UNIVERSITAT POLITÈCNICA DE VALÈNCIA

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Real-time haptic communications for immersive telerobotics

Master's Thesis

Master of Science in Telecommunication Technologies, Systems and Networks

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Objetivos

The main objectives of this Master's Thesis are to study the potential of haptic and immersive communications for tele-robotics and to implement a proof of concept that demonstrates their capabilities. For the purpose, several secondary objectives are proposed:

- Identify the enabling technologies for the remote control of mobile robots in real time, focusing on haptic and immersive communications, and the upcoming 5G-Advanced networks.
- Describe the state of the art of haptic and immersive devices and applications, as well as the innovations expected in the coming years
- Overview the use cases and key performance indicators (KPIs) of haptic and immersive communications applied to tele-robotics
- Design and implement a proof of concept that allows the testing of haptic and immersive communications using tactile and mixed-reality devices respectively, controlling a mobile robot in real time.
- Carry out drive tests to study the performance of the 5G networks deployed in the Valencia Port and the UPV campus.

Metodología

This Thesis takes place under the scope of the H2020 project iNGENIOUS (Next-GENeration IoT sOlutions for the Universal Supply chain), which has a particular use case regarding the application of mixed-reality and haptic devices to tele-robotics. All the content of this Thesis is fruit of the contribution of the author to the iNGENIOUS project or to autonomous research carried on during his stay in Turku University of Applied Sciences, Finland.

First chapter will introduce the benefits of haptic-assisted tele-robotics, as well as the scope and motivation of the project. Second chapter will consist in a literature review about the state-of-the-art of the main tele-robotics enablers identified, including haptic communication. In third chapter, the theoretical research carried out will be complemented with the description of a proof of concept that demonstrates the remote driving of mobile robots in real time using haptic and immersive devices. Fourth chapter will describe the implementation of the proof of concept by two different demonstrations, followed by a KPI collection and 5G drive test campaign to test the viability of the proof of concept. Finally, fifth chapter will provide the conclusions and future research areas related to this Thesis.

Desarrollo de prototipos y trabajo de laboratorio

Two different demonstrations have been implemented, each of them using different architectures, components and protocols. Both consist in a mixed-reality application developed in Unity, designed to integrate tactile devices into an immersive cockpit. The aim of the demos is to enable the collection of key performance indicators that allow to study the feasibility of the use case with the current technology, analyzing the impact of the network in the end-to-end solution.

On the one hand, the first demo (so-called remote driving demo) consists in the teleoperation of an educative tank robot located in Turku University of Applied Sciences, Finland. The user is attached with VR goggles to visualize the robot and the environment through a digital twin, while he is able to remotely drive the robot in real time using a VR controller and a haptic glove. Haptic feedback is implemented when the robot moves to make the user able to feel in which direction the robot is moving.

On the other hand, the second demo (so-called route control demo) is a direct contribution to the iNGENIOUS project, and therefore an industrial Automated Guided Vehicle (AGV) is used. Instead of driving the AGV, it works autonomously following a predefined route, so the user can use the haptic glove to stop, resume or change the route. Apart from telepresence in the area via video feedback, haptic feedback is activated whenever an obstacle appears, vibrating more intensely the closer the obstacle is.

Resultados

The KPI collection shows that both application-level latency and network-level latency do not fulfil the requirements identified in the literature, due to technological limitations. The route control application demonstrates that robot actuators are the bottleneck of the application, since the perceived E2E latency is 362 ms for braking vs 736 ms for acceleration, despite the network latency is only 29 ms. The remote driving application proves that teleoperation over vast distances does not add much more latency, resulting in a perceived E2E latency of 446 ms between Valencia and Turku (Finland). Though 5G mmW frequencies can benefit tele-robotics use cases, the 5G measurement campaign shows that such high frequencies are not appropriated for outdoor environments, unless the operating area is constrained in the pointing direction of the antenna.

Líneas futuras

The next steps include the optimization of the AGV use case and its implementation in the Valencia Port, as well as the creation of an immersive laboratory in the UPV campus to study the application of haptic communications to several verticals including tele-robotics.

Publicaciones

A. Sierra; R. Lozano; I. Ibáñez; D. Gomez-Barquero; M. Lorenzo; M. Fuentes, «5G-Enabled AGVS for industrial and logistics environments,» 2021.

I. Benito; J. Ruiz; M. Fuentes; M. Cantero; M. Pasamontes; R. Lozano, « iNGENIOUS D3.4 Bio-haptic and XR-enabled IoT devices,» 2022.

Abstract

This Master's Thesis explores the role of 5G networks within the metaverse, especially as an enabling technology to implement haptic communications in telepresence and tele-robotics applications. The importance of low latency and its impact on the user experience are explained, as well as the technical solutions provided by the fifth generation of mobile networks. As a complement to the theoretical work, the implementation of a use case framed in the H2020 project iNGENIOUS (Next-GENeration IoT sOlutions for the Universal Supply chain) is demonstrated. This demo consists of the immersive, remote control of robots using state-of-the-art haptic gloves and mixed-reality goggles, with the aim of guaranteeing the safety of the operator. Finally, a campaign of 5G sub-6 GHz and mmW measurements is carried out in order to analyze several key performance indicators of the solution.

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I. Introduction

People trust on digital technologies to interact over long distances when they cannot be physically present in a certain place, either due to economic challenges, agenda overlaps, or mobility restrictions related to sanitary issues. In those situations, two different forms of remote interaction can be distinguished today: (i) audiovisual telecommunication, widely extended, and (ii) communication in virtual worlds, which provides more audiovisual immersion but is less extended. However, a third approach could be to eventually include other senses like touch, smell or heat as feedback to the remote control of objects, creating an even more immersive interaction.

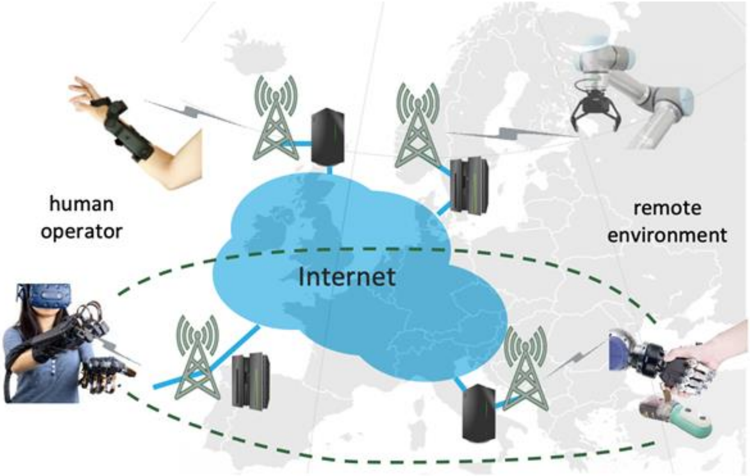


Figure 1 Scheme of the remote interaction between humans and robotic arms over the Internet *[1]*

As illustrated in Figure 1, the more realistic form of remote interaction for a human operator should include robotic devices capable of precisely moving and manipulating objects, controlled by interfaces that provide haptic feedback by resisting hand and finger motion as well as stimulating the skin with vibrations; all of it communicated through the Internet, capable of carrying the commands sent by the user and the haptic feedback back to him. This should be complemented by metaverse technologies like mixed reality (MR), holograms and digital twins, which allow to visualize virtual environments that mimic the behavior of the real world. Until we do not develop this system, we will fail to achieve both truly immersion into remote locations and real-time teleoperation.

However, haptic interactions would require application-level delays as low as 10 ms or even lower in order to be perceived in real-time by humans [2]. Performing such interactions locally in the range of milliseconds is beyond our technical capabilities today, and performing them over long distances will add even more latency. Furthermore, this problem will not be solved with the development of 5G networks that target significant network-level latency reductions (down to 1 ms), since sensors and actuators are usually the bottleneck of the application-level delay. For example, 5G-PPP found that the maximum application-level latency for remote surgery must be 200 ms, while the immanent latency of a modern operating robot is already around 180 ms; leaving only 20 ms for visual/haptic feedback, application processing and network-level latencies. It would require the use of complex Artificial Intelligence and Machine Learning (AI/ML) algorithms capable of anticipating the situation and the intention of the surgeon to make the use case feasible [3].

Thus, the future of a wide variety of tele-robotics use cases does not depend on telecommunications, but on mechanics. Solely minimizing network delay does not allow humans to efficiently control a robot in real-time if the motors do not respond instantly. However, the haptic feedback for tele-robotics (and for many other applications) will definitely benefit from low-latency networks. Haptic actuators, much quicker than mechanical actuators, are able to achieve haptic feedback delays of just 20 ms, in the case of Meta's haptic glove prototype [4]. In this case, Meta identified that the unnoticeable delay margins range from 15 to 50 milliseconds, meaning that the use of low-latency networks can make the difference between real-time and no real-time haptic communication.

Haptic communications, enabled by low-latency networks, are expected to transform the ways humans interact over long distances, revolutionizing verticals such as healthcare, education, entertainment and industry. But as mentioned before, haptic communications need a companion that complements and enriches the experience of the user, and it is metaverse technologies capable of providing immersive audiovisual content. Combined, they will contribute directly to the promotion of remote interaction, which as a consequence will also contribute to the UN's Sustainable Development Goals [5] by: (i) reducing our carbon footprint and the effects of climate change, (ii) adding resilience to the economy by mitigating adversarial health conditions as well as disruptions due to major weather events, and (iii) making the access to education and training less dependent on resources or travelling.

I.1. *Scope.*

The goal of Industry 4.0 is to improve the efficiency by incorporating cutting-edge technologies in all processes and assets, as well as to provide information of the processes in real time [6]. The design principles identified in the literature focus on the automation and digitalization of the processes in order to guarantee interconnection, information transparency, decentralized decisions and technical assistance [7]. The next generation of telecommunication technologies (i.e. 5G and beyond), together with emerging technologies such as robotics, Edge/Cloud computing and AI/ML, are expected to implement these principles. These next-gen networks will support simultaneously human-centric and machine-centric use cases thanks to the use of network slicing, making it possible to combine features of the following types of communication: (i) Enhanced Mobile Broadband (eMBB); (ii) Ultra-Reliable Low Latency Communications (URLLC); and (iii) Massive Machine Type Communications (mMTC).

The 5G Automotive Association (5GAA) is leading the definition of Tele-operated Driving (ToD) scenarios, depending on the level of control of the vehicle: from Level 0, where the robot is fully automated, to Level 3, where the operator fully controls the vehicle [8]. Nowadays, there are many sophisticated mobile robots available in the market that have a high level of automation and are able to navigate without human input, thanks to the perception of the environment (by sensors such as LIDARs, RADARs, and cameras) and predefined traffic rules. However, occasional failures occur when the scenario is unseen for them or the inputs are contradictory, situations where human drivers still outperform machines. Some of these situations, identified by [9] may be: (i) Low visibility due to extraordinary weather or light conditions; (ii) Malfunctioning traffic signal; (iii) Unclear or handwritten text; and (iv) Sensor failure. A remote-control system promises to be the best option to solve these problems and provide a safety backup for self-driving vehicles, while maintaining the advantages of autonomous vehicles such as improved efficiency and lower costs. Some ToD use cases are listed in the Table 1, where it can be observed that low latency is a KPI for the majority of them.

