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Haptic and Mixed Reality Enabled Immersive Cockpits for Tele-operated Driving

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Abstract

In the last few years, the use of automated guided vehicles (AGVs) and autonomous mobile robots (AMRs) has experienced a sustainable increase in different verticals such as factories and logistics. However, they still have some technical limitations that hamper their autonomous operation in unpredictable or dynamic environments, requiring them to be supervised and/or controlled by human operators. In such situations, current tele-operated driving (ToD) systems lack the required stimulation and spatial perception to precisely manipulate the AGVs/AMRs, besides suffering from real-time challenges that limit the accuracy of movement. This chapter describes a proposal to solve these problems, by combining low-latency 5G-IoT networks and immersive cockpits equipped with haptic and mixed-reality devices. It also explains how such devices provide intuitive feedback for ToD and facilitate context-aware decision-making. The results are validated in the context of two innovative demonstrations deployed in the environment of a

seaport, where ToD of multiple AGVs/AMRs is supported by a 5G mm Wave network infrastructure.

Keywords: 5G, IoT, haptics, metaverse, mixed-reality, robotics.

15.1 Introduction

Automated robots, which can be mobile (i.e., autonomous mobile robot – AMR) or guided (i.e., automated guided vehicle – AGV), are becoming increasingly sophisticated machines capable of navigating without human input, thanks to the multiple sensors attached (e.g., LiDAR/RADAR, cameras, IMUs, ultrasounds, etc.). The data gathered by the different sensors is processed by powerful AI-assisted tools to detect people, obstacles, and patterns, and even to perform the robot's simultaneous location and mapping (SLAM). In a collaborative industrial environment with multiple robots working at the time, next-generation IoT networks will make possible not only the real-time communication among the robots and other assets to optimize the collaborative task but also the offloading of the complex AI algorithms to the edge/cloud computing infrastructure in order to mitigate the cost of hardware and allow the robot to complete more complex missions.

Self-driving vehicles have been proposed for plenty of applications in the literature, the majority of them motivated by security or economic reasons. For instance, AGVs/AMRs can be very useful in scenarios where the physical presence of human beings can pose a risk to their safety, such as fires, toxic gas leaks, chemical or nuclear contamination, manipulation of explosives, logistics, etc. Similarly, they are key for the inspection of critical infrastructures such as factories, power stations, refineries, railways, ports, etc., especially in remote locations or in the case of extensive infrastructures where inspection by a local operator would be very expensive or inefficient [1].

Nevertheless, when deploying the mentioned use cases to a real scenario, occasional failures occur, especially if the inputs are contradictory or unseen for the AI modules. In the unpredictable real world, there is a myriad of situations that expert human operators are more capable of solving than state-of-the-art robotics. Some identified situations where human's pattern recognition and judgment still outperform machines are [2]: (i) low visibility due to extraordinary weather or light conditions; (ii) confusing or malfunctioning traffic signals; (iii) unclear or handwritten text indications; and (iv) sensors providing conflicting data.

To overcome such issues, the use of tele-operated driving (ToD) systems as a safety backup is the best option, especially in critical tasks and tasks that involve transporting or manipulating dangerous cargo. The idea is that the AGV/AMR asks a remote operator to take control of the robot when it cannot handle the situation [3], delivering to him all the necessary sensor data (e.g., video stream, detected obstacles, telemetry information, etc.). In that regard, we consider the state-of-the-art solutions to provide insufficient time responsiveness and stimulus to perform ToD precisely and intuitively in any environment.

For a correct implementation of ToD, we identify that an appropriate IoT communication infrastructure along with dedicated protocols and an intuitive cockpit setup is needed. From the communication perspective, 5G seems to be the best candidate to satisfy the QoE requirements (e.g., strict throughput, latency, and loss rate), although they depend on multiple factors such as the level of control of the vehicle. From the application perspective, we propose to integrate the cockpit with a combination of head mounted displays (HMDs) and haptic devices to engage the user in multisensory and realistic 3D environments that facilitate the ToD. We think that such combination will be the standard for any kind of remote control in the next decade, transforming the ways humans interact over long distances and revolutionizing verticals such as healthcare, education, entertainment, and industry.

