Proceedings of the ASME 2022 International Mechanical Engineering Congress and Exposition
IMECE 2022
October 30 – November 3, 2022, Columbus, Ohio, USA

IMECE2022-94305

SMA-BASED HAPTIC GLOVES USAGE IN THE SMART FACTORY CONCEPT: XR USE CASE

Rupal Srivastava[*]
SFI Confirm Smart Manufacturing
Materials Research Institute
TUS: MM
Athlone, Ireland
rupal.srivastava@tus.ie

Vladimir Kuts[*]
SFI Confirm Smart Manufacturing
Department of Electronic
Computer Engineering
University of Limerick
Limerick, Ireland
vladimir.kuts@ul.ie

Eber Lawrence Souza Gouveia
Materials Research Institute
TUS: MM
Athlone, Ireland
A00289880@student.ait.ie

Niall Murray
Department of Computer
and Software Engineering
TUS: MM
Athlone, Ireland
nmurray@research.ait.ie

Declan Devine
Materials Research Institute
TUS: MM
Athlone, Ireland
ddevine@tus.ie

Eoin O'Connell
Department of Electronic
Computer Engineering
University of Limerick
Limerick, Ireland
Eoin.OConnell@ul.ie

ABSTRACT

Conceptualization of the Smart Factory started with introducing the Industry 4.0 paradigm and its nine pillars, which it stands. The paradigm itself is automation and robot-centric focused, which means less and less involvement of the humans on the manufacturing shop floor. However, even robots and simulation aspects of the factories are the most crucial aspects; Industry 4.0 still focuses on the Augmented and Virtual Reality (AR and VR input methods for the human operators, making the smooth transition to the Industry 5.0 concept a human-centric. Although VR/AR is still being enabled and widely used in the Human-Robot Interaction (HRI) research aspect, the heavy headset is limited in the observation field of view. The input methods, such as headsets, have voice and gesture recognition; however, those are mainly limited by factory noise and cameras pointing to the human hands. These headsets constrain the use of smart wearables to a given boundary inside the factory environment. A Shape Memory Alloy (SMA) based haptic glove with discrete data outputs from the kinaesthetic analysis of the hand bending can remove the need for gesture recognition. The paper proposes a modular framework using the SMA-based Haptic Gloves in the Smart Manufacturing environment. These gloves, without additional wearables, can enable interactions with heavy machinery, screens, and all other assets of the industrial area, even with holographic. In this paper, the authors aim to prose the context, design, and framework with the chosen use-cases mainly based on the robotic system applications in the Technological University of the Shannon: Midlands Midwest (TUS: MMW), Ireland, and Tallinn University of Technology (TalTech), Estonia.

Shape Memory Alloy, Haptics, Industry 5.0, Industrial Robots, Human-Robot Interaction

---

[*] Marie Sklodowska Curie Fellow-Smart4.0
Marie Skłodowska-Curie Grant co-funded by the European Regional Development Fund and Science Foundation Ireland (SFI)

1 Introduction

Robotics and Automation (RA) are critical paradigms of Industry 4.0 in the modern manufacturing industry. Industry 4.0 is and has brought about massive changes via its nine technological pillars [1]. One of these pillars, robotization, has brought significant industry benefits and fear from the public perception perspective (job losses). Besides, interfaces and interactions between human and robotic systems have many issues. Whereas I4.0 focused on Cyber-Physical Systems (CPS) and digitalization, Industry 5.0 aims to bring humans back into the loop from the perspective of human-robot collaboration. The aim is to delete a barrier between robotic and human routines in manufacturing. Such routines can be achieved simultaneously, in parallel, and collaboratively. Thus, Industrial robotics in both revolutions is a critical enabling technology that allows enterprises to innovate while improving their business performance. Robotics and automation comprise an interdisciplinary technology stack that links mechanical engineering, electrical engineering, and information communication technology (ICT). From a pragmatic perspective, different methods of programming and integration are used to add robotic systems to the manufacturing process flow with the aim of automation. There are three primary methods employed for Industrial Robot programming [2]:

1. Offline method – every large manufacturer has its software tool for programming the robot. Every step can be simulated, performed, and downloaded to the robot controller.
2. Manual method – using flex-pendant by operator gives an intuitive and real-time feeling of what is happening with the machine.
3. Online method – robot controller connected to the external control unit, which affects robot movement online, interrupting or re-writing performed by robot task.

Analysis of the different programming methods highlights that each method demands specific skills and in-depth knowledge about machinery. To date, a narrow and fragmented approach has emerged, focusing on specific robotics systems and tasks and not much focus on the process. As a result, there is a lack of transparent and intuitive robot control and interaction methods [3]. Moreover, those methods are mainly for single robot user control and lack support for multi-robot systems management in real-time and collaboration with the human stakeholder. Moreover, the HRC ISO standard controls and regulates the abovementioned robot programming methods for safe and reliable co-work between the operator and the machine [4]. Automation equipment like industrial robots (IR) must operate efficiently for the manufacturing process while being safe for a human operator. HRC is accepted as the most crucial aspect of the Industry 5.0 concept. HRC will be centered on the personalization of the interaction and thus will be user-centric. This should be simulated precisely to enable integration and testing of various HRI methods, not harming and avoiding mistakes in human experiments. Simulations through VR and digitalization have been a successful aspect of Industry 4.0. In order to be ready for Industry 5.0, it is crucial to understand human behavior patterns near heavy machinery in terms of HRI. This brings us to the different ways of interaction with the machinery, such as Virtual/Augmented Reality and Haptic devices.