Use Case	Description	KPIs	Type
Remote Robot Control	Manually controlling vehicles that perform hazardous tasks	Ultra-Low Latency	URLLC
Automated Guided Vehicle SLAM	Coordinating autonomous vehicles without needing to pre-define routes	Low Latency Reliability Location-awareness	URLLC
Mixed Reality Remote Expert	Using Head Mounted Displays (HMDs) to guide a worker when performing a task	Ultra-Low Latency Bandwidth	URLLC + eMBB
Predictive Maintenance	Using dozens of sensors to represent the status of a machine in real-time	Reliability Device Costs Device Density	URLLC + mMTC

Table 1 ToD use cases enabled by 5G *[6]*

I.2. *Motivation.*

Logistic port environments are key parts of the supply chain, especially in the case of the port of Valencia, the sixth largest of Europe in terms of traffic volume. Every year, this port handles around 2 million trucks, 3 million containers, 8 thousand ships and 3 thousand trains [10]. Such traffic volume is supported by a variety of infrastructures and equipment managed by different stakeholders, which include terminal operators, maritime agencies and logistic suppliers. In order to maintain its relevance in the Mediterranean Sea, the Port activities and processes need to be digitalized, helping to transform the supply chain into a smart and connected network that complies with the vision of

Industry 4.0. To do so, the iNGENIOUS project proposes to take advantage of the data richness that IoT can provide [11], changing how products are made and delivered and enabling the exploitation of the supply chain by new actors.

iNGENIOUS identifies several key technologies for the successful implementation of IoT in the Port architecture, including 5G networks, Edge/Cloud computing extensions, AI/ML algorithms (for smart management of the supply chain at the device, application and network level), and DLTs (for securely and dynamically storing the information gathered). These technologies are applied by six different use cases that merge the vision of the Next Generation Internet initiative with the future necessities of the supply chains [12]. The most innovative use cases describe the use of Automated Guided Vehicles (AGVs) in different parts of the logistic scenario, as it is the case of the “Improved driver’s safety with Mixed Reality and haptic solutions” use case that inspired this thesis, henceforth called “AGV use case”. It proposes the ToD of AGVs using immersive and tactile devices, which is expected to improve the efficiency of the Port activities by optimizing the loading and unloading of assets, avoiding accidents and hazardous situations for human operators, and allowing predicting maintenance.

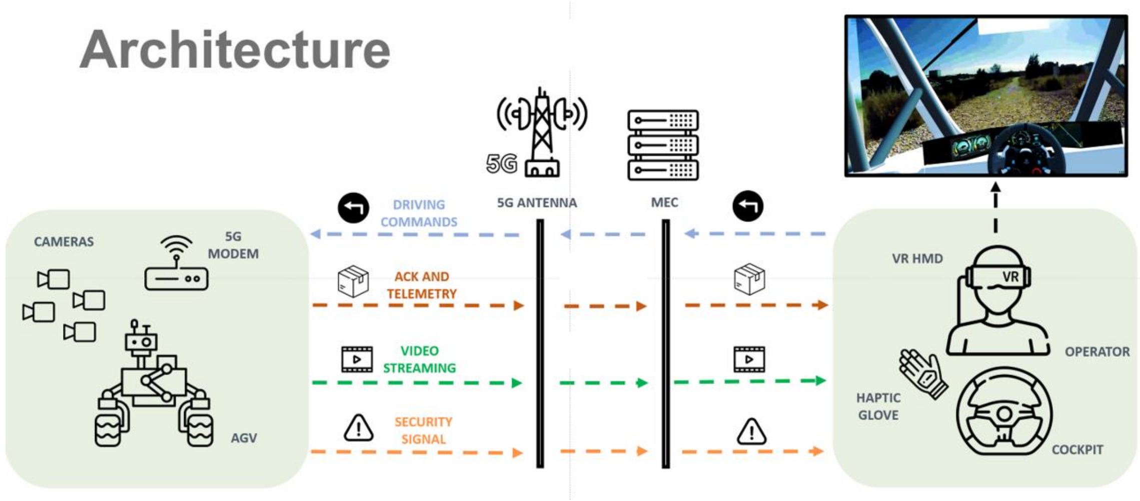


Figure 2 Data flows in the proposed architecture of the AGV use case *[13]*

The AGV use case architecture can be seen in the Figure 2. It has 3 key parts [10]: (i) 5G mmW antenna compliant with 3GPP Rel16 (URLLC) installed in the Valencia port; (ii) Indoor cockpit composed of VR goggles, haptic gloves, steering wheel and pedals, connected to a MEC via fixed fiber and/or 5G hotspot; and (iii) AGV equipped with 360º cameras, proximity sensors and a 5G modem. The combination of these three actors is innovative in logistics, since it makes possible to remotely and immersively control the robot in real-time (with low latency) only when necessary, whereas the rest of the time the AGV follows programmed routes for loading and unloading assets. In case that the routes cannot be followed due to an obstacle or adverse event, the operator receives a tactile warning and is asked to drive the vehicle. Thanks to the flexibility and versatility of the solution, several AGVs with different traffic priorities will be driven simultaneously in the port area, supporting even alternative types of control.

This Thesis explores the possibilities that the AGV use case opens regarding the ToD of robots using immersive and tactile devices, implementing one of the alternative types of control mentioned, with the haptic glove playing a pivotal role.

II. Tele-robotics enablers.

As a safety and latency critical application, ToD will need not only the use of URLLC and other network technologies provided by 5G and 5G Advanced, but also to engage the user in multisensory and realistic 3D environments that facilitate the remote driving. This section will provide an overview of the main tele-robotics enablers, including haptic communications, mixed-reality, digital twins, and 5G low-latency networks.

II.1. *Haptic communications.*

People often use physical haptic interaction (exchange of force and tactile information) to coordinate in collaborative tasks, such as dancing or moving heavy objects. In fact, it has been demonstrated that haptic interaction between humans improves the performance of the task, regardless of the skills of the subjects [14]. With robots increasingly demanded on the workplace, the logical way to go is to replicate the benefits of human-human interaction into human-machine interaction, by implementing haptic communication between humans and robots.

Despite the advances in robotics, mobile robots cannot be fully autonomous on unpredictable or dynamic environments, but they need to be supervised and/or controlled by human operators. The best technique to minimize conflict or facilitate the understanding between humans and machines is clearly haptic communication, specially for changing situations when the robot reaches its functional limits [15]. Even supposing a fully autonomous navigation, haptic feedback could be useful for human operators wearing haptic devices for avoiding collisions with the robot or receiving information about the robot state [16].

Typical haptic systems for mobile robots are two-way systems consisting of a master domain (i.e. the user), a slave domain (i.e. the robot) and a communication medium. The master domain generates commands that are transmitted over the communication medium to the slave domain, who responds sending back haptic feedback to the master domain. However, when the cooperation between humans and robots is performed remotely, timing issues appear caused by transmission over a network. An excessive delay on the communication medium affects twice to the total latency, which in mobile robots leads to instability or imprecision, whereas in humans it causes the sensation of discomfort or lack of interaction [17]. In fact, it has been identified that the expected Quality of Service (QoS) for haptic communications is higher than the expected for audiovisual communications. Depending on the subject and the conditions of the test, the two-way turnaround time between master and slave (i.e. RTT) for perceived real-time communication is between 1 ms and 100 ms [18]. This value includes haptic feedback, application processing and network-level latencies.

The development of haptic applications, protocols, devices and actuators is key, not only for reducing the latency, but to achieve true immersion and unlock the full potential of haptic communications. The same happened with audiovisual (multimedia) communications, whose success is mostly due to the development and optimization of screens and streaming services. For instance, haptic data compression will be key for Quality of Experience (QoE) of haptic communications, but it is still unexplored. Similarly to the compression of multimedia signals, lossy compression algorithms that remove irrelevant information (i.e. haptic signals that cannot be perceived by humans or represented by the hardware) are the most suitable [19]. But, as a novel technology, there are too few commercially available haptic devices to define which are the hardware limits, and hence it impedes the development of software and protocols.

Device	Tactile feedback	Force feedback	Tracking	Price (pair)
HaptX DK2	133 Pneumatic points	133 Pneumatic points (175 N)	Magnetic sensors	80000 €
SenseGlove Nova	2 LRA + 1 voice coil	5 DC servomotors (20 N)	5 IMUs	5400 €
Sensorial XR	10 LRAs	No	7 IMUs	4500 €
Manus Prime X Haptic	5 LRA	No	6 IMUs	4000 €
Senso DK3	6 LRAs	No	8 IMUs	1210 €
bHaptics TactGlove	10 LRAs	No	No	360 €

Table 2 Relevant haptic gloves available at 2022

Indeed, most of available haptic devices are expensive and primitive vibrotactile gloves, being even more difficult to find gloves that include force feedback. State-of-the-art vibrotactile actuators are mainly LRAs (linear resonant actuators) due to their small form factors and low power consumption, whereas other technologies such as voice-coils and piezoelectric actuators lack these features despite delivering richer and more expressive sensations [20]. On the other hand, state-of-the-art force feedback actuators consist of exoskeletons that restrict the movement either passively (using brakes or dampers) or actively (using DC servomotors) [21]. Most sophisticated technologies include the use of pneumatic or hydraulic actuators that deliver simultaneously tactile and force feedback, simulating a realistic and multi-dimension sense of touch. Some relevant haptic gloves available in the market can be seen on Table 2 and Figure 3, where Sensorial XR is the one that has been used in iNGENIOUS for the implementation of the AGV use case.

Figure 3 Haptic gloves from Table 2

II.2. *Mixed reality.*

In the upcoming era of metaverse, people will be able to get immersed in simulated scenarios and experience new ways of interacting with tools and machines. The simulation can occur in a virtual world (Virtual Reality – VR), overlaid on the real world (Augmented Reality – AR), or as a combination of the above (Mixed Reality – MR). In general, eXtended Reality (XR) serves as an umbrella term that covers all the immersive technologies mentioned, but it is less used in the literature than VR, AR or MR. In fact, VR is the most used term since VR HMDs are already available at scale on the market today and VR applications are considerably popular in the gaming industry. AR and MR HMDs are currently restricted to enterprise use due to their expensive prices and a lack of content availability. However, MR headsets are more appropriate for mobile tele-robotics, since they will facilitate ToD by providing detailed user interfaces and extended spatial perception that will boost human problem-solving and manipulative skills [22]. By capturing data from the environment using the robot's sensors, MR-aided teleoperation allows real-time visualization and interaction with virtual objects that enrich the information for the operators. In addition, the 3D rendering can then be complemented with tactile feedback and 360º video transmission to create a complete representation of the working environment.

So far, the problem of AR and MR applications is that they are more complex than VR ones because the placement of virtual content over the real world requires the real environment to be analyzed in real-time. This is done by heavy duty algorithms and processing blocks that interact with each other as follows [23]:

- Sensor Capture and Preprocessing: RGB cameras, depth cameras, IMUs and LIDAR/RADAR sensors produce hundreds of Mbps of raw sensor data that cannot be compressed due to the real-time constraints.
- Simultaneous Location and Mapping (SLAM): The device uses the sensor data to build a 3D map (3D point cloud) of the unknown environment, and then locates itself in it using statistical estimators.
- 3D Reconstruction: The 3D point cloud is processed to create a more detailed 3D model (3D mesh) of the real world, allowing to properly anchor the virtual objects so they are perceived realistically.
- Semantic Understanding: The 3D mesh is segmented using artificial vision algorithms in order to differ the different objects that compose the scene, increasing the accuracy of the anchoring and allowing features such as hand tracking.
- Dynamic Occlusion: The object segmentation is used to properly hide the virtual objects behind the real ones, but the real-time constraints make this process difficult for moving objects.
- AR Engine and Frame Rendering: The processed data in the previous algorithms is used to simulate the physics and render the virtual content accordingly.