The rest of the chapter is structured as follows. Section 15.2 details the challenges of the state-of-the-art ToD systems, especially regarding real-time working. Section 15.3 proposes a generic architecture and components to overcome these challenges, identifying haptic communications, mixed reality, and 5G as the main enablers for ToD. Section 15.4 describes the implementation of the architecture and components into a proof of concept deployed in the environment of a seaport, including a KPI collection to study the viability of the use case. Finally, the chapter's conclusions and next steps are included in Section 15.5.

15.2 Tele-operated Driving challenges

15.2.1 Real-time issues

All the use cases described above intend to control the vehicle in real time, which is with an imperceptible latency for the user. This means that the system will only be felt as intuitive and natural if the end-to-end (E2E) latency of the system is below a certain threshold, the so-called human factor.

However, the studies found on the literature do not provide firm conclusions about the value of such threshold, with results that range from 10 to 400 ms. For example, the 5G Automotive Association (5GAA) defines a maximum admissible latency from 400 ms when the robot is only supervised to 120 ms when the operator fully controls the vehicle [4]. Moreover, the human reaction time depends on factors such as the age and qualification of the subject, the expectancy to the event, or the participating senses [5].

Regarding ToD specifically, the human factor for both sight and touch is also dependent on the characteristics of the application (e.g., velocity of the robot, size of the scenario, and other moving objects). In fact, some studies identify that the strictest human factors come from the combination of visual and tactile feedback controlling an immersive, highly dynamic visual scene, when an E2E latency of few milliseconds is needed in both senses for unnoticeable delay [6].

Unfortunately, such extremely low values cannot be satisfied with current technology, considering that sensors and actuators are usually the bottleneck of the application-level delay. For example, if the maximum E2E latency for a certain ToD application is 200 ms and the immanent latency of a modern operating robot is (in the best case) around 180 ms, only 20 ms are left for visual feedback, application processing, and network-level latencies. For a typically lower human factor for sight, this threshold is impossible to reach, although some studies propose to anticipate the user's intention via complex AI/ML algorithms [7]. On the other hand, the human factor for touch (i.e., around $10-50$ ms) may be easier to satisfy, given that haptic actuators are quicker than mechanical ones, as is the case of Meta's haptic glove prototype, which was able to achieve haptic feedback delays of just 20 ms [8]. For that reason, we envision that by applying haptic feedback to ToD, the user can be warned about a certain danger faster than only using visual feedback.

Hence, the reduction of network-level latencies for ToD will not make the difference by itself but can contribute to enable some specific use cases. Under specific configurations, 5G networks target latencies down to 1 ms, which is a reduction between 30 and 50 ms compared with current networks. Nevertheless, the main challenge is not to achieve ultra-low latencies but to achieve them while maintaining high reliability and throughput. Even with dedicated networks and proper dimensioning, such combination requires combining two 3GPP families: (i) enhanced mobile broadband (eMBB) and (ii) ultra-reliable low-latency communications (URLLC), which entails challenging tradeoffs. On the one hand, increasing the reliability requires more resources for signaling, re-transmission, redundancy, and parity, resulting in an increase of the latency. On the other hand, low latency modes are only valid in a multi-user network for a fraction of the load in the system, and at the expenses of higher latencies for the rest of the users.

15.2.2 Immersive devices

The scope of ToD is closely linked to racing simulation games. Those games are intended to emulate the behavior of real-world cars, making the user feel to be physically in the vehicle through the use of racing cockpits equipped with haptic-feedback steering wheel, gearbox, and pedals. Nevertheless, the visual feedback is usually provided by one or several 2D screens, which do not provide a sufficiently immersive experience.