As we entered Industry 4.0, the need for novel Human-Machine Interaction (HMI) methods became vital. The initial work in the field to inspect all production phases, trace, and manage through remote-controlled HMIs was discussed by [5]. The shop floor control was introduced through programmable logic controllers and data acquisition systems, and the future of the control systems using sensors for automatic calibration and diagnosis was further proposed. Prior to direct control of automation and manufacturing through HMI, there have been several hierarchical models [6] and object-oriented modeling for robotic flexible manufacturing cell (FMC) [7], [8]. In the mid to late 2000s, direct human-robot contact in the industrial environment became the essential research domain; voice-based [9], and gesture-based [10] recognition of commands for industrial robot control was explored. While the former was focused on pick-and-place commands for the industrial robot, visual identification was developed to spot human presence in the robotic work area, and possible pick-and-place commands through finger-pointing-like gestures. The next generation of HMI concepts moved further into the realm of robotics and focuses on an immersive human-robot interaction, and the voice and gesture-based recognition methods pose a challenge through feasibility, high noise, and constrained access. One of the earliest concepts was given in this field employing *man-machine interface* using projective virtual reality for intuitive control of a multi-robot system [11]. The authors further worked in the field and proposed several concepts and experiments focusing on automatic action planning in a virtual environment [12], [13].

Next, the smart factory concept moved to sensory and haptic feedback for several workplace tasks. In the mid-1990s, a human factor study evaluating the effect of sound feedback on the work of a plant operator was carried out [14]. During the mid-2000s, the effectiveness of several feedback methods, haptic feedback, sensory augmentation, and sensory substitution on participants doing clockwork assembly tasks was analyzed [15]. The late 2000s brought further proofs-of-concept wherein augmented reality was used to manipulate tasks and create a haptic-based virtual environment for mostly pick-and-place applications [16], [17]. More recently, the focus has not only shifted to the inclusion of haptics in smart factory-based virtual environments [18], [19], but also on the ergonomics and conformability of the haptic device and the evaluation of best sensory feedback for the workers [20], [21]. As within mentioned robotic systems, Haptic devices also need to be tested within the simulations, and technology that gives the immersive surrounding to the user are the Virtual and Augmented reality technologies.

Widely, VR is considered glass for entering digital worlds to feel a presence somewhere out of reality. However, this statement is misguiding. VR is a digital world that is created with the help of software and hardware. It is not necessary to use a headset to enter. Every computer game that has been done in the past and done in the future is a VR environment. However, a headset adds presence to the simulation in this world and helps one feel the surroundings of digital representations in an immersive and more precise way [33]. VR headset technologies have existed since 1965 and were created by Ivan Sutherland [34]. Research has been done by different institutions and authors since. However, the main so-called boom and development came simultaneously as the Industry 4.0 revolution, as headsets such as Oculus and HTC Vive were developed for the consumer public. For the related research, the VR domain is of interest from two perspectives: industrial and education/demonstrational:

1. Industrial usage: many well-known equipment brands use VR to show production simulations and even robot offline programming tools from the inside, simulating presence [35]. There is a more detailed investigation for DT simulations, changing the layout and monitoring data flow from the inside and robotic arms and mobile robotic systems control via telepresence simulations.
2. Education, research, and training: usage in educational institutions and training facilities within developed scenarios of the learned domain– guidelines, troubleshooting, construction, collaboration, and teaming with robots.

The concept of augmented reality (AR) in the field of smart manufacturing can date back to 1992, wherein the authors described a HUDset, a see-through head-mounted display for aircraft manufacturing applications [22]. More recently, to create safer environments, the focus has moved on to collating data for high-risk conditions and using this data in real-time to guide the users through the spatial data of the environment, thus helping them with unfamiliar tasks [23]. Further work has been done on human-robot interaction in an augmented environment for manufacturing or industry setup, thus blurring the boundaries between the real and virtual [24], [25], [26]. The applications of the augmented reality-based human-robot interaction approach in the field of smart industries are not limited to manufacturing or pick-and-place applications [27]. The applications range from quality assessment [28], maintenance [29], sustainability and optimization study [30]. A further step in Augmented or Extended Reality takes us to the Virtual Environment.

VR (Virtual Reality) headset usage is essential for person precision simulation in different environments. Moreover, most immersive experiences are being developed in so-called Game Engines such as Unity3D, Unreal Engine 4, and CryEngine. These allow additional functionalities such as a multiplayer mode, which is a multi-user connection to one environment, not limited to a regional location [36]. This functionality is being integrated, utilizing gamification in various domains [37], [38]. We take the best of both worlds and try and create a haptic feedback-based environment as an extension of its real-world counterpart for smart industry applications.