In MR (and AR) systems, the latency is defined as the time between the movement of a tracked object and its corresponding movement displayed on the HMD’s screen, and hence it is also called motion-to-photon latency. Although it is not clear which deadline is needed to avoid cybersickness and discomfort in the user, some literature reviews identify that the motion-to-photon latency must fit between 15 and 50 ms [24]. This means that the sum of all the previously described processing blocks needs to comply with this constraint, requiring a huge computing power in the HMD and/or in the supporting PC. Nevertheless, MR HMDs will not be attractive to neither consumers nor enterprises until they are lightweight and mobile, so the processing tasks need to be offloaded from the device to an Edge/Cloud server. This concept, called MR offloading or split rendering, takes advantage of the modularity of the processing blocks and the versatility of 5G network slicing to dynamically offload the MR algorithms to the Edge/Cloud depending on the resources available [25].

II.3. *Digital twins.*

The 6G vision is to connect the digital and the physical worlds via human interaction with virtual objects and experiences that simulate the real ones through all the senses [26]. In this vision, the virtual and interactive real-time representations of real objects, so called digital twins, promise to be a key application of 6G, especially in the supply chain or the Industry 4.0 application areas. Digital twins use the MR technology and algorithms to build 3D models in real time that engineers can utilize to freely interact with objects and to test their functionalities without physical limitations. The 3D models can also show real-time status, shape, condition, and other important information of the real asset, increasing the awareness on the system [27].

AI/ML algorithms play a fundamental role in digital twins, especially regarding data filtering, data processing and decision making. Based on the processed data, models for decision making can apply or suggest the optimized actions according to the observed situation [28]. For example, digital twins for tele-robotics can provide optimization of robot trajectory thanks to the use of AI/ML algorithms that can learn which paths are less often obstructed. Using appropriate AI/ML data analytics, digital twins can enhance decision making by predicting the behavior of the robots, facilitating its maintenance and guaranteeing its operation [29].

The concept of digital twins appeared in the 1960s, but it was not developed until the 2000s with the emerging of 3D modeling and simulation software, and it is expected that the enhancements on information and communication technologies allow them to release their full potential in the 2020s. Recently, digital twins have been widely proposed mainly for Industry 4.0, Healthcare and Smart Cities in the literature, but many of them are still proofs of concept. Three main types of digital twins can be distinguished in the literature:

- Simulation-based digital twins, where the virtual objects are programmed to behave with the desired performance, acting as a reference to the performance of the real objects which is corrected in real time in case of deviation. It requires the design of 3D models in a CAD software previously to their use in a simulation software, as well as the definition of their physics and behavior using a kinematic model [30]. In complex systems, models need to be lightweight for faster processing, which is done by selecting only the necessary details on their geometry or attributes [31].
- Shadow-based digital twins, where virtual objects mirror the performance of the real objects in order to allow the user to monitor and analyze the asset enriched with status data. The 3D models are captured and/or updated in real time and are usually represented in VR/AR for higher immersion and easiest interaction with the 3D model.
- Bi-directional digital twins, where the real asset or process is modeled in the virtual world in order to be optimized and then the results are transferred back to the real world. It is a combination of the two latter categories, and therefore the most complex.

Digital twins however, similarly to the majority of 6G applications, demand a huge amount of data to be captured and communicated in real time for its processing, and hence 5G may not be suitable for satisfying them. The requirements vary depending on the use case, but in general it is needed a combination of IoT, URLLC and eMBB technologies, with the inconvenient that achieving low latency, high reliability and high throughput is a well-known trade off of 5G networks (see Figure 4) that 5G-Advanced and 6G are expected to solve. In the meantime, it is also expected that the combination of key technologies such as 5G-A-IoT, Edge computation and AI/ML analytics provides the intelligence needed to implement at least some of the use cases of real-time digital twins. Moreover, a literature review performed by [32] identifies the network domain as a key enabler for ensuring real-time processing, modelling, and visualization of the digital twin once the data is gathered by the sensors.

II.5. *5G low latency.*

The 3rd generation partnership project (3GPP) is currently defining the next steps for 5G and beyond 5G (B5G) of communication networks. The current and upcoming 3GPP Releases will play a decisive role in tele-robotics, helping to offload heavy algorithms and data processing from the robot to the Edge/Cloud, thus mitigating the cost of hardware and allowing the robot to complete more complex missions. According to [33], robotic wireless networks have different QoS requirements than conventional networks, since they need uninterrupted and ubiquitous connectivity to avoid collisions and guarantee operating safety. This translates into the need of mobility, reliability and low latency, as well as high uplink and downlink bandwidth to be able to offload the processing outside the robot.

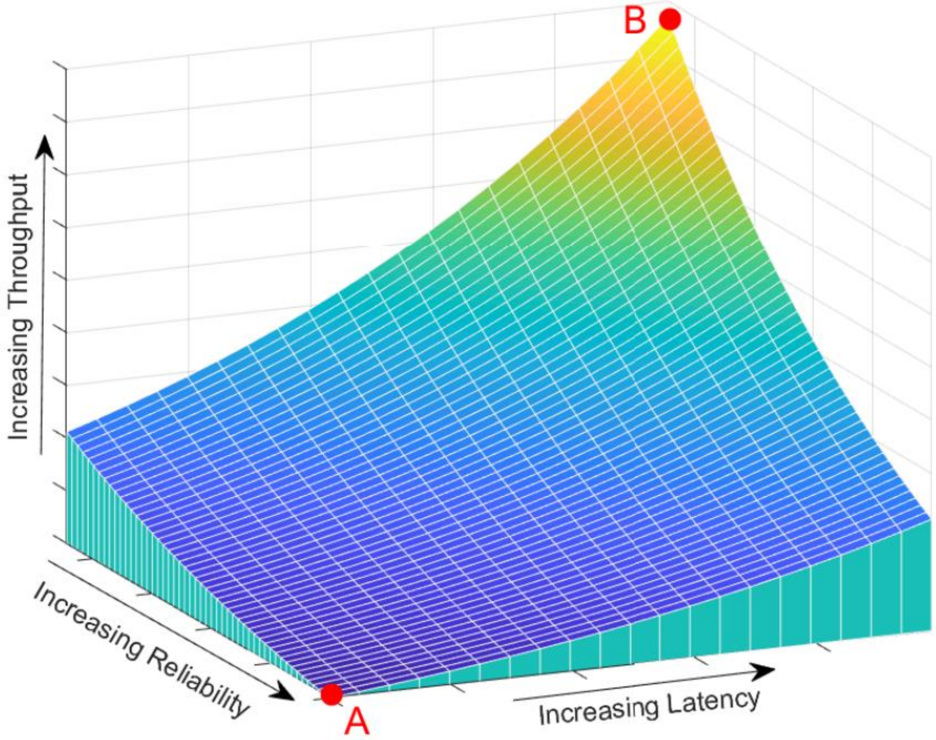


Figure 4 Tradeoff between latency, reliability and throughput *[34]*

Although they can coexist for different users thanks to network slicing, implementing simultaneously URLLC and eMBB is challenging due to the tradeoff between stringent latency, reliability and throughput (see Figure 4), since the three KPIs can only be guaranteed in a multiuser network for a fraction of the load in the system, and at the expenses of higher latencies for the rest of the users [35]. It would be required the use of techniques such as massive MIMO, coordinated multi-point, and QoS-aware scheduling that current 5G networks have not implemented yet.

The main problems of 5G have been the delay of the specifications due to the pandemic and the marketing strategies of the operators. The first phase of 5G (Release 15) was sold in 2018 as if it included specifications that would not be a reality until the third phase (Release 17), more than four years later. In reality, the new specifications will not be fully operational in commercial equipment until 2023 or 2024 at the earliest, because manufacturers must comply with the new regulations [36]. Hence, the majority of 5G equipment available today corresponds to Release 15 (eMBB), which main improvement over LTE is the increased bandwidth.

On the other hand, URLLC is a more important enabler for tele-robotics and any kind of mission critical applications. According to [37], 3GPP used a brute-force approach based on system-level simulations to guarantee user plane latencies of 1 ms and connection reliability of 99.999%. The main enhancements were included in Release 16, but some minor features were also defined in Release 15 or even Release 17. Some of them are: (i) new numerologies that provide shorter transmission times (mini-slot based scheduling); (ii) transmission diversity by dual connectivity; (iii) downlink multiplexing with eMBB, via pre-emptive scheduling; (iv) uplink grant-free transmission; and (v) fast HARQ retransmission. It should be noted that 5G private networks are the best option to implement these tools, because private networks can be customized and optimized for the desired industrial application. URLLC is defined as a toolbox, meaning that each network can implement only the features needed, as did for example in [38].

5G mmW networks are of particular interest considering that their numerology naturally enhances both throughput and latency. Using a larger bandwidth translates into subcarrier spacing up to 120 kHz (5G sub-6 GHz provides up to 30 kHz), each slot of 14 OFDM subcarriers has a duration of 125 μs (5G sub-6 GHz slot has 500 μs). Moreover, a comparison of LTE, sub-6 GHz and mmW published in a SRG benchmark study [39] reached the following conclusions:

- LTE networks have a spectral efficiency between 5-7 bps/Hz in downlink and half in uplink. Considering the limited amount of spectrum available, this provides reduced data speeds with noticeable impact on the user experience, especially when consuming video content. Although 5G NR in Bn78 can multiply the capacity by a factor of 2.3, the improvement is not sufficient.

- Using 5G NR mmW instead, the throughput is increased by a factor of 10 in downlink and 2 in uplink. The improvement in uplink is even bigger if data is transmitted simultaneously over both networks using PDCP combining. However, mmW bands have two main outcomes: line of sight conditions and reduced range. They don’t provide ubiquitous coverage as LTE or 5G NR sub-6 GHz, especially in indoor deployments, so this increase is only possible in a small part of the sector.

- Ensuring both coverage and capacity requires a simultaneous deployment of 5G NR mmW and sub-6 GHz networks. By offloading mid-band traffic onto 5G NR mmW, resources are freed up and can be assigned to users outside of the mmW range, increasing the capacity density around 4.4 times.

The benefits of 5G will be even greater with the outcome of 5G-Advanced, the name that 3GPP has given to Release 18 and beyond until 6G (Release 21). It will introduce more intelligence to mobile networks by adding AI/ML algorithms to different levels of the network, which will learn the optimized configuration for every application and vertical, maintaining at the same time backwards compatibility and maximum simplicity [36].

III. Proof-of-concept components.

It has been explained that tele-robotics enablers are still on their very early stages, so this first proof of concept is constrained to the available technology. The proposed alternative implementation of the “AGV use case” avoids the use of steering wheel and pedals to focus the ToD on the haptic glove. This intends to serve as a first approach for haptic communications applied to tele-robotics, where the haptic feedback should be used as the main input for the user to control de robot in the desired way. However, it was noted during the first trials that controlling the robot trajectory with the glove may lack the precision needed in the port terminal. This motivated the decision to limit the alternative implementation of the AGV use case to route control, whereas the ToD with the glove was left to a more experimental approach (so-called remote driving demo) using an educative robot. To better understand the role of the different components in each solution, this section will explain the state-of-the-art equipment used. Next section will describe the architecture of each solution and how the components are connected.

III.2. *Haptic gloves.*

The haptic glove used in both demos is the Sensorial XR model manufactured by NeuroDigital Technologies. It has a total of 10 haptic actuators built with the LRA technology, one of them located at each fingertip and five of them located near the palm. This LRAs allow 1024 vibration intensities with an amplitude up to 1.8G and a resonant frequency of 205 Hz, while maintaining a latency under 30 ms [13]. The motion capture is performed by seven 9-axis IMUs working with a sample rate over 200 Hz, allowing to capture adduction, adduction and rotation degrees of freedom in contrast to flex/blending sensors which only provide one degree of freedom per sensor [40]. The gesture capture is realized by four conductive fabric zones located in thumb, middle, index and palm. A representation of the different sensors and actuators of the glove can be appreciated in Figure 5.

