Edge Accelerated AI for Robotic Teleoperation

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***Abstract*—This paper presents a body of work on the development of edge accelerated AI hardware and software components related to robotic teleoperations. In particular, the paper proposes a system based architecture incorporating teleoperations communications layers in the form of a local to remote edge based stack, along with a Time of Flight (ToF) sensor layer, delivering user controls via real time hand and gesture signals for robotic teleoperations. Typical use cases include, remote skills delivery, precision robot manipulation, factory of the future, dangerous work environments and many other Industry 4.0/5.0 scenarios.**

Keywords— Industrial Automation, Artificial Intelligence, Industry 4.0, Industry 5.0, Edge Computing, PLCs, Profinet, RapID.

I. INTRODUCTION

Industry 4.0 is where connected and smart cyber-physical systems introduced new concepts, such as flexibility, decentralisation, self-organisation, and personalised products to production lines [1]. Rapidly evolving from Industry 4.0, is Industry 5.0 [2], which will bring Human Centred Artificial Intelligence (HCAI) to multiple industries and sectors in the future. Today, Artificial Intelligence (AI) and Machine Learning (ML) technologies play a pivotal role in achieving smart cyber-physical systems in industries, acting as the embedded brain of such systems.

Intelligent MOtion COntrol under Industry 4.E (IMOCO4.E) [3] is a project that primarily aims to address this AI/ML computation challenge for industrial sensing. The IMOCO4.E project provides edge-to-cloud intelligence for machines, robots, sensors and other human in-the-loop cyber-physical systems with actively controlled moving elements. This paper is a direct result of the IMOCO4.E project and describes how tactile robotic forms (incorporating fixed, teleoperations, mobile (MoBots, UAVs and Humanoids)) constitute the next generation of collaborative robotics for Industry 5.0.

A. Related literature

Edge computing architectures for Human Computer Interfacing (HCI) and their expanding relationship with the next generation of robotic systems are studied and discussed in [4], concluding that 5G gigabit speeds and low latencies will see developments of ubiquitous communications between robots and humans based on real time sensed data. Suman et. al. [5] describe the challenges for HCI and teleoperations in terms of communications parameters such as low latency, high reliability for real time user haptic feedback and control precision. In [6], the role of edge AI in sustaining real-time and intelligent enterprises is evaluated , and the authors argue that complexities in relation to multiplicity and heterogeneity in industrial automation highlight that true edge AI powered robots and drones will be necessary in industrial automation. Specialised edge AI architectures for sensors in industrial automation are explored by Liang et al. in [7]. Shankar et al. in [8], presents further justifications for advancing edge AI accelerators. Their work discusses low latency; bandwidth efficiency; improved security and privacy; scalability; resilience and reliability; and context awareness as the key motivations and challenges for the field. With reference to robotic teleoperations, in [9], Fu et al. explains how teleoperations based on multi-channel electromyography (EMG) signals to control a robotic arm is impacted by latency, which will directly impact on user control. Similarly, Chu et al. [10] present a multisensory system for controlling a robotic arm based on EMG and inertial measurement units (IMUs). Rezeck et al. [11] present haptic integration into a teleoperation's platform. Their research describes a local end based Unity system that communicates through ROS to receive haptic feedback. In other work, the domain of robotic surgery in investigated by Xu et al. in [12].

B. Paper overview

Highly relevant from the literature review, is the research on edge sensing devices, systems and platforms for automation. In particular, this paper contributes to edge based infrastructure and addresses challenges in local edge to remote edge, latency, and communications. The research also explores user driven ToF technology for robotic teleoperations which can typically operate on the edge communications stack discussed below. In particular, both of the research contributions presented in this paper are components of an overall teleoperations reference architecture/framework which is a significant and novel outcome of the IMOCO4.E project. The remainder of the paper is structured as follows. Section II discusses SoC-FPGA edge AI accelerators that have been developed and tested in relation to direct local edge to remote edge communications and ToF sensor driven robotic teleoperations components. Section III presents selected results relating to the edge AI accelerators work on communications and robotic teleoperations based on real time sensed data. Section IV provides discussion and conclusions with Section V providing a paper summary and outlook for future research.

II. Materials and Methods

A. *Robot Teleoperations System Architecture*

Fig. 1 shows an overall system architecture for a teleoperation system which incorporates both a local sensor end and a remote robot end. In terms of AI accelerators used, research was conducted on the STM32H747/757 (STM32) [13], MicroChip PolarFire [14], Intel NUC [15] and the Nvidia Jetson Orin Nano 8GB [16] edge devices.

