**Title: Immersive Telerobotics for Industrial Work from Home**

**Background**

The recent COVID pandemic has disrupted the normal lifestyle of people all over the world. The terms such as “self-isolation”, “quarantine”, “work from home (WFH)” have become commonplace in our day-to-day conversations. The losses to the world economy due to this pandemic has been staggering to say the least. It is estimated that the global economic GDP will shrink by about 2.4% in 2020[1] equivalent to a loss of about $6-7 trillion dollars[2]. The UK GDP fell by 5.8% in March 2020[3] recording its sharpest monthly fall since 1997 and it is estimated that UK GDP will shrink by 9% in 2020 putting nearly 7.6 million jobs at risk[4]. Many companies are trying to cope with the forced lockdown by allowing their employees to work from home (WFH) by leveraging advances made in the field of information communication technologies (ICTs). This however may not be a solution for other industries where people are required to be in their workplaces to carry out physical activities such as picking, lifting, packing, transporting, assembling or operating machines, tools etc. Social distancing and health related concerns will also force companies to reduce human presence in workplaces even in a post-COVID world. Many analysts believe that the COVID pandemic will help accelerate the adoption of robots in almost all spheres of human activities[5]. However, the level of autonomy in physical robots has not yet reached a level where they can fully replace humans, particularly in activities where dexterous manipulation of objects are required. Capital intensive factory-level assembly lines may not be affordable for SMEs for such tasks. The conventional tele-operation capabilities are limited by several factors, such as network latency, lack of real-time and first-person perceptual feedback, fusion of multi-modal signals and immersive experience for the remote user. The objective of this project is to develop an immersive teleoperation interface that would enable users to carry out various industrial activities, such as, picking, packing, grasping or manipulating objects remotely while working from home. This will be achieved by leveraging the recent advancement made in the field of Augmented, virtual or mixed reality, haptics, computer vision and control theory. Such systems will prevent loss of jobs for a large number of factory workers and SMEs who have been furloughed because of the ongoing COVID pandemic. Factories will be able to operate and meet their production deadlines without laying off its staff and meeting the government enforced social distancing laws at the same time.

**Objectives:**

- To build an HMD-based intuitive interface for immersive visual experience for the remote user that includes 360 degree view and stereoscopic visual depth perception. This forms the work package 1 (WP1).
- To build an haptic-based interface for manipulation and grasping. This forms the content for work package 2 (WP2).
- To explore the use of 5DT Ultra data glove for integrating gesture-based interaction with the remote environment. (WP3)
- To develop algorithms and architecture to improve the real-time performance of human-robot interaction over the internet. (WP4)

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[1] https://www.statista.com/topics/6139/covid-19-impact-on-the-global-economy/
[2] https://www.bbc.co.uk/news/business-52671992
[3] https://www.ons.gov.uk/
[4] https://www.mckinsey.com/
[5] https://innovator.news/the-role-of-robots-post-covid-19-63b6cc833540

- To demonstrate the effectiveness of the immersive teleoperation interface by carrying out tasks such as device assembly, pick & place of objects, feeding materials into machines, carrying out precision tasks such as putting a plug into its socket etc. (WP5)