Figure 5 Sensors and actuators of Sensorial XR

Sensorial XR is compatible with both wired and wireless (via Bluetooth 5.0) communication with the supporting PC. According to NeuroDigital, the first case provides a negligible latency and a sample rate over 200 FPS, whereas the second case has an added latency of 7.5 ms and works at a lower sample rate of 120 FPS. This will be corroborated later in the “KPI collection” section.

The glove firmware utilizes an API programmed in C# language to communicate with the Unity3D application that defines its behavior after an event. The application can simulate complex sensations easily by utilizing the pre-defined SDK functions, such as inter-finger collisions, surfaces rugosity, or customized vibrations.

III.2. *Head Mounted Displays.*

The two different HMDs utilized are depicted in Figure 6. On the one hand, the route control demo integrates the Varjo XR-3 goggles, a high-end MR device worth over 7000 €. This premium device provides advanced features such as hand tracking, eye tracking, and autonomous SLAM, as well as the top resolution of the industry with over 70 pixels per degree. Thanks to its 12-megapixel video pass-through cameras and LIDAR sensors, it is capable of precisely overlay virtual objects on the real environment, perceived as photorealistic by the user. It processes all the algorithms described before (in the “Mixed Reality” section) in local mode, and therefore it needs to be tethered to a local PC with a powerful GPU in order to work. The goggles’ functionalities are controlled by the Varjo Base software, which handles the compatibility with the developer’s applications via OpenXR.

Figure 6 HMD devices Varjo XR-3 (left) and Oculus Quest 2 (right)

On the other hand, the remote driving demo makes use of the Oculus Quest 2 goggles. This is a pure VR HMD with much lower resolution and field of view than the Varjo HMD, but with a better software consistency due to being the most popular device in the market thanks to its 400 € price and the possibility of working standalone. The Oculus Quest 2 can work as an Android player and run the compatible applications locally, but for running the Sensorial XR SDK it is more appropriate that they are connected to a PC either wired or wirelessly (via WiFi). It was decided however to use the wired connection to avoid high variability in terms of latency and bitrate, as explained in [13].

III.3. *Robots.*

The robots controlled with the immersive cockpit are also different, as shown in Figure 7. On the one hand, the Robotnik RB-1 Base is used in the route control demo since it can work either as an AGV or as a mobile robot. This industrial machine is designed for logistics in indoor environments as well as R&D applications, which is the case. It can carry up to 50 kg of cargo despite its compact dimensions (0.515 m of diameter vs 0.303 m of height), at a maximum speed of 1.5 m/s thanks to a pair of motor wheels of 250 W each. The attached sensors include a LIDAR and a depth sensing camera, allowing the robot to perform autonomous SLAM and obstacle detection in the whole room. All the functionalities are controlled by Robot Operating System (ROS) embedded into an internal PC and capable of listening to orders from external servers by attaching for example 5G modems.

Figure 7 Robots Robotnik RB-1 Base (left) and XiaorGeek Tank Robot (right)

On the other hand, the remote driving demo utilizes the XiaorGeek Tank Robot that can only work as a mobile robot. It is a very simple machine consisting in a driver board, an arm and a claw controlled by a Raspberry Pi. The robot arm is designed with 4 degrees of freedom that permit the user to grab objects, whereas the movement of the robot is provided by two motor tracks of 12 W each that can support a maximum load of 8 kg despite its small size (0.3 m of length, 0.23 m of width and 0.233 m of height). The way of controlling the robot is programming from scratch Python scripts that read and write the voltage of the pins of the driver board, although the camera has a dedicated interface. The connectivity with the network is performed exclusively via WiFI, but it is recommended to create a private hotspot for better performance.

III.4. *5G Equipment.*

The 5G network has been only used in the route control demo due to the resources available and the compatibility of the robots. The AGV use case of the iNGENIOUS project will utilize a private 5G network that has been recently installed in the Port of Valencia for the final demonstration. As it can be seen in Figure 8, the antenna deployment is composed by a 4G mmW Remote Radio Head (mmRRH) and a 5G mmW active module. The 5G network is SA, with the 5G core located inside the shelter.

Figure 8 5G antenna deployment in the Valencia Port

Nevertheless, the difficulty of performing trials in the port facilities due to the constant traffic and the need of asking for permission, motivated the decision to develop the use case outside of the port. In particular, a commercial 5G NSA network installed in the UPV by Orange was used. It works with 3GPP Release 15 (eMBB) in the mid-band (3.5 GHz), and therefore network latency improvements are discarded. A mmW node is also available in the same location, but the 5G modems available (Huawei 5G CPE Pro 2) that connect the AGV and the cockpit to the network do not support it.

IV. Integration and demonstration.

IV.1. *Route control demo*

This alternative implementation of the AGV use case will be utilized in the final demonstration that will be performed in the Valencia Port in early 2023. As commented in the Introduction and depicted in Figure 9, the intention is that several AGVs are working autonomously in the port following predefined routes. At the same time, the operator attached with the haptic glove will be visualizing the robot either by a remote cockpit or by an on-site cockpit, so he can select or stop the route in any moment. The route has checkpoints where the AGV must pass following the path it considers. When the robot finds an obstacle in the path, the control will shift to the cockpit that contains a steering wheel and pedals (out of the scope of this Thesis) for a more precise ToD, but the control will return to the haptic glove when this process ends.

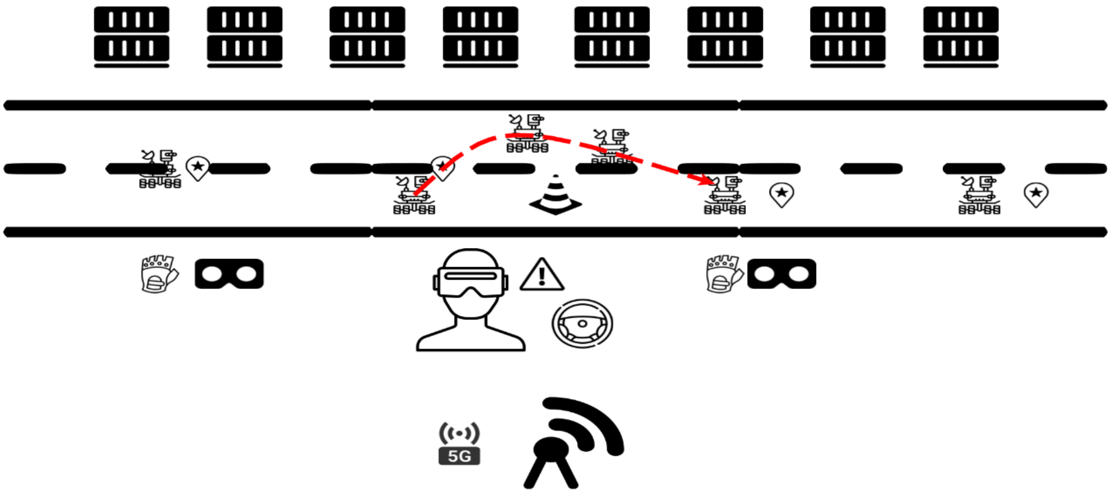


Figure 9 AGV use case scenarios: route control demo and ToD demo *[13]*

In the on-site architecture, the operator does not make use of the HMD because he maintains visual contact with the robot. The Sensorial XR haptic glove needs to be wirelessly connected to the PC via Bluetooth in order to allow the operator to follow the robot. The freedom of move that the Bluetooth connection gives will be tested in the "KPI collection" section. The PC is running the Unity application that controls the haptic feedback and communicates the commands to the robot thanks to the 5G modems connected to both components (see Figure 10). Note that the robot appears different to the Robotnik RB-1 Base, but this is because Fivecomm added a humanoid torso to it.

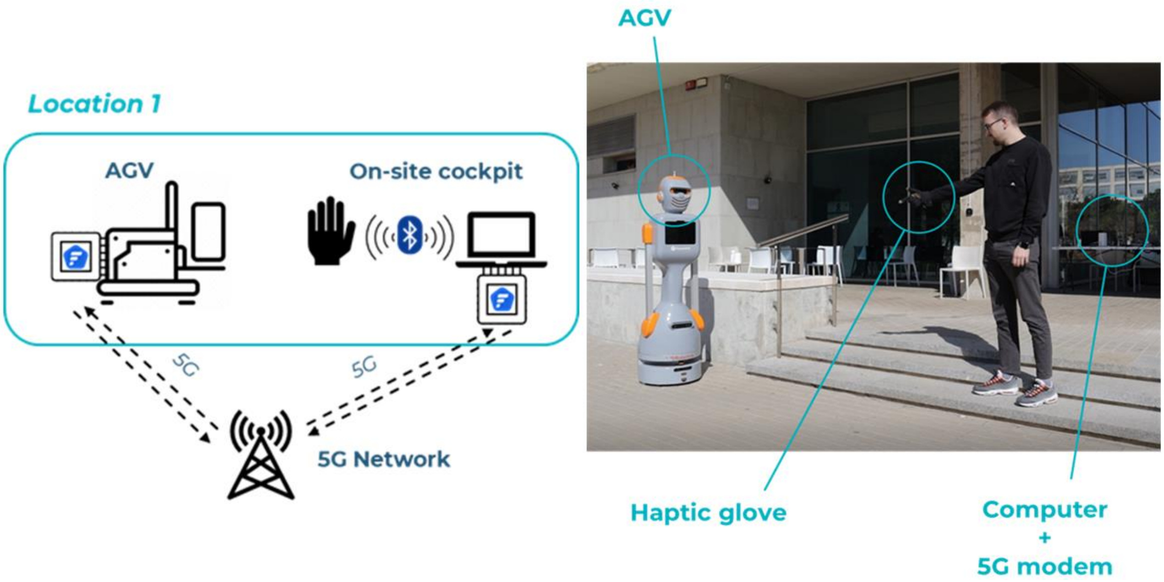


Figure 10 On-site route control architecture and components *[13]*

In the remote architecture, the user is equipped with a pair of Varjo XR-3 glasses and one Sensorial XR haptic glove, both attached to a PC that runs the same Unity application and communicates the commands to the robot via 5G (see Figure 11). The HMD is connected via USB-C and OpenXR framework, which makes possible to create an immersive MR scene dominated by a real-time video stream received from the camera attached to the robot's head, simulating the point of view of the robot. The haptic glove is connected via USB cable to the PC for more precise haptic feedback, that is more important in this case because the user has not direct visual perception of the distance to the obstacles. However, this solution is more appropriate that the on-site control due to safety implications, as the AGV use case is intended to protect the operators from hazardous situations encountered in the port area.