With reference to Fig. 1, Layer 2 Decentralized Controllers and Layer 3 System Behaviour, is where an industrial edge to edge hardware and software stack is deployable. Layers 2 and 3, receive inputs from Layer 1 Sensors and Actuators.

ToF vision sensor data is communicated from the operator local end to the remote end (edge to edge communications) to drive a teleoperated robot, described in the following sections. Layer 4 is outside the scope of this paper.

B. *Edge accelerated AI industrial components*

The industrial edge-device developed uses SoC-FPGA technology as the AI accelerator. As a prototype, a combination of two technologies, the STM32 and the RapID [17], an industrial multi-protocol Ethernet network interface module from Analog Devices were integrated to create both local and remote ends of a platform to simulate robotic teleoperations. A SIEMENS, SIMATIC S7-1500 PLC [18] was also added to the architecture. To test the communications, an Ethernet protocol called Profinet [19] was deployed.

1) *Industrial edge hardware*

RapID module: The RapID carries all process loads necessary for communicating over an industrial Ethernet to reduce the computational burden on the main/host processor.

S7-1500 PLC: The S7-1500 CPU was selected to test and validate the proposed edge AI infrastructure for robotic teleoperations. In the infrastructure developed, the PLC CPU knows the local-end edge device, the remote-end edge device, and the robot as Profinet I/O devices. The Totally Integrated Automation (TIA) Portal v17 is used to develop the PLC program, upload the program, diagnose any PLC issues, configure the network (Profinet), and other related tasks.

Fig. 2 presents the described hardware setup, where the local (L) and remote (R) ends of the platform are connected via the STM32, RapID and the PLC.

2) *Industrial edge software*

The communications network that connects an operator/user of the teleoperation system (and related technical infrastructure/sensors) to the robot actuators at the remote-end, is Profinet-RT, which is the Real-Time version of Profinet. Profinet is an open international standard for industrial Ethernet communications. Selected core software components of the edge stack are presented in the following paragraphs.

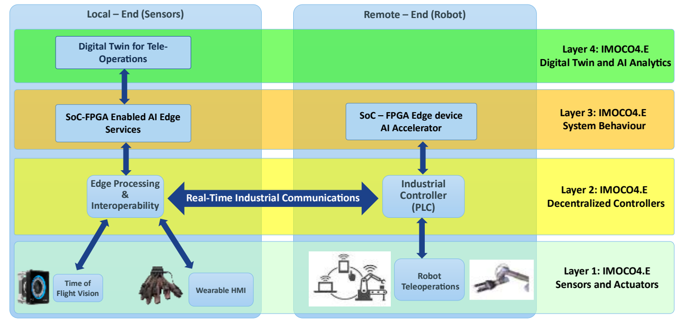

Fig. 1. Robot teleoperations system architecture.

General Station Description (GSDML): The GSD (General Station Description) file is an XML file describing Profinet I/O devices.

RapID C driver stack: The C driver stack has been engineered for Profinet-RT and consists of four layers on top of the Hardware Abstraction Layer (HAL).

- **Platform layer:** HAL is the only layer with hardware/platform dependency. The Platform layer sits above and interfaces with the lower HAL layer.
- **Driver layer:** The Driver layer connects the user input/output data to the industrial automation network running Profinet.
- **Application (APP) layer:** The APP layer sends data over the Profinet, processes data received from the PLC, maintains input/output values, and prints debugging/monitoring messages to a terminal.
- **User Interface layer:** The top layer provides for the user interaction with the APP and Driver layers, for configuration, debugging, and test purposes. It also provides access to selected functions at the APP and Driver layers.

C. *Edge accelerated AI ToF sensor components*

ToF vision and related AI algorithms to develop and test edge based robotic teleoperation were based on the Analog Devices 3D ADTF3175 ToF [20] module with integrated CMOS, imaging sensor technology.

Time of Flight (ToF): The ToF sensor module is used to generate infra-red (IR) and depth images. Using machine vision, an algorithm is trained to detect a person's hand and follow its movement trajectory. The IR image, together with the depth image from the ToF sensor are used to find the position of the wrist in 3D space. The most successful approach tested was IR images with a pretrained RGB hand-tracking model calculating the operators movement images from frame to frame and converting these to robot joint angles to operate the robot. Further details on the ToF pose detection methods and related algorithms, can be found in the IMOCO4.E project deliverables from work packages three and six.