Although many consumer-grade VR HMDs are available in the market today (e.g., HTC Vive, Meta Quest, Sony Playstation VR, and Valve Index), their lack of quality content has made them commercially unsuccessful, discouraging developers to create more VR content for their games. Moreover, sophisticated peripherals capable of immersing the user into the in-game action, such as pass-through mixed reality (MR) HMDs (e.g., Varjo XR3, Meta Quest Pro, etc.), haptic vests (e.g., bHaptics TactSuite, OWO, etc.), or force-feedback haptic gloves (e.g., HaptX DK2, SenseGlove Nova, etc.), are at the moment industrial-grade devices due to their expensive prices.

We consider it a matter of time that the technology evolves enough to make immersive devices commercially attractive, allowing people to get immersed into artificial scenarios and witness new ways of interacting with tools and machines. Indeed, immersive devices have the potential for providing complex user interfaces and extended spatial perception that boosts human problem-solving and manipulative skills [9].

15.3 Immersive Cockpit Architecture and Components

15.3.1 Overall architecture

As the core part of any ToD scenario, the use of the immersive cockpit influences the design of the whole architecture and the rest of the actors involved, including network, AGVs/AMRs, or UEs. In the end, data flows are the essence of IoT; so the whole architecture must be oriented to exploit this data.

In order to supervise and/or control the AGVs/AMRs in industrial environments, where every task is critical, accuracy is the main requirement. Hence, it is critical to communicate the immersive cockpit and the AGVs/AMRs with low latency, while maintaining high reliability and throughput. Using Wi-Fi, LTE, or other IoT networks different from 5G might lead to in undesired accidents costing money and even potential injuries to people. 5G is the only network capable of offering advanced slicing or QoS-prioritization schemes.

The architecture we propose can be appreciated in Figure 15.1. It has three key parts [10]: (i) 5G mmWave antenna compliant with 3GPP Rel-15 (eMBB); (ii) indoor cockpit composed of MR HMD, haptic gloves, steering wheel, and pedals, connected to an MEC via fixed fiber and/or 5G hotspot; and (iii) AGV/AMR equipped with 360ž cameras, proximity sensors, and a 5G modem. Its flexible and versatile design allows for several AGVs/AMRs with different traffic priorities to be working simultaneously in the area.

There are four different data flows from or to the immersive cockpit. In the uplink, one unique flow is used to transmit driving commands to the AGV/AMR, either using the haptic gloves or the steering wheel. In the downlink, the ACK message to these commands contains the telemetry data, used to monitor the status of the robot. The E2E latency for the haptic data flow is expected to be between 20 and 30 ms. On the other hand, the video streaming is received in a different downlink data flow, which provides a 360ž first-person view of the area (displayed in VR or MR) with an expected latency of 100 ms. Finally, a security signal that contains the information about the LiDAR and depth cameras is used to create haptic feedback that warns about the obstacles and other events on the automated route.

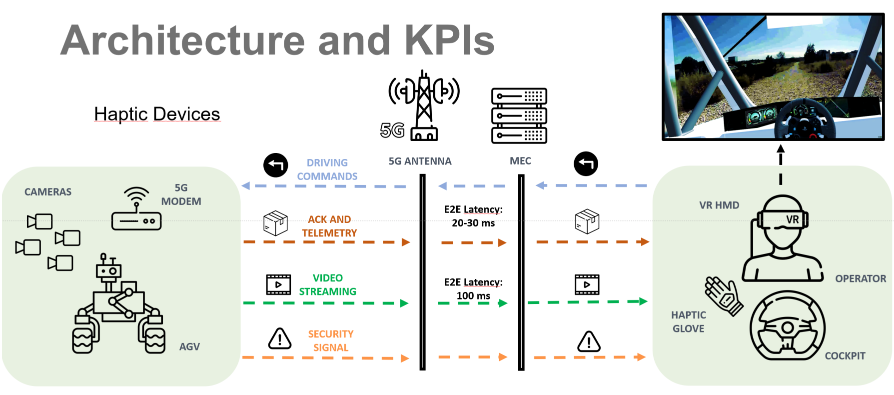

Figure 15.1 Data flows in the proposed architecture of the immersive cockpit [11].