In this article, the authors propose the modular framework using the SMA-based Haptic Gloves in the Smart Manufacturing environment. These gloves, without additional wearables, can enable interactions with heavy machinery, screens, and all other assets of the industrial area, even with holographic. The proposed design also discusses the user's location, calibrates the data to the comprehensive factory assessment data, and identifies hazardous hotspots to work as an alarm for the worker for proactive injury prevention and situational awareness. This concept can be explored further for a remote on-the-job training tool for hands-free training on-site in immersive task simulations. Non-touching design is crucial in scenarios such as the recent COVID19 spread and reduces surface transfer-based diseases. Another field where the authors find this technique a vital application is in hazardous conditions, where human involvement and interaction with the environment must be minimized to a large extent.

The paper's main aim is to introduce a framework for utilizing the haptic gloves together with extended reality solutions to enable remote teleoperation of both virtual assets and physical machinery. The paper is structured as follows: Section 2 presents the system architecture and framework of the solution, describing the three main layers as manufacturing unit, haptic, and extended reality representation. Section 3 aligns the chosen use-cases with the proposed framework, and Sections 4 and 5 discuss on system overall and state the future directions within the conclusion of the manuscript.

2 System Architecture and Proposed Framework

The proposed framework combines the individual research at the Technological University of the Shannon: Midlands Midwest, Ireland (TUS, previously Athlone Institute of Technology), and Talinn Institute of Technology, Estonia (TalTech). The assembly line at TUS focuses on multiple pick-and-place robots working over multiple assembly lines. The research aims to optimize and create a seamless pick-and-place environment, thereby reducing human involvement as much as possible. This requires reinforcement learning and multi-robot collaboration and includes remote or autonomous control of the robotic arms if required. For this purpose, at TUS, we have another aspect to the project: designing and developing a shape memory alloy embedded hand exoskeleton or smart glove. This smart glove sends relevant actuation commands to the robotic arm by recognizing the finger movements and using the kinaesthetic feedback as signals for robotic arms. Further, it is proposed that the glove be fitted with ERM (Eccentric Rotating Mass) actuators at the tip of the fingers, and corresponding pressure sensors will be attached to the robotic grippers. This will then complete the open-loop problem, and the user will be able to send commands to the robotic grippers and sense the object gripped and the intensity of the grip. This further resolves the issue of how much force is required to lift delicate, heavy, or inconsistent in shape, size, or mass objects.

At TalTech Industrial Virtual and Augmented Reality Lab [31], the researchers have created an augmented environment to interact with the robots in virtual or extended reality. The machinery can be controlled by virtual interfaces such as VR, AR, PC, and mobile applications. All applications are being synchronized between each other and physical representations of their digital machinery. From these applications, it is possible to observe and monitor the manufacturing equipment layout and watch the machines work online. Further, the operator or user can take over the control of one or more units and either reprogram it or move around. Hence, giving the task-based signals to machines with a predefined delay or nearly in real-time.

The outline for the proposed conceptual framework is shown in Figure 1. Here, the idea is to establish a seamless environment between the real and virtual environment wherein a haptic glove is integrated to control the real-world pick-and-place robotic gripper and the extended reality. This minimizes the boundary between the two environments, thus taking this concept into the realm of Smart Factory and Industry 4.0. The three essential parts of the architecture are discussed in detail in the following sections.

2.1 Pick-and-Place Multi-Robot Assembly Line

The assembly line is in the physical layer side of the system framework and is composed of a robotic arm with an attached two-fingers End-effector, a 3D scanner, and a conveyor belt. The ABB's IRB 1200 robotic arm is the component responsible for the navigation between different system parts. This robotic arm uses the Gimatic's PB-0013 pneumatic two-finger gripper as End-Effector to grab objects placed on the conveyor belt, allowing the object displacement to any subsequent part of the system. The Phoxi 3D Scanner from Photoneo is parallel to the robotic arm, completing the assembly line on the physical layer. This scanner is responsible for obtaining the point cloud of the objects and transferring it digitally to the system control scripts. Figure 2 exemplifies the interconnection of these system components for operating collaboratively during a pick-and-place task.

The 3D scanner is connected to the computer via a LAN port, allowing the obtaining the point cloud using ROS services and topics. Further, such a point cloud might be loaded into Rviz for the data visualization in real-time. The point cloud generated by the 3D scanner is vital to the next steps of the assembly line since this data is used to obtain the object coordinates and define the best approach to pick this target object. Although it has not been shown in Figure 2, the IRC5 compact controller is another core component of the framework since it is responsible for sending commands to the robot through RAPID code. However, the robotic arm navigation must be planned and executed using ROS and MoveIt. In this way, the robot setup is divided into two steps. First, the controller is connected to the computer via a Local Area Network (LAN) port. Second, the ROS-Industrial package is used to write/read data of the robotic arm via a socket connection between Python and RAPID scripts, allowing the robot visualization and control in real-time using ROS packages. Moreover, the IRC5 controller can handle external circuits through its I/O ports, such as the gripper's pneumatic valve, the conveyor belt on/off, and the sensors.