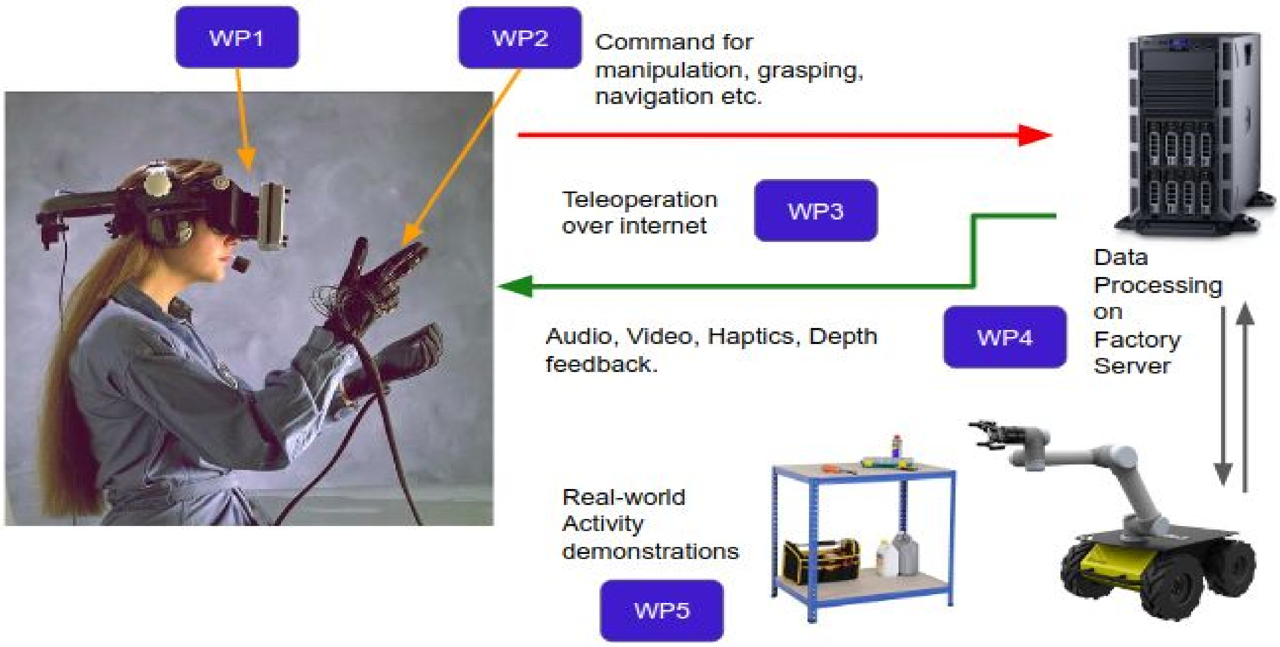


Figure 1: Conceptual diagram for immersive telerobotics

**Research Outline:**
Telerobotics finds application in several areas such as space, subsea exploration, medicine (surgery), nuclear plants etc. While teleoperation has been used for special cases as above for several decades now, its application for day-to-day activities has been limited due to factors such as the cost of implementing such systems, increased cognitive overload for the remote user, network latency which makes it difficult to obtain real-time feedback over longer distances etc. The recent advancement in the areas of Augmented, virtual and mixed reality, computer vision, cloud computing, haptics has rekindled the interests in the field by offering potential solutions to prevailing problems of teleoperation. These advances promise to provide an immersive experience for the remote user by providing first-person perception of the environment with 360 degree view, stereoscopic depth visualization, directional audio and haptics feedback. This will reduce the cognitive load on the remote user thereby making it easier to operate robots remotely. While many of these technologies have been demonstrated in isolation for a few special use-cases, a holistic approach is needed to combine these isolated efforts towards creating a unified teleoperation interface which would enable the remote users to seamlessly interact with robots remotely over the internet.

An illustration of the proposed solution is shown in Figure 1. The overall system consists of a mobile manipulator system located remotely in a factory environment. The user will operate this robot remotely over the internet. The individual activities to be carried out are explained in the following work packages.

***WP1: HMD-based immersive and intuitive visual interface for tele-operation***
This work package will focus on developing algorithms for making visual experience intuitive for the remote user. The teleoperation interface will consist of a VR device such as Occulus RIFT[6] which will act as the

[6] https://www.oculus.com/rift-s/

head mounted display (HMD) for the remote operator. The user will be able to get a 360 degree view of the environment as the remote camera on the robot moves exhibits 6D motion (3D position + 3D orientation). This will be combined with directional audio feedback and stereoscopic visual depth perception obtained from the on-board robot sensors. The activities under this work package can be broadly divided into the following two subpackages:

***WP1.1: Creating a virtual version of the actual factory environment***

Providing live video feedback continuously is not practical (due to network bandwidth limitation) and affects both the degree of immersion as well as situational awareness due to the restricted field of view of the remote camera. Hence, a virtual replica of the original world will be created which will be updated dynamically over time based on sensor feedback obtained from the remote robot. As the robot moves in the actual environment, the RGBD sensor data will be processed (on the robot) to create a 3D model of the world by using a voxel-based volumetric SLAM method [stotko2020]. While this 3D scene will be maintained and updated on the factory server, a low bandwidth representation will be streamed to the remote operator for rendering on his HUD. The remote operator can navigate in the reconstructed environment independent of the current robot view and even when the network is disrupted. The virtual environment will be created using the UnrealEngine 4 (UE4) game engine for realistic visualization with server-client architecture for optimal load distribution between the remote server and the end-user client [Wilson2018][Tava2020].

***WP1.2: Overlaying context-specific information***

The VR-HUD of the remote operator will be populated with various task related data and context specific information overlaid on the operator's screen. The user can request for live video feed or image from on-board camera as and when required. Annotations to be populated on the operator's screen will be generated by running various deep learning algorithms on actual video for object recognition, grasp pose detection and gesture recognition. Many of these algorithms will run on the factory server and only low-bandwidth information will be passed onto the remote operator for annotation as well as rendering.