15.3.2 Components

15.3.2.1 Head mounted displays

HMDs are devices that allow users to experience VR or MR. HMDs typically consist of a headset that includes a display and lenses, as well as sensors and other hardware for tracking the user's movements and providing a realistic experience. MR-backed tele-operation permits the 3D visualization of the scenario while displaying useful data acquired from the ambient using the robot's sensors, enriching the information for the drivers. This allows users to interact with virtual objects as if they were real, making the experience more engaging and realistic. One of the key advantages of MR headsets is their ability to track the user's movements in the real world, allowing to move around freely and interact with virtual objects in a natural way. In contrast, VR headsets often require users to stay in a fixed position, limiting their ability to interact with the virtual world. Additionally, the pass-through cameras of MR headsets can provide a more comfortable and natural experience for users, preventing motion sickness and other discomforts that can be caused by fully immersive VR experiences.

Hence, the immersive cockpit has been tested with two different HMDs (one MR and other VR). The first one is the Varjo XR-3, a high-end MR device with advanced features (e.g., hand tracking, eye tracking, and autonomous SLAM) and a top resolution of 70 pixels per degree. It also includes pass-through cameras and LiDAR sensors to enable the overlaying of virtual objects on the real world, perceived as photorealistic by the user. The second device tested is the famous Meta Quest 2, a pure VR device with lower resolution and simpler features but capable of working standalone (i.e., via Wi-Fi and not tethered to a PC). However, it was found out that the wired mode provides better latency and performance.

15.3.2.2 Haptic gloves

People trust on digital technologies to interact over long distances when they cannot be physically present in a certain place, either due to agenda overlaps or mobility restrictions. However, current approaches are limited to the communication of sight and hearing, which, although are becoming increasingly capable of simulating physical presence thanks to the development of metaverse technologies such as mixed reality and holograms, lack the ability to simulate physical interaction as touch does. In fact, it has been demonstrated that haptic interaction improves human performance over any kind of task [12], showing that the sense of touch is crucial for perceiving the environment. It seems logical to try to replicate these benefits in human–machine interaction, by implementing haptic communication into ToD. Haptic feedback can be used not only for ToD when the robot reaches its functional limits [13] but also for receiving information about the robot's state in the supervision mode [14].

Haptic communications are still an unexplored technology, meaning that the development of haptic applications, protocols, devices, and actuators is very poor. The few commercially available haptic devices are quite expensive and limited, which impedes the growth of the industry and the unlocking of the potential of haptic communications. In fact, the haptic glove used in our proof of concept is a prototype that only provides vibrotactile feedback, created by NeuroDigital Technologies.

The Sensorial XR haptic gloves feature 10 haptic actuators with LRA technology, one at each fingertip and five near the palm. Each LRA has 1024 vibration intensities with an amplitude up to 1.8 G and a resonant frequency of 205 Hz, ensuring a high level of realism and immersion. The gloves also have a low latency of under 30 ms, ensuring a seamless and responsive user experience [11]. In addition to the haptic actuators, the gloves also feature seven nine-axis IMUs working at 200 Hz. The IMUs allow for motion capture, enabling the gloves to track and replicate a user's hand movements in the MR environment. This is executed by the capture of abduction, adduction, and rotation degrees of freedom, providing a more detailed and accurate representation of hand movements compared to flex/blending sensors [15]. Finally, the gloves have four conductive fabric zones located in the thumb, middle, index, and palm. These allow for gesture capture, enabling the gloves to recognize and respond to specific hand gestures made by the user. A picture of the different sensors and actuators of the gloves can be seen in Figure 15.2.