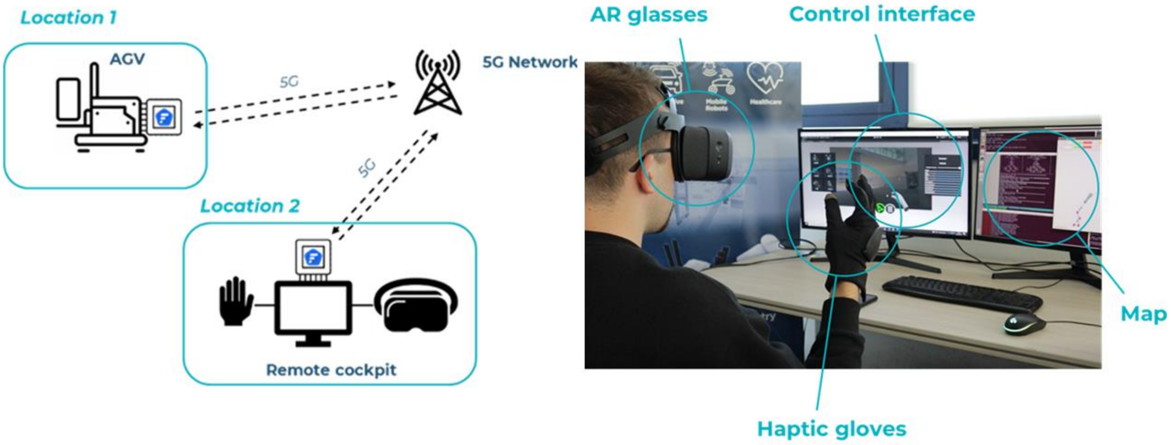
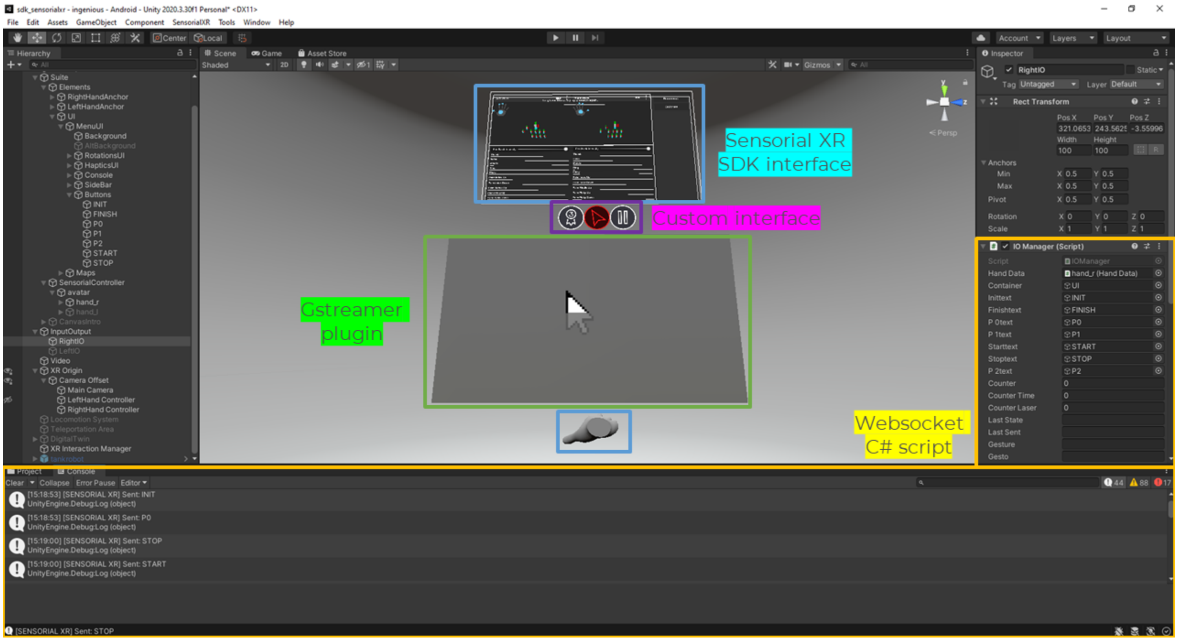


Figure 11 Remote route control architecture and components *[13]*

This Unity application used in both on-site and remote route control has the following components (see also Figure 12 below):

- Websocket C# script for handling the communication from and to the glove. This script creates a full-duplex connection between the PC and the robot, via TCP. It can send the gesture commands and receive haptic feedback asynchronously. It adds security and reliability to the connection, although its TCP-based scheme increases the latency with respect to a UDP-based solution.
- Gstreamer plugin for receiving the video feedback. The pipeline used consists in RTP and UDP protocols encapsulating JPEG frames, captured in different qualities.
- Sensorial XR SDK interface for representing vibration levels, hand position and rotation, and gesture performed.
- Custom interface for representing the current orders, such as the route number, the on/off flag, and the stop/resume flag.



```
[15:18:53] [SENSORIAL XR] Sent: INIT
UnityEngine.Debug:Log (object)
[15:18:53] [SENSORIAL XR] Sent: P0
UnityEngine.Debug:Log (object)
[15:19:00] [SENSORIAL XR] Sent: STOP
UnityEngine.Debug:Log (object)
[15:19:00] [SENSORIAL XR] Sent: START
UnityEngine.Debug:Log (object)
[SENSORIAL XR] Sent: STOP
```

Figure 12 Unity application from workspace

The protocols used for the communication are WebSocket (for sending gestures and receiving haptic feedback) and Gstreamer (for receiving video streaming). The different gestures that can be performed are the following: (i) go to a specific point in the route; (ii) stop the movement; (iii) resume the movement. Consequently, the user can avoid hazardous situations for the robot, for example when approaching to an obstacle in the route thanks to the reception of haptic feedback with an intensity dependent of the obstacle closeness (see Figure 13 below).

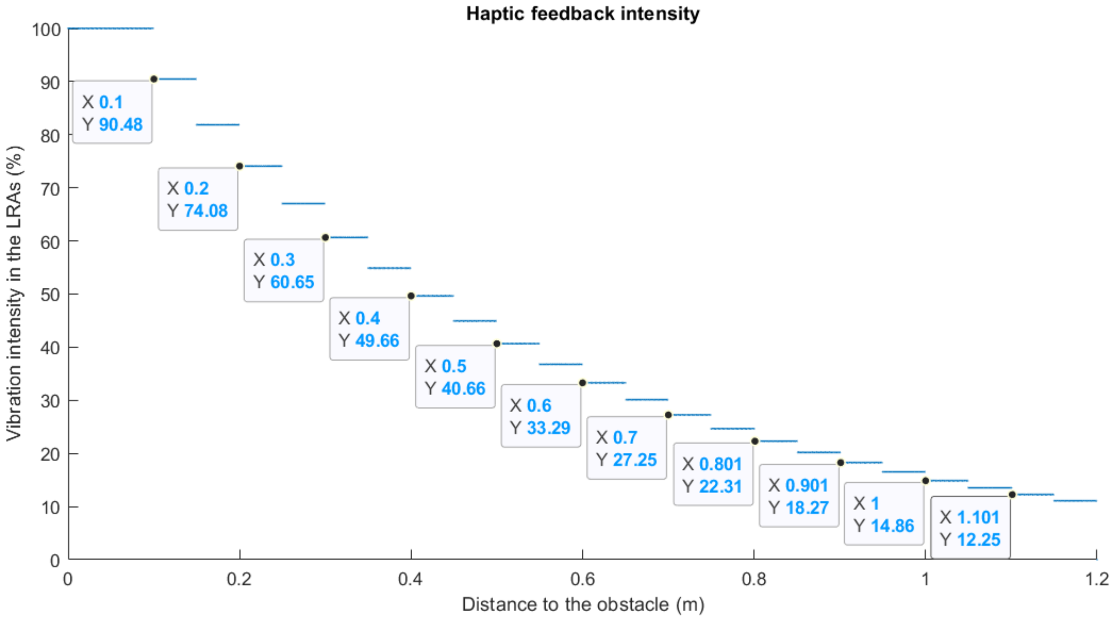


Figure 13 Haptic feedback intensity as a response to the obstacle closeness

Both the on-site and the remote route control implementations were presented to the European Commission on May 19th 2022 as part of the AGV use case for the mid-term review of the iNGENIOUS project. The following video shows the author of this Thesis manipulating the AGV in the UPV campus [41].

IV.2. *Remote driving demo.*

This demo is a result of the collaboration between UPV and TUAS through the Finnish project SMARTER, whose scope is also 5G-enabled ports, but can serve as a proof of concept for the AGV use case of iNGENIOUS. The main aim of this demo is the remote control of a robot in real time, creating a flexible solution that can be used in different systems and environments, allowing ToD between long distances. On the user side, the telepresence is provided by Oculus Quest 2 HMD and Sensorial XR haptic gloves, which offer haptic and visual feedback respectively. On the robot side, the telepresence is provided by a live video stream combined with a static LiDAR scan of the room, so-called Digital Twin. The architecture of the solution can be seen in Figure 14.

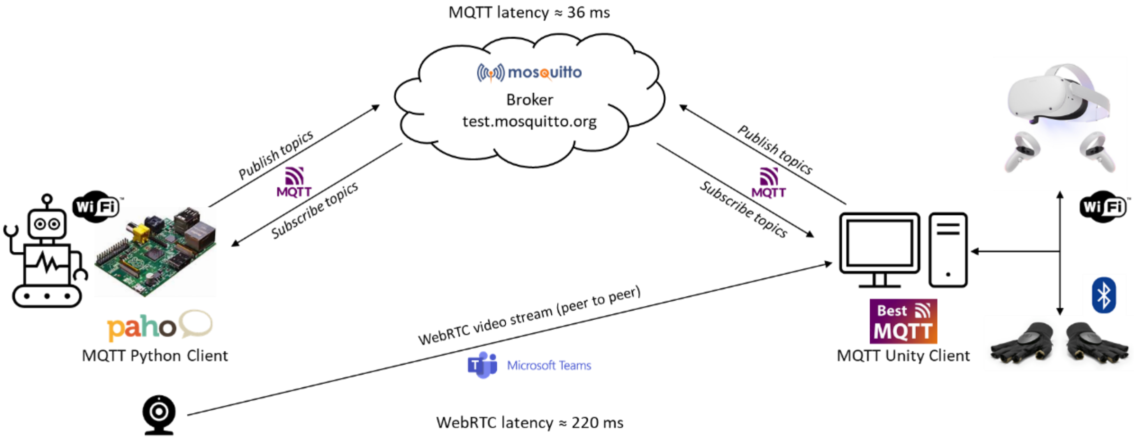


Figure 14 Architecture and components of the remote driving demo

During the realization of this demo, two haptic gloves where available (left and right ones), contrary to the route control demo where only one glove (right one) was available. However, in order to make the robot control more user-friendly and intuitive, only the right one is used, whereas the left hand holds an Oculus Touch controller. The glove is connected to the PC via Bluetooth, with a latency of only 7.5 milliseconds. The communication is bidirectional, meaning that it can send commands obtained by its 4 conductive zones and 7 IMUs, and receive haptic vibrations in its 10 LRAs. All the software needed by the glove is included in the SDK embedded into the Unity project, so the glove automatically connects when the application is running.

Regarding the robot side, everything is controlled by a Raspberry Pi 4. Thought the robot possess a built-in camera, it offers low-quality, poor field of view and high-latency (up to 2 seconds) video stream. For those reasons, it was decided to use an external webcam attached to a laptop, with full and easy support to WebRTC streaming. WebRTC is the fastest videoconferencing protocol of the market, which means a sub-500 ms delivery. It is UDP-based, which makes it faster but more sensitive to the network conditions. Since creating a WebRTC server is out of the scope of this demo, a standard public service such as Microsoft Teams is used.

Targeting low-latency communication and the avoidance of firewalls, the MQTT protocol was selected for the robot control. MQTT is a lightweight and efficient messaging protocol based on a publish/subscribe methodology structured in topics. Every client (i.e. the user and the robot) can send and receive messages to a specific topic by communicating with a MQTT broker, who acts as an intermediary.

The main task consisted in defining an intuitive and useful way to remotely control the robot, considering that it should be a standard solution capable of working with any similar machine. As a result, the following method was designed (see Figure 15): the right hand controls the robotic arm with 7 different gestures, varying the position and/or rotation of the hand in a specific axis. This also requires an Oculus Touch controlled attached to the top of the right glove in order to be used as a tracking device. The joystick of the left Oculus Touch controls the motors, but its trigger is also needed to enable the MQTT message delivery of both the gestures and the movement topics. A haptic feedback signal is felt by the user to make him know in which direction the robot is moving.