2.2 SMA-based Haptic Glove

The second essential aspect of the proposed framework is the smart glove integrated with the pick-and-place multi-robot assembly line. Apart from the 3D scan mechanism, we propose a shape memory alloy-embedded haptic glove which works based on binary data commands extracted through the kinaesthetic feedback from the movements of the fingers. SMA embedded structures have previously been explored to achieve morphing behavior upon thermal actuation of SMA by the process of shape memory effect [32]. Here, the pseudoelastic behavior of the SMA is made use of to ensure no change in shape upon finger movements. The SMA wires are fixed at one end of the finger, and another is connected to the potentiometer, giving the finger bending angle as voltage output. This output is then sent to the robotic gripper to convert into grasp or open finger conditions. Furthermore, the tips of the robotic grippers have pressure sensors attached to them which send the amount of pressure applied by the grippers on the object picked to the smart gloves. In return, the tips of the gloves are embedded with Eccentric Rotating Mass (ERM) actuators. These actuators spin based on the input received from the pressure sensors at the robotic gripper end. Thus, the stronger the grip, the higher the spin rate. Another feedback for the user is visual. Hence, the visual feedback combined with the haptic feedback will strongly act as a seamless and organic integration of the smart glove with the multi-user-multi-robot case in a Smart Factory concept.

We further extend this concept to the extended reality and utilize the data from the finger bending as input for open-close commands for the robotic gripper and the pressure sensor data for haptic feedback on the tip of the fingers.

2.3 Extended Environment for Haptic Glove-Robotic Gripper Integration

The main idea of the extended reality environment is to develop the digital representation of virtual manufacturing and be able to control it from remote distances. The central aspect of Digital Twin is to be able to make a decision in simulation based

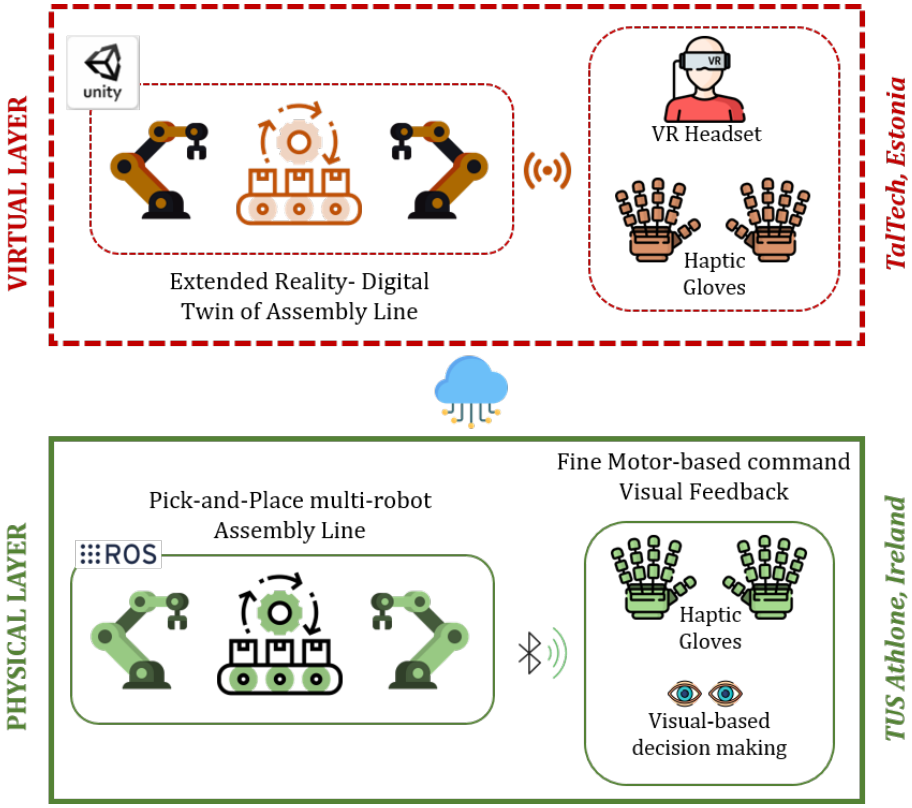

FIGURE 1. The architecture of the proposed conceptual framework in the robotic assembly line Cyber-Physical system.

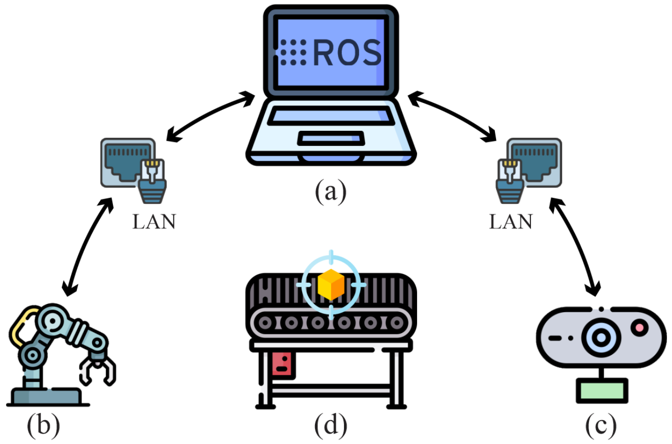

FIGURE 2. Schematic showing the core components of the assembly line: (a) A computer for running the ROS scripts and sending/receiving data from the peripherals sensors and components, (b) IRC1200 robotic arm plus the pneumatic two-fingers gripper, (c) PhoXi 3D Scanner, and (d) conveyor belt.