The Sensorial XR haptic gloves can be used with either a wired or wireless connection to the supporting PC. The wired connection offers negligible latency and a sample rate of over 200 Hz, ensuring a high level of responsiveness and accuracy. The wireless connection uses Bluetooth 5.0 and has an added latency of 7.5 ms, with a lower sample rate of 120 Hz. The gloves come with a dedicated API programmed in C# language, which enables communication with the Unity3D application that defines their behavior after an event. The application can simulate complex sensations such as inter-finger collisions, surfaces rugosity, or customized vibrations, providing a rich and immersive VR experience. Figure 15.3 shows an example of how the haptic sensations can be applied to ToD, creating haptic feedback to warn about the obstacle closeness.

Figure 15.2 Sensors and actuators of Sensorial XR [16].

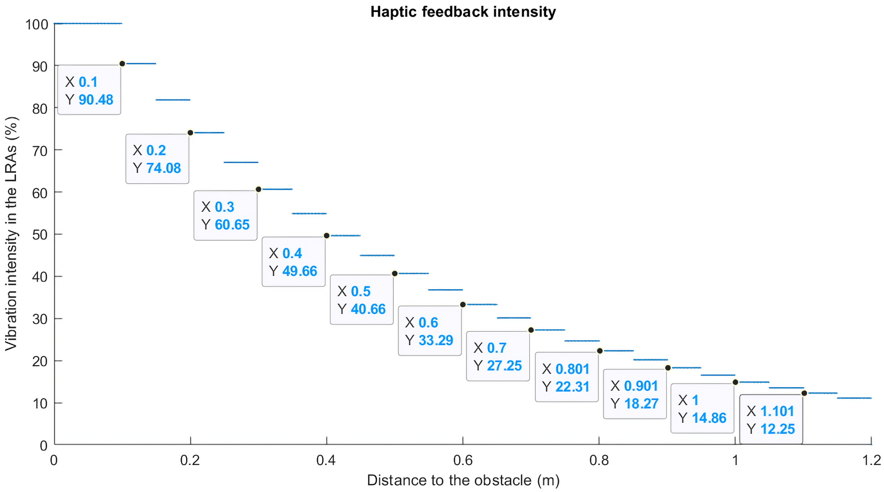

Figure 15.3 Haptic feedback intensity as a response to the obstacle closeness [16].

15.3.2.3 Wheels and pedals

The Logitech G29 is a high-performance racing wheel, pedals, and gearbox designed for use with gaming consoles and computers. The wheel features a durable, high-quality construction with a leather-wrapped steering wheel and stainless steel paddle shifters. The pedals are made of metal and feature a non-slip surface, while the gearbox offers six-speed manual shifting with a clutch pedal.

One of the standout features of the Logitech G29 is its force feedback system, which provides realistic and immersive racing experiences. Indeed, it has a dual-motor design, providing separate feedback for the wheel and pedals. The wheel also has a number of customizable buttons and dials, allowing users to customize their racing experience.

15.3.2.4 5G mmWave modems

The scarcity of mmWave modems and devices in the market has made it also challenging to implement such frequencies in our E2E solution. Only two of these devices were available for testing and integration, one on the AGV/AMR side and the other on the cockpit side. On the AGV/AMR side, we used an Askey mmWave 5G modem, which was directly connected to the AGV/AMR controller board. This modem also has a web user interface that allows for easy configuration. On the cockpit side, we used an Asus smartphone with mmWave capabilities, which was configured to create a VPN with the AGV/AMR. Both of these modems are capable of operating in the n258 5G band and provide an Ethernet link to the rest of the connected systems.

15.4 Proof of Concept

The huge traffic volume handled yearly by the port terminals, together with the variety of infrastructures and equipment managed by different stakeholders (e.g., terminal operators, maritime agencies, or logistic suppliers), make them one of the most complex parts of the supply chain.

We propose to digitalize and automate the port logistics by taking advantage of the data richness of IoT, implementing innovative use cases such as the "improvement of the driver's safety with mixed-reality and haptic solutions." It envisions a future when AGVs/AMRs will be used as mobile cranes to transport the ship containers around the port terminal, optimizing the loading and unloading of assets [15]. The ToD of the AGVs/AMRs will be available as a safety backup (i.e., for both supervision and total control), performed from a remote indoor cockpit to avoid accidents and hazardous situations for human operators. In an attempt to provide more intuitive and immersive ways of operating the AGVs/AMRs, the use of 2D screens and input devices (e.g., mice or keyboards) will be avoided. Instead, the immersive cockpit will be equipped by HMDs and haptic gloves, capable of providing multisensory information of the port area.