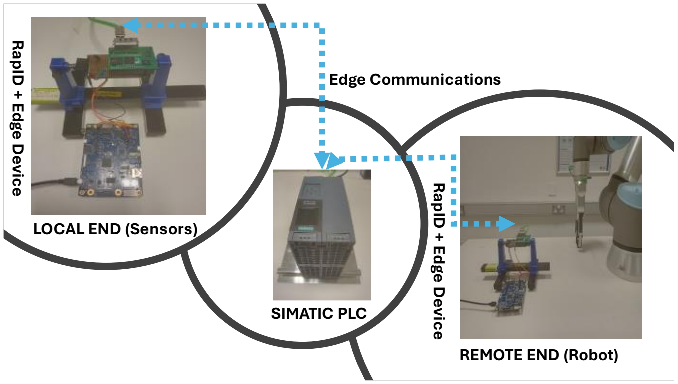

Fig. 2. Local edge to remote edge hardware stack.

III. RESULTS

A. *Edge accelerated AI industrial components results*

Tests were established to confirm that both float and integer values communicated from the STM32 local edge across the Profinet and RapID via the PLC, were correctly received at the STM32 remote edge of the system setup. Within the laboratory, test data was communicated via terminal software at the local end and it was confirmed that the data was received at the remote end with the potential to move both the robot arm and gripper. For validation of the gripper tests, data packets were captured and analysed for specific values using a network switch connected to the STM32 edge to edge hardware stack.

Validation tests were conducted to confirm data packet flows from local edge to remote edge. Both robotic arm and gripper data flows from the local to remote ends were 100% confirmed with Profinet-RT cycle times in the range of 1 – 10ms. Latency of the RapID C-Driver program module was recorded at 0.5ms which satisfies the real-time requirements of Profinet.

B. *Edge accelerated AI ToF vision components results*

The system latency identified was measured to be 0.3s through project partner testing reported in the IMOCO4.E project deliverables. Such latency is considered technically safe for surgical teleoperation processes [21]. Experiments were repeated multiple times during the project by two of the main project engineers under varying ambient illumination levels to measure the system performance. The detection rate was found to be 89% using Mediapipe [22] recognition algorithm with IR images from the ToF sensor. Mediapipe is trained mainly with RGB images so it has better accuracy using RGB images over IR.

The NUC based testing confirmed that the robot moves almost instantaneously with the user's hand movements and has achieved: overall system latency of 0.3 seconds; 30 frames per second (fps); 89% detection of the wrist from images. During the ToF engineering, an integration test was conducted using the PolarFire edge device. The test demonstrated robotic teleoperations using ToF processed hand gestures for the PolarFire edge accelerator. In the final phase, the engineering work focused on porting the full ToF hardware and software stack to the Jetson Orin Nano 8GB module. This enabled the concept to be proven on a smaller, more power efficient platform with greater agility and increased security compared to the initial NUC platform. The ToF Jetson demonstrator also involved a test/demo setup where random users could test the platform to remotely move the robot arm without any pretraining requirements.

IV. DISCUSSION AND CONCLUSIONS

The ToF gesture recognition system (PolarFire) allows for the embedding of additional gestures with minimal data (as few as 10 training samples). The versatility of the ToF edge systems allows for future integration into a range of scenarios, spanning from interactive user control of robotics and many types of industrial applications such as navigation, safety, and control.

With embedded AI across the proposed edge to edge architecture layers, AI prediction algorithms may be enhanced by having semantic/environment knowledge of the remote work area. For example, robot actions at the remote end may be augmented with the exact location of target objects within the workspace. The research has potential in other projects where vision sensors are used for user guidance of object/robots in the real world. Any future technical roadmap, will entail deploying robust communication channels between local and remote ends, acknowledging the pivotal role of time constraints in application deployment, along with addressing factors such as latency, jitter, and throughput.

V. SUMMARY

This research work involved the development of prototype components of a teleoperations system architecture. The paper presented the edge to edge hardware and software stack which was initially tested for both robotic arm and gripper movement data flows. The novel edge stack presented has the potential to form the communications backbone of future Industry 4.0/5.0 robotic teleoperations projects. The ToF research was based on user driven robotic control using a number of edge accelerated AI devices. The demonstrators presented edge futures for hand and gesture based control of robotic teleoperations platforms. In terms of integration and interoperability, the edge devices, sensors and robotic systems used throughout the research are open and capable of being fully integrated with varying types of hybrid robotic teleoperations processes in the overall context of Industry 4.0/5.0. Finally, the reader is reminded that this paper has presented selected hardware, software and communications components from the overall IMOCO4.E reference architecture/framework. The main novelty of this work is in the reference architecture combined with the edge and ToF based processing and the potential future digital twin technologies will offer in relation to generative AI and robotic training and learning.

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