeslund, O. Madsen. "Task Space HRI for Cooperative Mobile Robots in Fit-Out Operations Inside Ship Superstructures", 25th IEEE International Symposium on Robot and Human Interactive Communication, Pages 880-887 . 2016

[25] J. F. Buhl, R. Grønhøj, J. K. Jørgensen, G. Mateus, D. Pinto, J. K. Sørensen, S. Bøgh, D. Chrysostomou. "A Dual-arm Collaborative Robot System for the Smart Factories of the Future", 29th International Conference on Flexible Automation and Intelligent Manufacturing. Procedia Manufacturing, Volume 38, Pages 333-340 . 2019