15.4.1 End-to-end use case description

To understand the role of the immersive cockpit within the use case, it is necessary to provide a whole picture about the scenario and actors involved. As a proof of concept before the deployment in the port terminal, several AGVs/AMRs are programmed to follow automated routes around a specific area, simulating the logistics operations. Simultaneously, a remote operator utilizes the immersive cockpit to supervise the task, with the possibility of controlling (i.e., changing or stopping) the route at any moment. In the extraordinary case that the robot's autonomous mode is not available (e.g., SLAM fail, or non-avoidable obstacle in the path), the control of the AGV/AMR totally shifts to the cockpit for a full ToD. During this manoeuver, the visual and haptic feedback provided by the immersive cockpits allows the user to precisely overcome the obstacle and put the AGV/AMR back in its route; so it can work autonomously again.

While the ToD cockpit is integrated with all the peripherals mentioned before (i.e., steering wheel, pedals, haptic gloves, and HMD), the supervision mode can alternatively be performed through an "on-site cockpit" composed by the haptic gloves only (see Figure 15.4). This intends to prove the potential of such devices as both IoT sensors and actuators, as well as to explore new ways of controlling the AGVs/AMRs.

15.4.2 Remote cockpit

The remote cockpit implements all the described components into a unified solution. However, although the hardware is important in order to enable the features desired, the software is the true important part. The XR application we implemented is an MR simulation of a car interior and exterior, as depicted in Figure 15.5. The Unity scene was created by modifying a car model using Blender software and then importing it into Unity. The GStreamer unity plugin is used to receive H264 video streams from multiple cameras, which are projected into four rectangles within the car scene. In addition, UDP C# scripts are used to receive telemetry and security information from the nodeJS cockpit application. This information is displayed in the car's user interface components and the steering wheel is also moved according to the movement of the physical steering wheel being used to remotely drive the AGV/AMR. The telemetry information retrieved from the AGV/AMR every 100 ms includes longitude and latitude GPS position, RTT in milliseconds for the UDP commands, steering angle of wheels, vehicle speed (m/s), traffic lights status if sent, engine RPM, driving mode, battery energy, and encountered objects if any. On the other hand, the security signal serves for haptically warning the user about the events on the route, including the case that autonomous mode is no longer available and ToD is required.

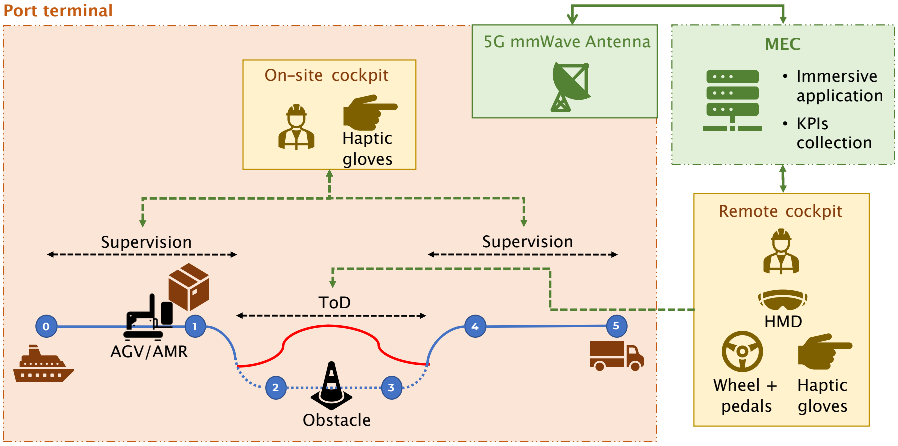

Figure 15.4 Immersive cockpit use case scenarios: route control (supervision) demo and ToD demo.