on the data fed from the physical equipment. The framework proposed in this paper expands the idea to the teleoperation part of what was done in previous work of authors [2] and expands it with additional input methods besides VR hardware as haptic devices described in the previous sub-section. The digital representation consists of the next parts:

1. Precise representation of the manufacturing unity of TalTech Industrial VR and AR Laboratory where the setup includes: Flexible Manufacturing System (FMS (See Fig. [4])- automatic warehouse, milling machine, industrial robot, and Mobile robot), Motoman, ABB, Omron Industrial robots, Robotnik and a custom-made mobile robot, conveyors, and office equipment.
2. Enabled XR functionality: ability to manipulate virtual equipment from VR and AR headsets (and mobile apps).
3. Synhronizisation system: based on the Robot Operation System (ROS): middle-layer for synchronization of virtual equipment with the physical.
4. Modular scripts and packages based on Unity3D: multi-user, control elements, and user interface (UX/UI) options.

For the proposed architecture, the aim is to add to the existing digital representation of the lab and the additional robot to simulate the SMA-based haptic glove's functionality. This way, the virtual and physical laboratory of TalTech is connected with

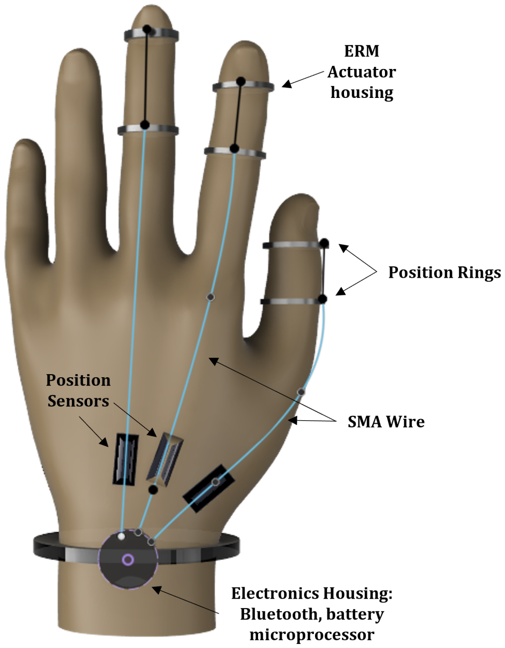

FIGURE 3. The proposed SMA-based haptic glove for integration with the Robotic Cell and Augmented Environment.

the physical representation of the ABB Robot placed in TUS. Haptic gloves can be used autonomously while located remotely in the VR application to simulate the control through ROS of the virtual and physical environment. Moreover, simultaneously, the physical equipment can be controlled from multiple locations.

3 Framework integration of the chosen use-cases

The proposed use case is based on the described assembly line in Section 2.1. As shown in Figure 5, the system consists of three parts: The robotic arm, a 3D scanner (which can play the camera role), and a two-finger gripper. The system is used to detect the object via camera and navigate the robot manipulator to grab the given object and use it for assembly or relocation. This concept can also be used alternatively in cases where the object for the pick-and-place is of unique shape, weight, or dimension, wherein the scanning method may not entirely work. In such cases, human involvement will give a better understanding and more accessible pick-and-place. The haptic feedback will also allow the user to understand the force exerted by the gripper on the object to carry on the task. This will further add to the sensitivity of the system.

The figure shows that the system consists of physical and virtual parts. The given use-case works as follows: the physical camera detects the object and gives the image to the virtual, which solves the kinematics of the industrial robot with the attached tool and sends the joint states to the physical robot. Thus, giving the command for the execution of the handling of the object. The integration of the proposed framework within the given use case is planned to export visual representation to the XR-enabled tool, including the stream from the camera. As the robot is being trained for each case to solve the task, the haptic device can be used as an assisting tool, enabling learning from the demonstration concept. Human operators can remotely solve the task for the robot, assisting in appropriately placing the tool and manipulating it in the correct direction. Users in XR can handle virtual objects with hands using three fingers simulating the gripper. The authors also propose a data collection mechanism that can determine the user-friendliness of the glove in the extended reality environment. A further homogenized and seamless virtual reality control environment can be devised by understanding primary performance metrics such as the learning curve, ease of access, and ease of use. This data can be collated and shared among designers and engineers as a tool for further development.

TABLE 1. Advantages and identified Limitations of the proposed system architecture

Advantages	**Limitations**
The safe and intuitive way of the control for the assembly line and the manufacturing unit.	*Latency: the possible lag for the user can change the whole experience of the control of the assembly line.*
The distributed multi location network gives the ability to test haptic devices both with the physical assemblies and their simulated counterparts.	*Covid19 restrictions can limit the amount of the users to be available for the system test.*
Data collation and calibration to identify possible limitations in the design can help determine more productive assembly lines.	*Various system data sources should be interpolated and converted to the unified format for the dual-way intercommunication.*

FIGURE 4. The virtual representation of Flexible Manufacturing System at TalTech, Estonia.