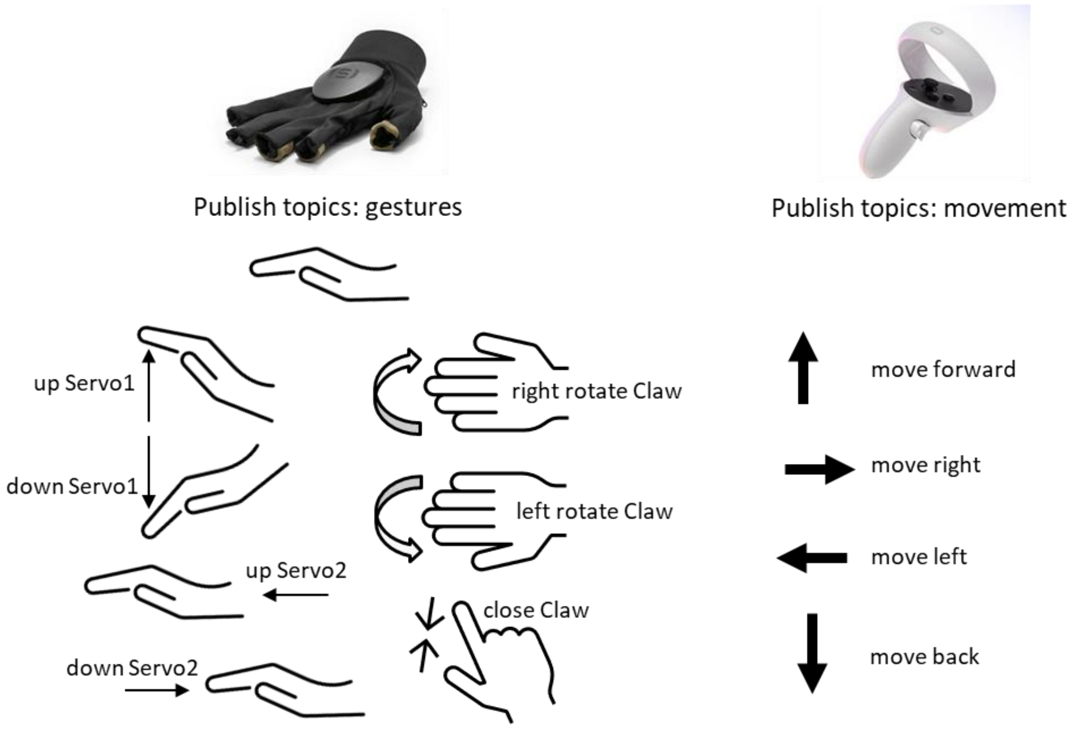


Figure 15 ToD commands designed for the remote driving demo

Nevertheless, the most immersive part of the demo comes from the integration of the user interface into a simulation-based Digital Twin created by TUAS colleagues (see Figure 16). It consists in a Unity scene that simulates the robot as well as a real room of the Game Lab department, thanks to the data obtained by a Leica 3D LiDAR scanner and an iPhone Pro smartphone. The user can control the virtual robot and the real one simultaneously, although a considerable delay of around 500 ms exists between them. This could be solved in future work by attaching laser sensors to the robot that precisely replicate the movements of the real robot in the virtual environment, which at the same time would allow the delivery of haptic feedback when an obstacle is near.

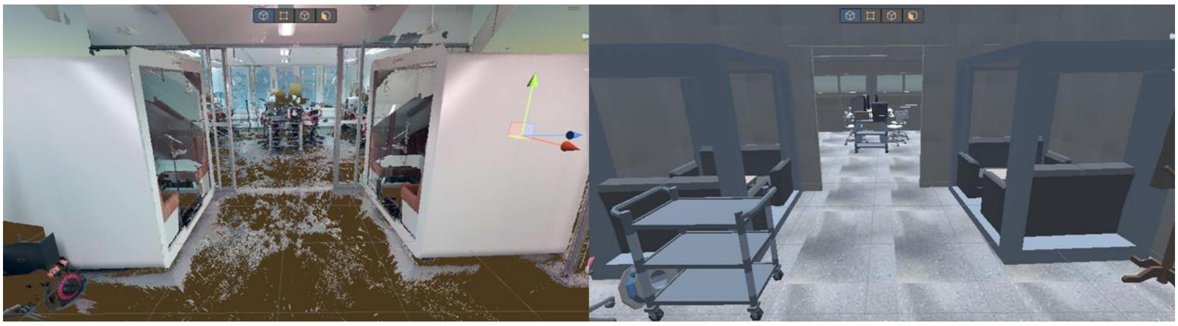


Figure 16 3D point cloud of the real environment (left) vs digital twin created in Unity3D (right)

This demo was showed in the Valencia V5G Days celebrated in Valencia on May 30th and 31st of 2022, so the participants were able to try themselves the ToD of the tank robot. A video of the event is available in [42].

IV.3. *KPIs collection.*

In order to test the viability of the use case proposed, the following Key Performance Indicators (KPIs) were chosen:

- Bitrate generated by the video stream
- E2E latency of the video stream
- Bitrate generated by the haptic glove wired vs wirelessly
- Bluetooth range of the haptic glove
- E2E latency of the route control
- Network latency (5G on the route control demo / MQTT broker on the remote driving demo)

The bitrate generated by the video stream was measured with the tool Wireshark. As explained before, the Gstreamer tool was used to configure different video resolutions, with the results that show the Figure 17. The bitrate captured is 2,5 Mbps for 360p resolution, 8 Mbps for 720p resolution, and 16 Mbps for 1080p resolution.

The previous configurations were also used for testing the video latency. The methodology used was to display a millisecond-sensitive clock in the same screen that is running the Unity scene, and then point the robot camera to the same screen in order to compare the difference. It should be noted that this has an error range of 50 ms, due to the camera frequency (30 fps, meaning a error of 33.33 ms) and the screen frequency (60 Hz, meaning a error of 16.66 ms), but several measures were obtained to minimize this effect. In the results displayed in Figure 18 we can observe that increasing the resolution of the video stream (the size of the frames) not only increases the throughput sent, but also the latency, because it takes more time to process and deliver the frames. For a standard video configuration of 720p, the latency measured was 156.4 ms, which is adequate considering the Route Control application is focused in supervision purposes and therefore is less latency-critical than ToD.

Figure 17 Bitrate generated by the video stream at different qualities

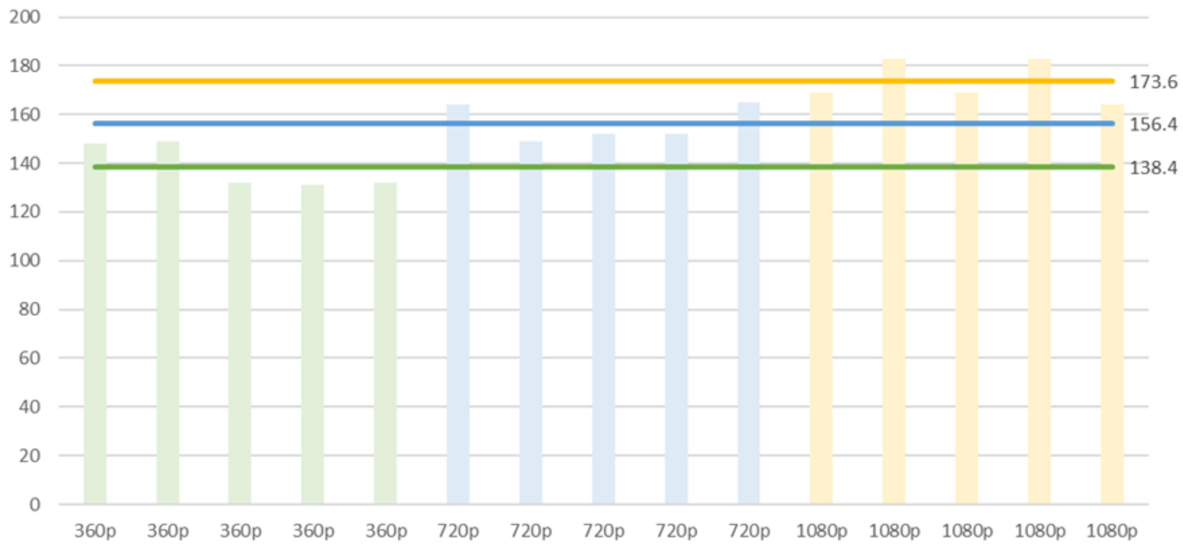


Figure 18 Video latency (ms) of the video stream at different qualities

The haptic gloves can be both wired and wirelessly connected to the PC. Using Wireshark, the bitrate for both connectivity solutions has been captured. In Figure 19 the bitrate for Bluetooth connection is shown, being around 75 kbps, and in Figure 20 the bitrate for USB connection, which reaches the value of 375 kbps. These values correspond to UL data (device to PC), whereas the DL data (PC to device) is considerably lower and intermittent, since it is only sent for haptic feedback. The graphs also show the total throughput involved in the Bluetooth connectivity, considering signaling as well as data delivery.

The behavior is the same for both Bluetooth and USB options, being the differences due to: (1) Bluetooth messages refresh less frequent (120 FPS) than USB ones (200 FPS), and (2) Bluetooth uses compression of packets while USB does not.