Figure 15.5 Remote cockpit implementation from first-person view (left) and third-person view (right).

Figure 15.6 On-site cockpit implementation (left) and route control schema (right).

15.4.3 On-site cockpit

This cockpit is only used for supervision and command of the AGVs/AMRs, with the Sensorial XR haptic glove playing a pivotal role. The application is focused on using the Sensorial XR SDK interface to handle the data received from the haptic glove, including vibration levels, hand position and rotation, and gesture performed. This allows the user to easily control and manage the AGV/AMR's actions. The gestures that can be performed include: (i) going to a specific point in the route; (ii) stopping the movement; and (iii) resuming the movement (see Figure 15.6). This allows the user to avoid potential dangers for the robot, such as approaching an obstacle on the route, by receiving haptic feedback with an intensity that depends on the proximity of the obstacle, as depicted in Figure 15.3.

15.4.4 KPIs collection

In a first attempt to test the viability of the immersive cockpit implementation, the following KPIs were analyzed during the proof of concept deployed in the port:

- Round trip time (RTT)
- Video latency
- Video throughput
- E2E latency

First of all, the RTT is measured from the application layer, and, therefore, it considers the time that it takes for a UDP control command to be sent from the application (either from the gloves or the wheel/pedals) to an AGV/AMR, and for the AGV/AMR to send back the telemetry information to the application. The RTT is automatically calculated for each UDP message

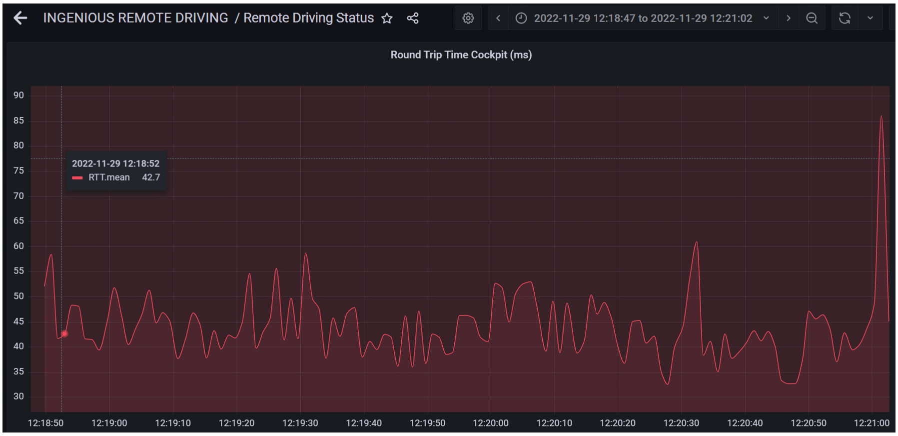

Figure 15.7 Round trip time of remote driving command in Grafana.

and stored in a Grafana database, as Figure 15.7 shows. In order to effectively manage and store all the data, we have implemented a Grafana-based system in the MEC. This system receives asynchronous UDP messages from the nodeJS application on the HMD side through the use of a Telegraf plugin, which then injects the messages into the Influx DB database for storage. It can be appreciated that the RTT is very low, of around 7.5 ms, thanks to the use of a 5G network.

The video latency and throughput are jointly measured via slow-motion analysis, using the GStreamer tool to configure different video resolutions. In this case, the communication is only downlink (i.e., from the AGV/AMR to the cockpit), and both KPIs are measured from the cockpit perspective. Hence, the throughput captured is 2.5 Mbps for 360 p resolution, 8 Mbps for 720 p resolution, and 16 Mbps for 1080 p resolution. The same resolutions offer average latencies of 138.4, 156.4, and 173.6 ms, respectively; quite high values considering that no video codec is used.