***WP2: Gesture and Haptics-based motion control of the remote-robot***

This work package will focus on creating an interface for motion control of the remote robotic system which is a mobile manipulator with two-finger gripper. Two kinds of interfaces will be used for controlling the robot motion forming the content for the following two sub-packages:

***WP2.1: Gesture-based motion-control***

Hand-gestures are an effective way to interact with a robot. In this work package, we will explore the use of Leap Motion Control devices[7] for recognizing various hand gestures and map them to various robot motion primitives. Leap motion (LM) devices are cheaper alternatives to data gloves (such as 5DT Ultra data glove [8]) and does not require wearing gloves. Deep learning methods will be developed for recognizing various hand gestures and mapping them to several robot motion primitives [Lupi2020]. Some of the motion commands for the mobile base will include motions such as moving forward, backward, rotate (left/right) and stop. Commands for grasping will include primitives such as 'holding', 'picking', 'releasing' or just reaching the target.

***WP2.2: Haptics feedback for manipulation & grasping***

Haptic feedback is used by a teleoperator to feel and control the forces that are applied by the robot or experienced by it (such as vibration), thereby providing a sense of touch for the teleoperator. We will explore the use of kinesthetic type haptic sensors such as Geomagic touch[9] for providing 6DoF force feedback to the operator. Algorithms will be developed to combine gesture-based motion control along with haptics feedback to provide precision control and efficient maneuvers for manipulation and grasping

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[7] https://www.ultraleap.com/
[8] https://5dt.com/5dt-data-glove-ultra/
[9] https://www.or3d.co.uk/products/hardware/haptic-devices/geomagic-touch/

activities. Feedback about critical and dangerous motion could be provided by using vibrotactile arm bands worn by the operator [Bimbo2017].

***WP3: Improving real-time performance of the interface by reducing network latency***

Network latency is one of the major concerns for telerobotics when the operator has to control a robot over a long distance. The delay in receiving sensor feedback can make it difficult for the remote operator to guide the robot appropriately leading to poor outputs and may even damage the robot. Transmitting real-time video (required optimal visual experience) may put additional constraints on the available network bandwidth. This work package will explore and evaluate several methods to optimize bandwidth usage while providing an seamless and comfortable experience for the remote user. Some of the approaches involve logically dividing available bandwidth between data and control signals so that the low bandwidth control signals are not restricted due to high-volume sensor data transmission. This will ensure that critical I/O commands can be made available to the robot as well as the remote operator. Another approach would be to provide intermittent feedback of critical information rather than providing live feed of all the signals continuously [Bohren2016]. Some of the computing architectures such as server-client models using CrossSock [Zaman2019] or VETO [Wilson2018] will be evaluated for their efficiency and resilience to sporadic network failures. We will also explore the use of 5G networks to solve some of the network related problems.

***WP4: Data Processing and Information Fusion***

As mentioned above, transmitting raw video and other sensor data (depth, laser) data over the internet will pose significant bandwidth challenges and hence, a good amount of data processing will be carried out at a server located within the factory premises. The data obtained from the on-board robot sensors will be transmitted to the local server over LAN WIFI having Gigabit bandwidth. The data that will be gathered will include video streams, depth/range information obtained from Laser/LiDAR sensors and audio sounds recorded using on-board microphones. Low-cost RGBD sensors, such as intel real-sense[10] will be mounted on the robotic arm wrist to facilitate grasping of objects requiring close-up view of the workspace. Once the goal tasks are received from the remote operator, the sensor data will be processed on the local server to compute the current state of the robot and prepare a motion plan for carrying out the task autonomously. For example, the RGBD point cloud of a target object will be processed to find the pose of the target object and the possible graspable handles required for picking the object. Similarly, the video frames could be processed to identify various objects in the environment. Laser data could be processed to locate obstacles on the path. This information could then be simulated on the operator’s end to provide the current state of the robot as well as its environment. The information from different sensors are required to be fused together to provide a coherent and holistic view of the remote environment to the operator. This simulated environment will be a digital twin of the actual environment.

***WP5: Demonstration on real-world use-cases***

The effectiveness of the proposed platform will be demonstrated in carrying out various industrial activities in the factory by operating robots remotely over the internet. Some of the tasks that will be carried out in this work package are as follows: (1) Making the robot move in the factory while receiving live video feed / 360 view / stereo depth. Several annotations about the environment will be displayed in the HUD making it easier for the remote user to understand the scene better. (2) Second task will be to make the manipulator on-board the mobile platform to pick and place things with precision. (3) Third task will involve the mobile manipulator to interact with a static machine to assemble devices. The task may involve turning on and off

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[10] https://www.intelrealsense.com/stereo-depth/

various switches on the machine to set its initial conditions. (4) Fourth task will be to attempt some precision tasks such as putting a plug into a socket.

