Research Vision

This project aims to develop new methods, architectures and frameworks to improve the efficiency and quality of telerobotics systems which would enable factory workers to carry out many of their routine activities while working remotely, a flexibility which is not currently available to them, particularly in the manufacturing sector. In addition, such telerobotic solutions will help reduce not only the **risks of downtime** (posed by the lockdowns during pandemics) but also **the safety risks** associated with working on factory shop floors (injury due to accidents, loss of life etc). The robots could be equipped with necessary on-board sensors in order to carry out remote measurements, inspection and several non-destructive tests which can **improve product quality control**, **reduce the overall time and cost for certification** and hence, **reduce time to launch new products**. The data gathered through teleoperation could also be used to **create and update digital models** (of products and robot work cells) required for simulation-based planning, prediction and analysis. Such models are an integral part of the production pipeline and the decision making process in smart factories operating within the purview of Industry 4.0 framework. These benefits will be achieved by leveraging the recent advances made in the field of information and communication technologies including AR/VR, robotics and AI to extend the capabilities of existing teleoperated systems making them more amenable to digital manufacturing.
The ability to control robots remotely in a reliable and efficient manner has the potential to disrupt the manufacturing industry by opening it to the service industry that can provide "**teleoperation as a service**" which will eventually make it possible to have lights-out shifts (with no people on shop-floor) in the production schedule. The recent rise of teleoperation start-ups [53-56] is an indication of the growing popularity of such systems that can potentially address issues such as labour shortage, talent squeeze and rising skill gap in the wake of recent covid pandemic and Brexit.

Research Challenge

The use of teleoperation has not been widely adopted in the manufacturing industry due to the fundamental limitations such as restricted perception (of remote environments), high network latency (delays), poor accuracy, complex and non-intuitive interfaces for robot/machine control and high equipment cost. While several isolated attempts have been made to address some of these challenges [23, 32, 36-37], a holistic approach is missing which motivates us to **create a novel end-to-end telerobotics platform** that is **extensible**, **modular**, **hardware-agnostic** and **scalable** (able to deal with multi-robot and multi-user operation). This platform will further accelerate the adoption of digital technologies in the manufacturing industry by supporting low-cost consumer-grade devices and communication infrastructure. Given the government's push to recover from the recent COVID pandemic through digital means, the project is **opportune and timely**.

Specifically, the main objectives of this project are as follows:

1. Advance the intuitiveness and immersiveness of the VR-based teleoperation interface by developing novel algorithms for data processing, visualisation and command generation for seamless interaction in complex, unstructured, physics-constrained environments.
2. Develop novel motion planning algorithms and robot control architectures to improve the accuracy and efficiency of manipulation & grasping activities with due consideration of incomplete, distorted, and noisy sensor data, including limited views.
3. Develop innovative communication architectures and methods to improve the real-time performance of teleoperation over consumer broadband and mobile networks.
4. To demonstrate the working of the proposed system on a real-world use-case in a factory environment.

The proposed platform (TeleRob4Mfg), shown in Figure 1, comprises three main components addressing three dimensions of the teleoperation challenges, namely, (1) Visualisation & Virtualization (2) Motion Planning & Control and (3) Communication. The details of these components and the associated activities are organised into four work packages as discussed below.

This project will make the following innovations. (1) the remote environment and the progress of tasks will be closely monitored by the operator with feedback and instructions provided in real time, combining the strengths of robots, network, VR/AR and human operators; (2) the model based object segmentation, classification, recognition and rendering will be adapted to reduce the requirement of bandwidth; (3) The robots will be taught skills by the human operator to carry out the tasks more effectively while making them available as retrievable libraries for future use and providing proactive response; and, (4) the effectiveness of the proposed WPs will be demonstrated through a the real world nuclear waste container inspection task for pragmatism and impact.

WP1: VR-based immersive and intuitive visual interface for tele-operation

WP1 will create a VR-driven teleoperation interface to provide an immersive visualisation of the remote environment with intuitive contextual information that will simplify decision-making while reducing the cognitive overload on the remote user. This will be achieved by developing algorithms for 2D/3D scene reconstruction, scene understanding and knowledge representation. A virtual replica of the remote environment will be created incrementally by stitching RGBD point clouds (sparse points require low bandwidth), as the robot is made to explore its environment. The voluminous sensor data collected using the robot sensors will be processed using deep learning on a local server (in the factory) to generate high level (and low bandwidth) information that can be sent to the client side for rendering and visualisation almost in real-time. The user will be able to visualise on-demand live video and depth data overlaid on the simulated environment which would help in resolving ambiguity. A knowledge database similar to OpenEase [19] will be maintained to keep a track of changes in the environment and activities carried out along with object models. This database will be queried to avoid repeated computation when similar objects or circumstances are encountered. While VR HUD will be used for visualisation, head pose tracking and positional hand tracking will be used for changing viewpoint selection and controlling robot motion. This work package will build on our recent works by AKP [28], YL [8, 11, 29], AB [2, 3, 7] and SK [34, 46] .

WP2: Robot Control Modes & Motion Planning Algorithms

Two modes of robot control will be provided to deal with tasks of varying complexity. In the first mode, the remote robot will be controlled by providing multiple subgoals which will be accomplished autonomously by the robot [1]. The user will be provided with a visual programming tool to facilitate creation of such plans on the fly [20]. This mode of operation will require minimal bandwidth and may even withstand intermittent connection failures. In case of failure, the robot will generate a notification and wait for the operator's intervention. In the second mode, the robot will be continuously guided by the remote operator. This mode will be used to deal with exceptional situations (e.g., faults) or for carrying out dexterous and complex manipulation tasks with precision (e.g., device assembly, material feeding, welding etc.). Compared with the first one, this mode will require stable connectivity with high bandwidth to facilitate live video feedback required for the task. The robot control modes will also be extended to multi-agent scenarios involving multiple robots and operators. The underlying communication and scheduling challenges associated with these modes of operation will be addressed in WP3.