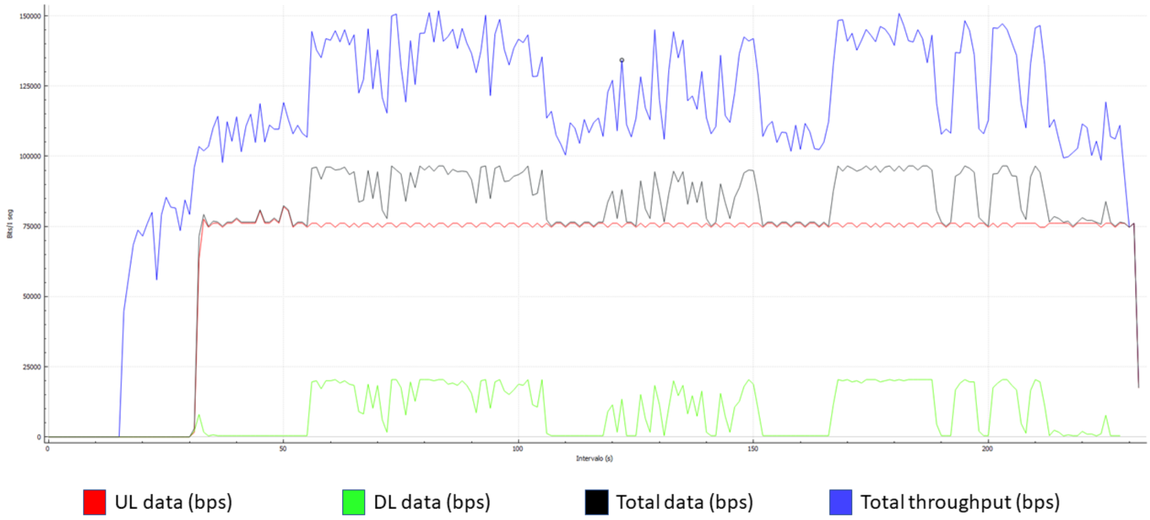


Figure 19 Bitrate generated by Bluetooth connection of Sensorial XR

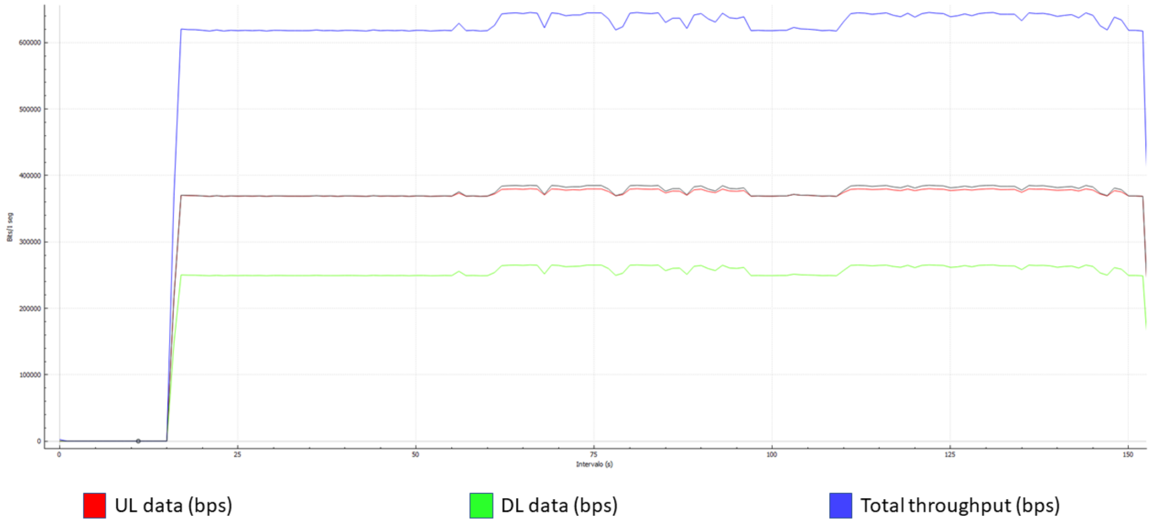


Figure 20 Bitrate generated by USB connection of Sensorial XR

In the Bluetooth option, the range is a KPI to have into consideration as it can be critical for the correct performance of the on-site route control demo. If the operator moves out of these limits, the connection may fade and even stop. For evaluating it, both indoor and outdoor test have been carried out in Fivecomm's office and the UPV campus, with the results shown in Figure 21. The method consists in a subjective measure depending on the perceived loss of connectivity and performance, so three different levels have been distinguished for a good (green), bad (yellow) or null (red) performance.

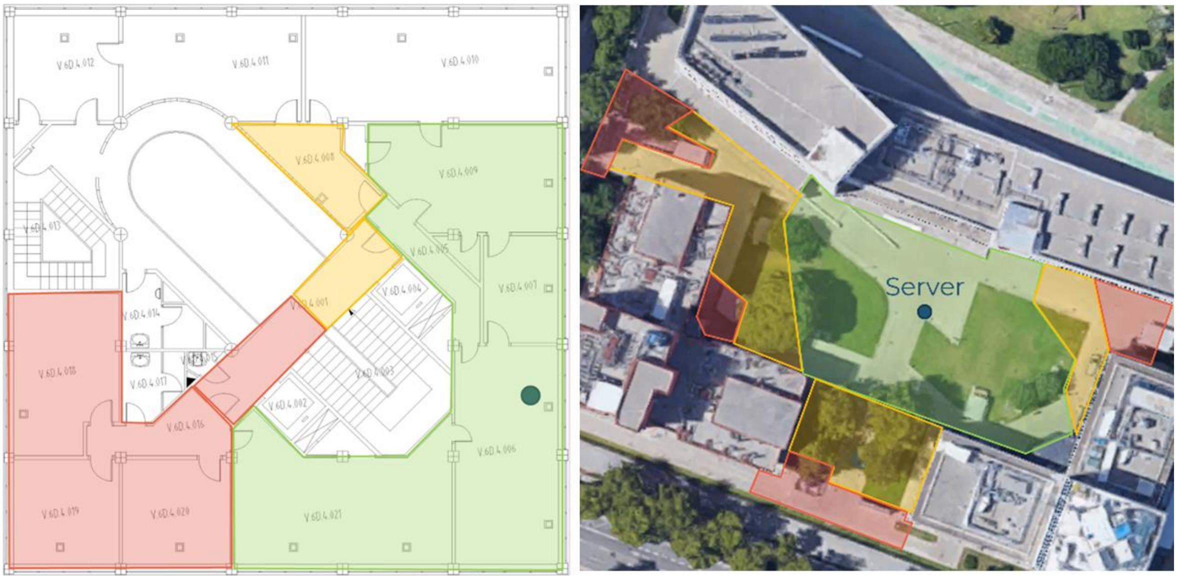


Figure 21 Bluetooth range of Sensorial XR in the Fivecomm's office (left) and in the UPV campus (right)

Regarding the gesture latency of the route control demo, two different methods were proposed: one automated method for measuring the 5G network delay, and other empirical method for measuring E2E latency. In the case of the network delay, the idea is to add a timestamp every time a gesture is send (by the user) and received (by the robot), and therefore the delay is obtained by calculating the difference between timestamps. However, for simplicity, this was implemented in a way that the robot sent back the messages to the user, meaning that the obtained value is the round trip time (RTT). It excludes the latencies of the glove and the robot but gives an idea of how fast the 5G network is (29.14 ms in average), as shown in Figure 22.

The E2E latency of the gestures includes several biases such as the behaviors of the glove and the robot. We defined it as the time that takes to appreciate that the robot is moving after doing a gesture. This has been measured by capturing the on-site application with a slow-motion camera that provides 240 FPS, meaning an error rate of only 4.16 ms. Nevertheless, it should be noted that the main error rate in this case is the human perception because the values can vary depending on the frame that the user decides that the robot is actually moving. In fact, the results displayed in Figure 23 show that the perceived latency is significantly higher when resuming a route than when stopping it (736 ms vs 362 ms on average). Apart from the human perception, we consider this gap to be due to the behavior of the robot itself. It was observed that the robot performed considerably faster the brakes than the accelerations. For this reason, we consider these higher latencies acceptable, since the route control application is not as dependent of the robot responsiveness as the ToD.

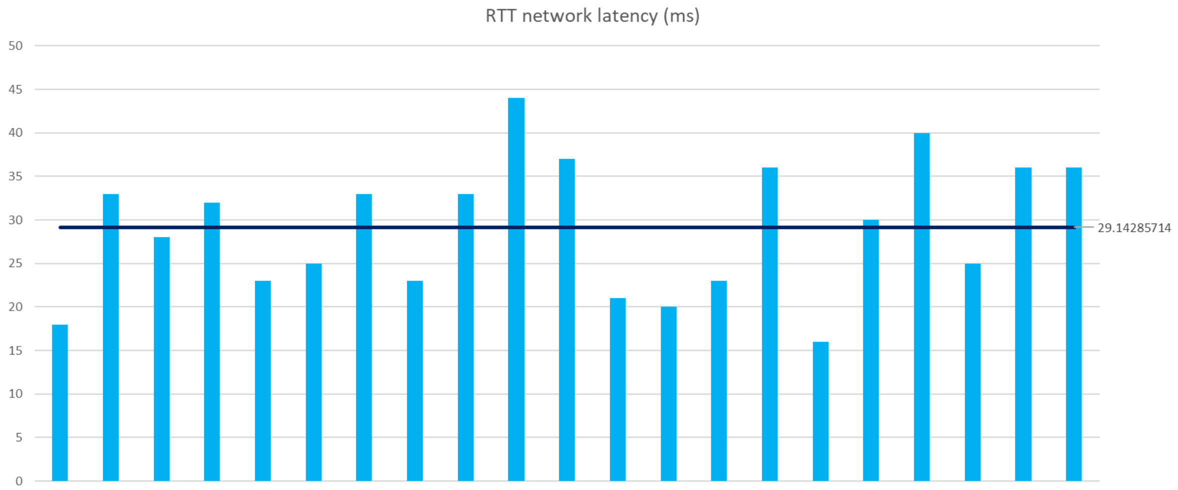


Figure 22 RTT network latency for route control commands

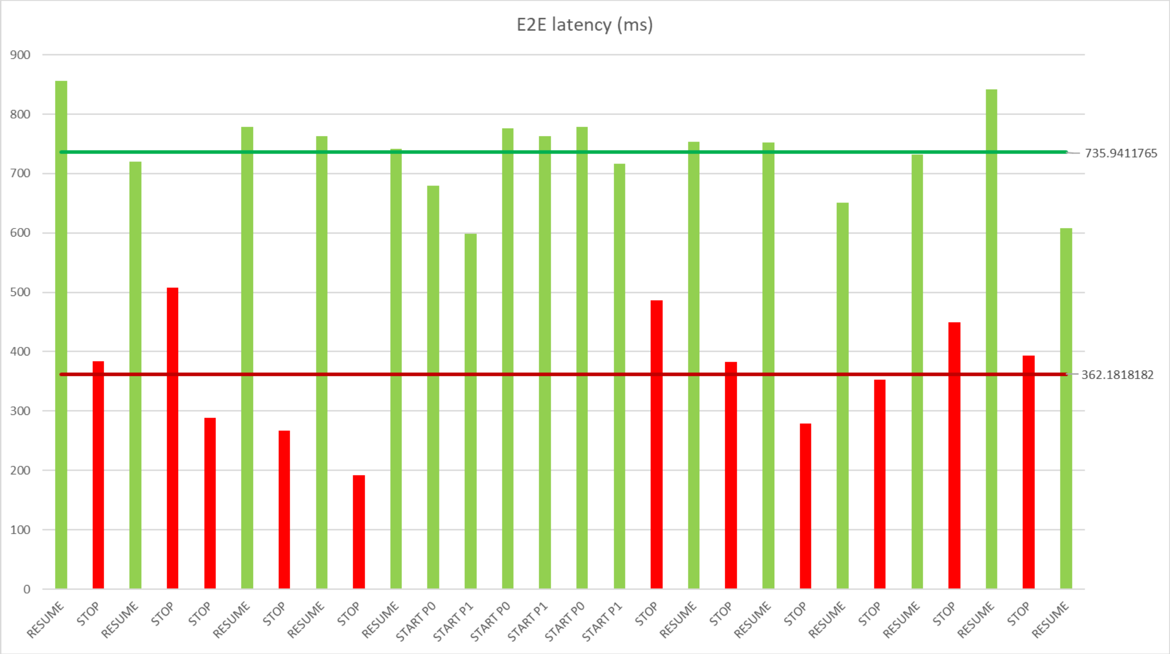


Figure 23 Perceived E2E gesture latency for on-site route control commands

On the other hand, the gesture latency of the remote driving demo was measured in the same way. The average latency of the MQTT broker was automatically calculated using timestamps, and after dozens of iterations the values obtained were around 42 ms. Contrary to the network latency measured in the route control demo, this value does not include the hotspot latency that adds around

60 ms on average. The perceived E2E latency has similar biases such as the error rates of the camera and the screen, that sum a total of 33 ms since both work at 60 Hz. The measure was performed from Valencia while the robot stayed in Turku, with an average perceived latency of 446 ms as seen in Figure 24. This is a good result considering the use of a low-end robot and a network latency of 102 ms, but not enough for real ToD purposes.