Finally, the E2E latency is measured via slow-motion analysis too. We are aware that such method includes several biases such as the behavior of the peripherals, the slow-motion camera or the AGV/AMR; but we chose this method as a first approach, due to its simplicity. The E2E latency is measured on the on-site cockpit and includes the RTT plus delays of sensors/actuators of the cockpit and the AGV/AMR. However, we identified that the bottleneck may be the specific AGV/AMR being used. Hence, the data shown in Figure 15.8 demonstrates that, on average, there is a noticeable difference in perceived latency when an AGV/AMR is resumed on a route or sent to a specific point (735 ms) compared to when it is stopped (362 ms). This is due to the fact that it takes less time to mechanically stop the wheels using the brake than it does to start movement.

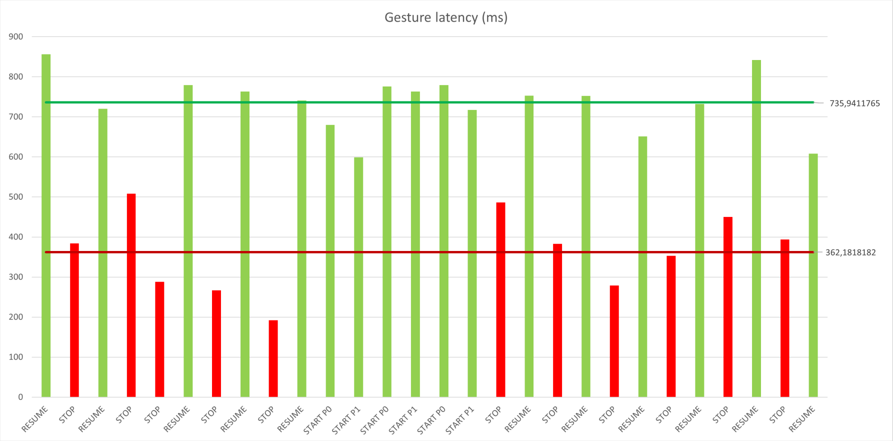

Figure 15.8 Perceived E2E gesture latency.

15.5 Conclusion

This chapter has explored the benefits of using immersive cockpits for ToD and supervision of AGVs/AMRs in real time, identifying key enabling factors such as haptic communication, mixed reality, and 5G. In order to demonstrate the viability of this technology, a proof of concept was deployed in a port environment with the goal of improving operator safety through indoor ToD. It was found that, while the literature defines an end-to-end (E2E) latency threshold of under 50 milliseconds for immersive ToD, this is currently not feasible due to mechanical limitations.

The performance metrics collected during these demonstrations resulted in average E2E gesture latencies of 362 ms for braking and 736 ms for acceleration, despite a network RTT latency of only 7.5 ms. Regarding the E2E video latency, the average values are between 138.4 and 173.6 ms, depending on the resolution demanded. These despair results, with a great gap between the E2E gesture latency and the RTT or video latencies evidence that the robot's mechanical actuators, are the primary bottleneck for ToD, and therefore the E2E gesture latency can be widely reduced using more mechanically advanced AGVs/AMRs.

Nevertheless, it must be considered that such mechanical latency is also present when manually driving the vehicle, not only when tele-operating it. Hence, more relevant KPIs (such as the communication and application latencies) should be prioritized when studying the real-time viability of immersive ToD. The low RTT provided by the 5G network, together with the low E2E video latency obtained show that the application latency is acceptable for this use case. Moreover, rudimentary subjective tests performed on different users that participated in the proof of concept agreed that the ToD was intuitive and smooth, whereas the latency was almost un-noticeable. In addition, throughput measurements showed that this ToD application has minimal bandwidth requirements that can be easily satisfied by 5G Release 15 (eMBB) networks.

Despite these challenges, the proof of concept showed the potential of haptic and mixed reality assisted ToD to revolutionize industries and logistics in the coming decades. We consider this use case to be completely open to future improvements and technological advances. Haptic communication will continue to be explored through the creation of an immersive laboratory at the Universitat Politècnica de València in late 2023, where QoE-based optimizations will be conducted for various sectors including education, industry, and logistics.

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