**Impact / Significance**

According to a study by IFR [IFR2018], the worldwide robotics sales will witness a double digit growth in the coming decade driven by the increased demand for service robots and wider adoption of Industry 4.0 technologies across all sectors - manufacturing, agriculture, healthcare, domestic as well as entertainment. The recent COVID pandemic has seen widespread use of robots[11] in activities such as collecting samples, decontaminating hospitals and public spaces, delivering services or carrying out aerial surveillance of affected areas and enforcing social distancing etc. It is widely believed that the COVID pandemic will further accelerate the adoption of robots as companies will strive to reduce human presence in their premises to meet the social distancing guidelines and avoid risk of infections[12]. Various sectors such as manufacturing, transportation, warehousing, agriculture etc. have high automation potential and may see a significant loss of jobs due to the ongoing pandemic[13]. The proposed research will help reduce the impact of automation by providing an alternative means of engaging workers. There is a growing indication that the telerobotics and teleoperation market will see significant growth in the post COVID world[14] with increased funds being made available for industrial IoT and robotics R&D activities. In this context, the proposed research is timely and opportune and aims to make teleoperation more mainstream by simplifying the human robot interface.

**Timelines and Milestones:** A visual overview of the project plan and linked milestones are presented below.

| Year | YEAR 1 | | | | | | | | | | | | YEAR 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Months** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| **Work packages** | | | | | | | | | | | | | | | | | | | | | | | | |
| WP1.1: Creating virtual interface (VI) for the factory environment using U4E | | M2 | | | | M3 | | | | | | | | | | | | | | | | | M9 | |
| WP1.2: real-time update of environment based on feedback - live annotations, on-demand live video | | | | | | | | | | M4 | | | | | | | | | | M6 | | | | |
| WP2.1: gesture-based Robot motion control using 5DTdata glove | | | | | | | | | | | M5 | | | | | | M7 | | | | | | | |
| WP2.2: Integrating haptics feedback obtained using Geomagic Touch x with virtual interface | | | | | | | | | | | | | | | M8 | | | | | | | | | |
| WP3: Design and development of architectures for reducing network latency | | | | | | | | | | | | | | | | | | | M10 | | | | | |
| WP4: Algorithms for multimodal data fusion and information processing | | | | | | | | | | | | | | | M11 | | | | | | | | | |
| WP5: real-world demonstration | | | | | | | | | | | | | | | | | | | | | | | | M12 |
| **Staff** | | | | | | | | | | | | | | | | | | | | | | | | |
| PI/Co-I/RAs | | | M1 | | | | | | | | | | | | | | | | | | | | | |
| Summer internships | | | | | | | | | | | | | | | | | | | | | | | | |
| **Outreach and Impact Activities** | | | | | | | | | | | | | | | | | | | | | | | | |
| Public engagements & research workshops | | | | | | | | | | | | A1 | | | | | | | | | A2 | | | |
| Publications (**C**: Conf. and **J**: Journals) | | | | | | | | | | | | | | C1 | | | | | C2 | | | | | J1 |

**M:** Milestones – M1: recruitment of RAs; M2: requirement analysis and literature survey; M3: Creation of common object models; M4: interface for including real-time updates; M5: demonstration of gesture based motion control for mobile base; M6: Inclusion of force feedback models in the VI; M7: gesture-based motion control of robot arm and gripper; M8: demonstrating force feedback for

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[11] https://www.weforum.org/agenda/2020/05/robots-coronavirus-crisis/

[12] ResearchandMarkets.com-Robotics industry to see demand increase.

[13] https://eiuperspectives.economist.com:will-covid-19-pandemic-accelerate-automation

[14] https://www.marketwatch.com: teleoperation-and-telerobotics-market-size-forecast-2020-2026

manipulation and grasping; M9: fine-tuning of the virtual interface; M10: fully functional sensor network; M11: demonstration of data-fusion algorithms; M12: Evaluation of the teleoperation interface

**A:** Actions – A1: Internal workshop for students and faculty members; A2: national workshop involving representatives from local industries.

## Outcomes and Deliverables

(1)Research outcomes will be published at peer-reviewed international conferences and journals. (2) the source code of the entire project will be made available publicly on Github (3) A working prototype of telerobotics interface will be demonstrated and efforts will be made for its commercialization and transfer of technology for further development.

## Organization & Planning - Feasibility

Given the short duration of the project, the focus will be on integrating existing technologies into a working prototype and improving its performance and usability. Keeping the practical application in mind, we will use low cost alternatives for various components required to realize this interface. The desirable features of the user interface will be finalized after consulting actual people working in the local factories. The working of the intuitive interface will be demonstrated on real-world tasks in collaboration with our industry partners.

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14. [rnm2020] Robotics industry to see demand increase post COVID pandemic. ResearchandMarkets.com

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