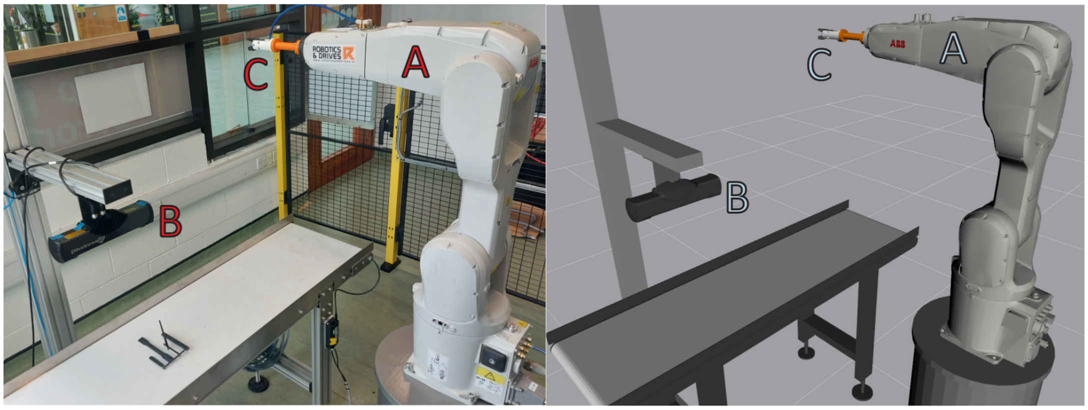

FIGURE 5. Physical layer at TUS, Ireland (left) and its digital representation inside Rviz visualizer (right). (A) The robotic arm, (B) the 3D scanner, and (C) the two-finger gripper.

4 System Advantages and Limitations

This section lists the system's possible shortcomings and advantages based on the proposed architecture and framework, description of the sub-systems, and the given use case. Moreover, this system presents the future developments of the proposed solutions. The current section presents the proposed system's possible limitations based on the given-use case and the system's advantages for manufacturing users. The simple and minimalistic design of the SMA-based Haptic Glove creates a safe wearable for its integration with heavy-duty industrial robots. The tension in the wire upon finger movement gives a resistive pull to the finger, thus creating an intuitive device for the user. Since the proposed framework takes the physical counterpart from TUS, Ireland, and the virtual counterpart from TalTech, Estonia, this multi-location network enlarges the domain of the usage of the haptic glove. Further, the authors have also proposed using the haptic glove for data collection. This will include collecting user training data, calibration time and sensitivity data, and other data based on human-robot interaction. The collected data can be used to analyze the efficient methods, optimize production, and identify user training methods.

Table 1 collates the identified significant advantages and limitations of the framework. In addition to the major points shown in the table, the authors predict that the proposed architecture will further improve the working environment during the Covid19 restrictions. The restrictions will limit the number of users; however, it will ensure continued work-from-home with minimum human interaction with each other. Hence, this limitation can also be a blessing in disguise in pandemic-like conditions. The current framework does not include a multi-robot collaboration setup using the smart glove. In such cases, the utility of the smart glove will be limited to one user controlling one robot. A possible lag between the input and output of the command between the user and the physical/virtual environment robot is anticipated. This issue can, however, be handled through multiple user training, thus embedding the lag as a part of the structure and helping the user/operator adjust and acclimatize to it. Finally, the data input/output web should be simplified to ensure a smooth work structure.

5 Conclusions and Future Work

The paper introduces a framework for utilizing the SMA-based haptic glove together with extended reality solutions to enable remote teleoperation of both virtual assets and physical machinery. Moreover, a use case that is ready for integration is being proposed. Further development will mainly be placed on the prototype development and user tests meanwhile improving the quality of the user experience. It is envisaged that the proposed conceptual framework will not only help with the manufacturing line but will also work as a training tool and data collation method for the users. The training tool, combined with the collected data regarding the user-friendly nature of the framework, will help us reassess the manufacturing line and keep track of productivity. In the future, it will also help develop enhanced working conditions, thus directly leading to higher output and more user-friendly.

Considering the estimated limitation of the proposed systems and the given use case, the main future developments will be:

1. The working prototype preparation will consist of three layers: assembly line, haptic device, and extended reality application. All those parts are separated in a working state; however, further work will be done to unite those together.
2. User tests with both general and expert groups from the Quality of Experience point of view to validate the shortcomings of proposed input and interfaces for the further improvements
3. The optimisation of the control algorithms and latency of working prototype.

Acknowledgment

This research was funded by Marie Skłodowska-Curie grant agreement No. 847577, co-funded by the European Regional Development Fund and Science Foundation Ireland (SFI) under Grant Number SFI/16/RC/3918 (CONFIRM).

REFERENCES

[1] i-SCOOP, ”Industry 4.0: the fourth industrial revolution – guide to Industrie 4.0,” 6 January 2019. [Online]. Available: https://www.i-scoop.eu/industry-4-0/Industry$_{4}0_{i}s_{n}ot_{j}ust_{a}bout_{f}actories_{a}nymore$.