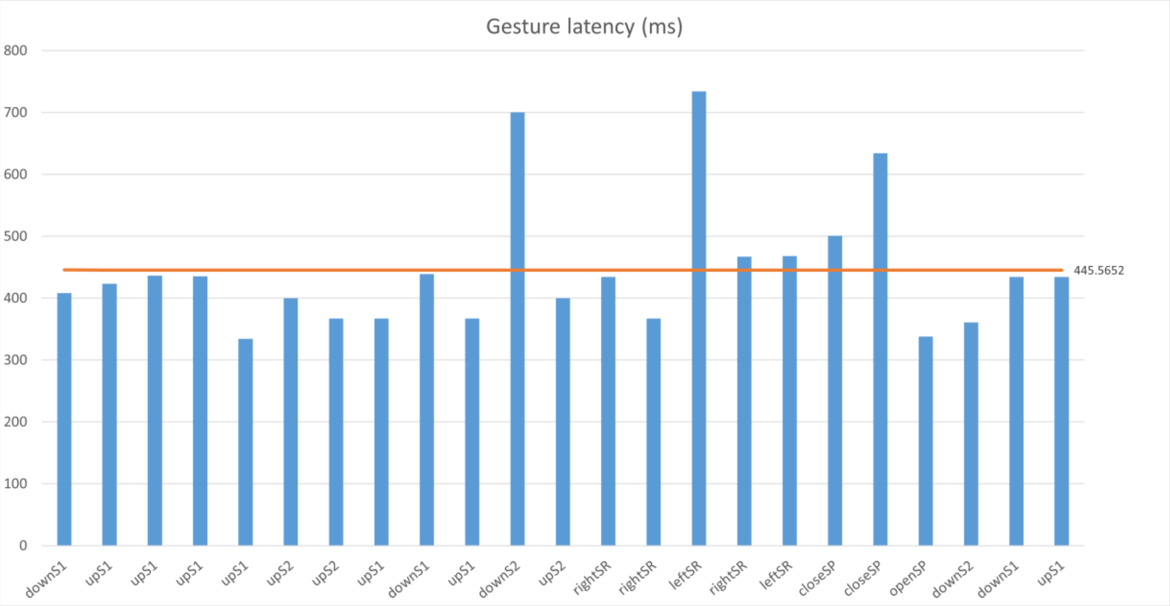


Figure 24 Perceived E2E latency for remote driving commands

IV.4. *5G drive tests.*

Finally, a measurement campaign of the 5G mmW networks deployed in the Valencia Port and the UPV campus was performed. At such high frequencies (26-28 GHz), propagation loses make the signal to quickly fade with the distance, so the antenna beams must be considerably directional to cover a few hundreds of meters. As a consequence, the signal does not break through the objects and any obstacle can block the signal by Non-line-of-sight (NLOS) conditions.

The idea of these drive tests is to check the coverage around the areas where the AGV is supposed to operate in the route control demo, as well as to study how critical are propagation losses and NLOS conditions in mmW bands. The measurement equipment used for the purpose is the Rohde & Shwarz TSME6 network scanner and the TSME30DC mmW converter, whereas the drive test software used is ROMES 4. The KPIs evaluated are the following:

- Reference Signal Received Power (RSRP): Average power received from the reference signal in a given bandwidth.
- Reference Signal Strength Indicator (RSSI): Average total power received from the reference signal in all the frequency band, including co-channel serving and non-serving cells, adjacent channel interference and thermal noise.

- Reference Signal Received Quality (RSRQ): Ratio between RSRP and RSSI, calculated as N*RSRP/RSSI where N is the number of resource blocks in the given bandwidth.
- Signal to Interference and Noise Ratio (SINR): Ratio between the desired signal and the undesired ones, including both internal and external noise.

IV.4.1. *Valencia port.*

The analysis has been carried out in the LTE band B7 (2.6 GHz) and the 5G mmW bands n257/258 (26.5-29.5 GHz / 24.25-27.5 GHz). The B7 band includes a 5 MHz channel in the 2622.5 MHz central frequency that works as an anchor band for control-plane functions, whereas the data delivery is done in the n258 band, in a 100 MHz channel located in the 26738.4 MHz central frequency.

The first area of measurement corresponds to the location of the antennas shown in the section “5G equipment”. The drive test results near the antenna displayed in Figure 25 show generally poor values, but they tend to increate as the scanner enters the antenna beam. At a medium distance, RSRP values are still insufficient, but RSSI, RSRQ and SINR values are acceptable, which means that the lack of interference and noise in the mmW band makes low power values sufficient for data delivery.

Figure 25 First drive test in the Valencia Port, results for RSRP (upper left), RSSI (upper right), RSRQ (lower left) and SINR (lower right)

The area where the second drive tests have been performed is actually the same area where the AGV is expected to operate. It can be appreciated that the results are better since that area is covered by the antenna beam. However, in the southern side of the track there is a wall that apparently blocks the signal by creating a NLOS situation, which has a slight impact on the RSRP (see Figure 26). The results are the expected in this case, considering that there are no buildings in the area that completely block the signal. Given the results, the AGV use case seems to be feasible in the port area, as long as the mmW band keeps lacking interferences.

Figure 26 Second drive test in the Valencia Port, results for RSRP (upper left), RSSI (upper right), RSRQ (lower left) and SINR (lower right)

IV.4.2. *UPV campus.*

The available bands are the same than in the Valencia port: LTE band B7 (2.6 GHz) and 5G mmW bands n257/258 (26.5-29.5 GHz / 24.25-27.5 GHz), with the difference that the bandwidth in the B7 is 20 MHz and the central frequency is 2650 MHz. In the n257 band there is a channel of 200 MHz with two different ARFCNs, located at 26600.160 MHz and 26807.52 MHz respectively.

The whole area of the UPV has been covered during this drive test, although more effort has been put in the antenna's pointing direction, that is indicated in Figure 27. Moreover, the results displayed in Figure 28 show that the KPI levels are indeed higher in the pointing direction of the antenna and for LOS conditions, but similarly to the drive tests carried out in the Valencia Port, the SINR is the only parameter that obtains good results. Outside the pointing direction, the levels are minimum or even null if the signal is blocked by a building. The same happens in the eastern zones, since it is the opposite direction to the pointing direction. Near the antenna the signal suffers the same problem that in the previous drive test, which evidences that there is also a high directivity in the vertical plane.

Figure 27 Pointing direction of the mmW antenna installed in the UPV campus

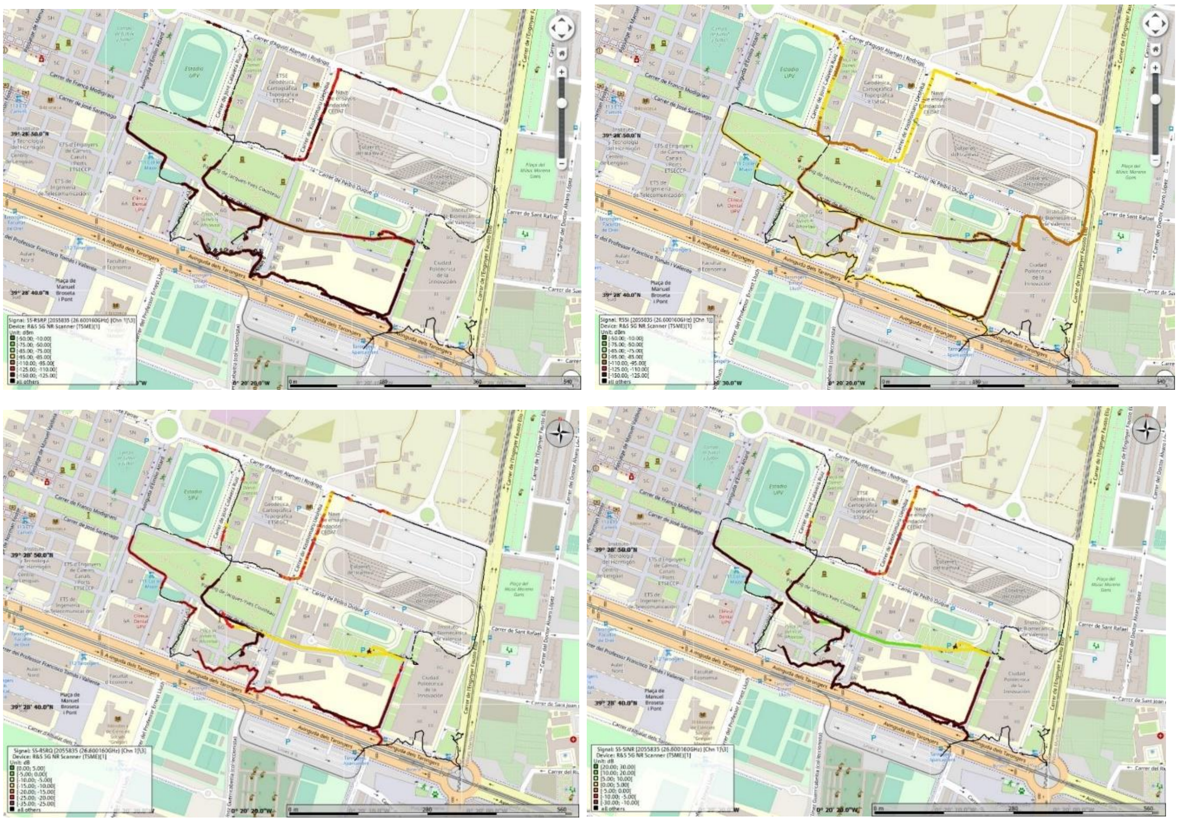


Figure 28 Drive test in the UPV campus, results for RSRP (upper left), RSSI (upper right), RSRQ (lower left) and SINR (lower right)

Considering all these aspects, it is obvious that mmW frequencies could not satisfy the AGV use case requisites in the whole UPV campus unless more antennas are distributed throughout the area. The AGV will quickly loose the connectivity as soon as it moved away from the pointing direction, due to the high directivity of the antenna and the sensitivity of the signals to NLOS conditions.

V. Conclusions and next steps.

This Thesis has highlighted the benefits of haptic-assisted teleoperation of mobile robots in real-time and identified its main enablers, including haptic communications, mixed reality, digital twins and 5G low latency. According to several sources, humans perceive real-time tele-operation for E2E latencies under 50 ms, but the proof of concept designed has proved this to be unfeasible nowadays. The proof of concept is based on the AGV use case of the H2020 iNGENIOUS project, that targets indoor teleoperation driving to improve the safety of the operators in port environments. The alternative approaches propose the use of digital twins (remote driving demo) and haptic-based control (route control demo), equipping the operator with haptic gloves and MR goggles that allow the immersive control of the robot.

The KPI collection performed over both demos shows that E2E latencies widely surpass the 50 ms value due to technological limitations, such as the lack of URLLC equipment, fast mechanical actuators or Edge computing services. Moreover, the route control application demonstrates that robot actuators are the bottleneck of the application, since the perceived E2E latency is 362 ms for braking vs 736 ms for acceleration, despite the network latency is only 29 ms. The remote driving application proves that teleoperation over vast distances does not add much more latency, resulting in a perceived E2E latency of 446 ms between Valencia and Turku (Finland), with a network latency of 102 ms. The throughput measurements, however, show that current tele-robotics applications have negligible demands of bitrate that can be easily satisfied by Release 15 (eMBB) networks, although it would be different in case that mixed reality offloading to the Edge/Cloud was included.

Although 5G mmW frequencies can benefit tele-robotics use cases in both throughput and latency, the 5G measurement campaign shows that such high frequencies are not appropriated for outdoor environments since they are very sensitive to obstacles and NLOS conditions due to their high propagation losses. They seem more feasible for indoor environments or constrained outdoor areas totally covered by the antenna beam, which tends to be highly directive.

Nonetheless, both demos have proved the potential of haptic-assisted telerobotics, which will surely be a game changer for industry and logistics in the upcoming decades. The next steps of the AGV use case will focus on the optimization of the E2E architecture in order to be demonstrated in the Valencia Port in early 2023. The latency will be reduced by the use of Release 16 networks and mmW bands, whereas versatility will be improved by the virtualization and execution of the application in an Edge/Cloud server. Haptic communications will continue to be studied thanks to the creation of an immersive laboratory in the UPV at the end of 2023, where QoE-based optimizations will be carried on for several verticals such as education, industry and logistics.

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