Several new algorithms will be developed to improve the accuracy of teleoperation which is a major concern in the manufacturing industry [23]. This will be achieved by combining data from multiple sensors - force feedback, depth and image data [18]. The mobile manipulator will be equipped with multiple cameras both in eye-in-hand and eye-to-hand configuration to provide a local as well as a global view of the robot environment. The robot motion will be controlled using the off-the-shelf hand tracking controllers that come with the VR-set (e.g. oculus touch). The efficacy of algorithms will be demonstrated by performing several precision tasks such as assembling devices (e.g. a gear or, a peg-in-hole with irregular shapes) in a lab environment. In addition, novel deep imitation learning algorithms will be developed to teach new skills to the robot through teleoperation [12, 25, 43]. These skills could be stored and reused to carry out similar tasks in a semi-autonomous fashion. This work package will build on prior works by SK [15, 26, 42] and AA [48, 49, 50].

WP3: Communication Architectures with Multi-Agent System Formulation

For seamless teleoperation from anywhere at any time, communication connectivity is imperative. Therefore, WP3 will develop a novel framework by incorporating intelligent and efficient scalable resource slicing to handle heterogeneous network service requirements such as low latency, high reliability and high throughput to guarantee services for near real-time experience. The overall communication and planning architecture for single and multi-agent scenarios is shown in Figure 2.

To support the human operator, the robots first need to understand what they are trying to achieve in terms of goals/tasks. To improve fault tolerance, latency and throughput related to networking issues and the (potentially incomplete/delayed) stream of actions that is received by the robot from the operator, an online learning system will be designed, for instance by developing reinforcement learning (RL) techniques. It can allow the robot to decide (or predict) its next tasks or sequences of actions by learning from their previous robot-operator interactions in a robust manner. To provide input to an online learning system and enable real-time operator-robot interaction, additional network constraints such as VR's QoS, reliability, latency (satisfied via proposed innovative transmission/compression strategy) and scalability will be considered. Therefore, we will develop a novel communication paradigm, formulating it as a multi-dimensional optimization problem to dynamically schedule the tasks/action decision-making based on network conditions and constraints.

Pushing our system one level further, we will design multi-agent on-line planning approaches to allow multiple robots to collaborate and assist each other through schemes such as proactive offloading [47] to perform with higher accuracy even in the face of uncertainty (breakdowns, accidents, communication failures etc.). This will be achieved by using a collaborative/cooperative multi-agent RL framework to provide predictive analytics about the system context, tasks and resource requirements prior to the actual offloading requests. This WP will build on the preliminary recent works of HP [57, 58], LSM on Reinforcement Learning [27, 33], on integrated on-line learning/planning systems [24, 41] and QN [59].

WP4: Real-world demonstration in a factory environment

In addition to experiments performed in WP2 under lab conditions, the effectiveness of the proposed VR-based telerobotics interface will be demonstrated through real-world experiments in an industry setting which will be facilitated by our industry partner NNL and SFL. The real-world demonstration will involve remote monitoring of waste containers for long term changes in container integrity [21, 22]. The task will mostly include visual inspection using RGBD and range cameras to detect instances of corrosion, deformation and damage (cracks or leaks). There will be two versions of this experiment. In one, the mobile robot will carry out a partial scanning of containers kept in a storage facility as shown in Figure 3(a) while moving along the aisles. In the second case, each container will be brought out of the storage facility for full scanning as shown in Figure 3(b). This container can now be scanned from all sides using the mobile manipulator platform. Even though this use-case is related to the nuclear industry, such inspections are also common in manufacturing industries which are mostly carried out manually either for carrying out non-destructive testing of products or for routine monitoring for detecting faults. The robotic arm may carry different sensors to scan the target product and the processed information could be displayed on the operator's heads-up-display (HUD).

Project Team

Academic Partners:

The project team includes members from two academic institutes, namely, Edge Hill University (EHU) and Lancaster University (LU). The investigator team comprises a balanced mix of senior, mid-career and early career researchers. EHU will lead the activities in WP1, 2 and 4 with its PI and 4 Co-Is. On the other hand, LU will lead the activities in WP3 with 3 Co-Is. The investigators have extensive expertise in the area of computer vision, robotics, communications and machine learning. Their roles will be discussed further in the next section.

Industry Collaborators:
The project team includes collaborators from National Nuclear Laboratory (NNL), Sellafield Ltd (SFL) and Socients.AI (SA). NNL will support this project by providing access to their facilities required for carrying out real-world demonstrations in WP4 while SA will provide consulting support for WP 1 & 2.

Amit Kumar Pandey (AKP) from SA led a team that participated in the ANA Avatar Xprize Challenge where they built a teleoperated robot for a healthcare application [28]. We will build on his experience to develop our telerobotic system.

Steve Hepworth (SH), John-Patrick Richardson (JPR) and Melissa Willis (MW) are senior researchers from NNL and SFL having engaged in several robotic projects related to nuclear decommissioning, nuclear waste disposal and waste segregation. They would provide guidance and mentoring required for completing the WP4.

Proposed Program

The relationship between work packages and the roles and responsibilities of investigators are shown in Figure 4. The time-lines and milestones for the project are provided in Figure 5. The project will recruit 3.5 postdocs for a duration of 3 years to carry out the main research work required for these work packages.

References are available here.