[2] Kuts V., Sarkans M., Otto T., Tähemaa T., Bondarenko Y. ”Digital Twin: Concept of hybrid programming for industrial robots – Use case” ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), 2019, 2B-2019, DOI: 10.1115/IMECE2019-10583

[3] J. A. Marvel, S. Bagchi, M. Zimmerman, and B. Antonishek, ”Towards Effective Interface Designs for Collaborative HRI in Manufacturing,” ACM Trans. Human-Robot Interact., vol. 9, no. 4, pp. 1–55, 2020, DOI: 10.1145/3385009.

[4] ISO/TS 15066:2016, “Robots and robotic devices — Collaborative robots”, 2016 [Online]. Available: https://www.iso.org/standard/62996.html

[5] K. Astrom, ”Process control–Past, present and future,” in IEEE Control Systems Magazine, Volume 5, No. 3, Pages 3-10, August 1985, DOI: 10.1109/MCS.1985.1104958

[6] Gau Rong Liang, ”A Hybrid Model of Hierarchical Control Architecture in Automated Manufacturing Systems,” Editors: Michel Cotsaftis, François Vernadat, Manufacturing Research and Technology, Elsevier, Volume 16, 1993, Pages 277-286, DOI: 10.1016/B978-0-444-89856-2.50030-2

[7] Li Lin, Masatoshi Wakabayashi, Sadashiv Adiga, ”Object-oriented modeling and implementation of control software for a robotic flexible manufacturing cell,” Robotics and Computer-Integrated Manufacturing, Volume 11, Issue 1, 1994, Pages 1-12, DOI: 10.1016/0736-5845(94)90002-7

[8] J.Norberto Pires, J.M.G. Sá da Costa, ”Object-oriented and distributed approach for programming robotic manufacturing cells,” Robotics and Computer-Integrated Manufacturing, Volume 16, Issue 1, 2000, Pages 29-42, DOI: 10.1016/S0736-5845(99)00039-3

[9] Norberto Pires, J. (2005), ”Robot-by-voice: experiments on commanding an industrial robot using the human voice,” Industrial Robot, Vol. 32 No. 6, Pages 505-511, DOI: 10.1108/01439910510629244

[10] S. van Delden and M. A. Umrysh, ”Visual detection of objects in a robotic work area using hand gestures,” 2011 IEEE International Symposium on Robotic and Sensors Environments (ROSE), 2011, Pages 237-242, DOI: 10.1109/ROSE.2011.6058529

[11] E. Freund and J. Rossmann, ”Intuitive control of a multi-robot-system by means of projective virtual reality,” 1996 IEEE/SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems (Cat. No.96TH8242), 1996, Pages 273-280, DOI: 10.1109/MFI.1996.572188

[12] E. Freund and J. Rossmann, ”Intuitive control of a multi-robot-system by means of projective virtual reality,” 1996 IEEE/SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems (Cat. No.96TH8242), 1996, Pages 273-280, DOI: 10.1109/MFI.1996.572188

[13] E. Freund, J. Rossmann and K. Hoffmann, ”Automatic action planning as a key to virtual reality-based man-machine-interfaces,” 1996 IEEE/SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems (Cat. No.96TH8242), 1996, Pages 647-654, DOI: 10.1109/MFI.1996.572242

[14] Rauterberg M., Styger E., ”Positive effects of sound feedback during the operation of a plant simulator,” In: Blumenthal, B., Gornostaev J., Unger C. (eds) Human-Computer Interaction. Lecture Notes in Computer Science, Vol 876. Springer, Berlin, Heidelberg, EWHCI 1994, doi: 10.1007/3-540-58648-224

[15] Bernd Petzold, Michael F. Zaeh, Berthold Faerber, Barbara Deml, Hans Egermeier, Johannes Schilp, Stella Clarke, ”A Study on Visual, Auditory, and Haptic Feedback for Assembly Tasks,” Presence: Teleoperators and Virtual Environments 2004; 13 (1): 16–21, DOI: 10.1162/105474604774048207

[16] Valentini, P.P., ”Interactive virtual assembling in augmented reality,” International Journal on Interactive Design Manufacturing, 3, 109–119, 2009, doi: 10.1007/s12008-009-0064-x

[17] Chen, C.J., Ong, S.K., Nee, A.Y.C., et al., ”Haptic-based interactive path planning for a virtual robot arm,” International Journal on Interactive Design Manufacturing, 4, 113–123, 2010, DOI: 10.1007/s12008-010-0088-2

[18] Xia, P., Lopes, A.M., Restivo, M.T. et al., ”A new type haptics-based virtual environment system for assembly training of complex products,” International Journal of Advanced Manufacturing Technology, 58, 379–396, 2012, DOI: 10.1007/s00170-011-3381-8

[19] Mustufa H. Abidi, Ali Ahmad, Saber Darmoul, Abdulrahman M. Al-Ahmari, ”Haptics Assisted Virtual Assembly,” IFAC-papers online, Volume 48, Issue 3, 2015, Pages 100-105, DOI: 10.1016/j.ifacol.2015.06.065

[20] Markus Funk, Juana Heusler, Elif Akcay, Klaus Weiland, and Albrecht Schmidt, ”Haptic, Auditory, or Visual? Towards Optimal Error Feedback at Manual Assembly Workplaces,” In Proceedings of the 9th ACM International Conference on PErvasive Technologies Related to Assistive Environments, PETRA ’16, Association for Computing Machinery, New York, NY, USA, Article 43, 1–6, DOI: 10.1145/2910674.2910683

[21] B. Otten, P. Stelzer, R. Weidner, A. Argubi-Wollesen and J. P. Wulfsberg, ”A Novel Concept for Wearable, Modular and Soft Support Systems Used in Industrial Environments,” 49th Hawaii International Conference on System Sciences (HICSS), 2016, Pages 542-550, DOI: 10.1109/HICSS.2016.74

[22] T. P. Caudell and D. W. Mizell, ”Augmented reality: an application of heads-up display technology to manual manufacturing processes,” Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences, 1992, pp. 659-669 vol.2, DOI: 10.1109/HICSS.1992.183317.

[23] V. Paelke, ”Augmented reality in the smart factory: Supporting workers in an industry 4.0. environment,” Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA), 2014, pp. 1-4, DOI: 10.1109/ETFA.2014.7005252.

[24] George Michalos, Panagiotis Karagiannis, Sotiris Makris, Önder Tokçalar, George Chryssolouris, ”Augmented Reality (AR) Applications for Supporting Human-robot Interactive Cooperation,” Procedia CIRP, Volume 41, 2016, Pages 370-375, DOI: 10.1016/j.procir.2015.12.005.

[25] Moritz Quandt, Benjamin Knoke, Christian Gorldt, Michael Freitag, Klaus-Dieter Thoben, ”General Requirements for Industrial Augmented Reality Applications,” Procedia CIRP, Volume 72, 2018, Pages 1130-1135, DOI: 10.1016/j.procir.2018.03.061.

[26] Tariq Masood, Johannes Egger, ”Augmented reality in support of Industry 4.0—Implementation challenges and success factors,” Robotics and Computer-Integrated Manufacturing, Volume 58, 2019, Pages 181-195, DOI: 10.1016/j.rcim.2019.02.003.

[27] Uva, A.E., Gattullo, M., Manghisi, V.M. et al. ”Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations,” International Journal of Advanced Manufacturing Technologies, 94, Pages 509–521, 2018, DOI: 10.1007/s00170-017-0846-4

[28] Federica Ferraguti, Fabio Pini, Thomas Gale, Franck Messmer, Chiara Storchi, Francesco Leali, Cesare Fantuzzi, ”Augmented reality-based approach for online quality assessment of polished surfaces,” Robotics and Computer-Integrated Manufacturing, Volume 59, 2019, Pages 158-167, DOI: 10.1016/j.rcim.2019.04.007.

[29] Riccardo Palmarini, John Ahmet Erkoyuncu, Rajkumar Roy, Hosein Torabmostaedi, ”A systematic review of augmented reality applications in maintenance,” Robotics and Computer-Integrated Manufacturing, Volume 49, 2018, Pages 215-228, DOI: 10.1016/j.rcim.2017.06.002.

[30] Sunil Luthra, Sachin Kumar Mangla, ”Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies,” Process Safety and Environmental Protection, Volume 117, 2018, Pages 168-179, DOI: 10.1016/j.psep.2018.04.018.

[31] (TalTech IVAR Laboratory – TalTech Industrial Virtual And Augmented Reality Lab, 2022)

[32] Srivastava, R. & Bhattacharya, B., ”Thermoelastic and vibration response analysis of shape memory alloy reinforced active bimorph composites,” Smart Materials And Structures. 30, 015033 (2020,12), https://doi.org/10.1088/1361-665x/abc56d

[33] Anthes, C., García-Hernández, R. J., Wiedemann, M., and Kranzlmüller, D., “State of the Art of Virtual Reality Technology,” IEEE Aerospace Conference Proceedings, 2016.

[34] Watkins, C. D., and Marenka, S. R., ”FROM WHENCE VIRTUAL REALITY—A BRIEF AND INCOMPLETE HISTORY,” Virtual Reality Excursions with Programs in C., 1994.

[35] Kuts V., Cherezova N., Sarkans M., Otto T. ”Digital twin: Industrial robot kinematic model integration to the virtual reality environment,” Journal of Machine Engineering, 20 (2), pp. 53 - 64, 2020, DOI: 10.36897/jme/120182

[36] Kuts V., Otto T., Bondarenko Y., Yu F., ”Digital twin: Collaborative virtual reality environment for multi-purpose industrial applications,” ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), 2020, 2B-2020, DOI: 10.1115/IMECE2020-23390

[37] Baur, K., Schättin, A., De Bruin, E. D., Riener, R., Duarte, J. E., and Wolf, P., ”Trends in Robot-Assisted and Virtual

Reality-Assisted Neuromuscular Therapy: A Systematic Review of Health-Related Multiplayer Games," J. Neuroeng. Rehabil., 2018.

[38] Chernova, S., Depalma, N., Morant, E., and Breazeal, C., "Crowdsourcing Human-Robot Interaction: Application from Virtual to Physical Worlds," Proceedings - IEEE International Workshop on Robot and Human Interactive Communication., 2011.