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Metaverse hyperconnected for operators training within industry 5.0

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Contents

List of Figures iii

List of Tables iv

List of Symbols and Abbreviations v

Abstract vii

Resumen ix

1 Objectives and thesis organization 1

1.1 Objectives 1

1.2 Main contributions 3

1.3 Thesis Organization 3

1.4 Research framework 5

2 General introduction 6

Bibliography 9

3 Evolution of Research and Linking Chapters 13

Bibliography 18

4 Hyperconnectivity proposal for Smart Manufacturing 22

5 Digital twin for automatic transportation in industry 4.0 24

6 Analysis of navigation algorithms for a fleet of mobile robots by means of Digital Twins 26

7 Convergence of virtual reality and digital twin technologies to enhance digital operators' training in industry 4.0 27

8 Towards Industry 5.0 through Metaverse 29

9 Conclusions and outlook 31

9.1 Conclusions 31

9.2 Future works 33

10 Conclusiones y Líneas Futuras 35

10.1 Conclusiones 35

10.2 Trabajos futuros 37

List of Figures

List of Tables

List of Symbols and Abbreviations

ACK	Acknowledgement.
AGV	Automatic Guided Vehicle.
AI	Artificial Intelligence.
AMR	Autonomous Mobile Robot.
AR	Augmented Reality.
BLE	Bluetooth Low Energy.
CIM	Computer-Integrated Manufacturing.
CPS	Cyber-physical Systems.
CSMA/CD	Carrier Sense Multiple Access with Collision Detection.
CSV	Comma-Separated Values.
DCS	Distributed Control System.
DDoS	Distributed Denial of Service.
DOF	Degrees of Freedom.
DPI	Deep Package Inspection.
DT	Digital Twin.
DWA	Dynamic Window Approach.
ERP	Enterprise Resource Planning.
FLP	Facility Layout Problem.
HMI	Human Machine Interface.
HSI	Human Simulation Interface.
HTTPS	Hypertext Transfer Text Protocol Secure.
ICT	Information and Communication Technologies.
IE	Industrial Ethernet.
IEN	Industrial Ethernet Network.
IIoT	Industrial Internet of Things.
IIRA	Industrial Internet Reference Architecture.
IoT	Internet of Things.
IPv4	Internet Protocol version 4.
ISP	Internet Service Provider.
JSON	JavaScript Object Notation.
JSSP	Job Shop Scheduling Problem.
KPI	Key Performance Indicator.
LIDAR	Laser Imaging Detection and Ranging.

M2M	Machine to Machine.
MES	Manufacturing Execution Systems.
MESIC	International Conference of the Society of Manufacturing Engineering.
MIMO	Multiple-input Multiple-output.
MIR	Mobile Industrial Robots.
MQTT	Message Queuing Telemetry Transport.
MRP	Material Requirement Planning.
PLC	Program Logic Control.
PPI	Platform for Industrial Internet.
QoS	Quality of Service.
RAMI	Reference Architectural Model Industrie.
RFID	Radio Frequency Identification.
ROS	Robot Operating System.
SCADA	Supervisory Control and Data Acquisition.
SDF	Special Data Files.
SDGs	Sustainable Development Goals.
SIMFAB	Intelligent Systems for Mechanics and Manufacturing.
SM	Smart Manufacturing.
SOA	Service-Oriented Architectures.
TCPROS	TCP Transport Protocol in ROS.
TEB	Timed Elastic Band.
UAV	Unmanned Aerial Vehicle.
URDF	Unified Robot Description Format.
UWB	Ultra Wide Band.
VLAN	Virtual Local Area Networks.
VPN	Virtual Network Protocol.
VPNs	Virtual Private Networks.
VR	Virtual Reality.
WAN	Wide Area Network.
WLAN	Wireless Local Area Network.
XML	Extensible Markup Language.
XR	Extended Reality.

Abstract

THE digital transformation is revolutionizing the manufacturing industry, fostering a convergence between physical and virtual realms through Cyber-Physical Systems (CPS). These systems, equipped with sensors, actuators, intelligence, and connectivity, forge a crucial collaborative environment. Yet, overcoming technological challenges inherent in the merging of diverse Smart Manufacturing-associated technologies is pivotal to attaining industrial virtualization. This digital shift has opened novel perspectives for process simulation and operator training, elevating efficiency and collaboration in industrial landscapes.

Developing these applications requires virtualizing the CPSs, requiring modeling their behavior by understanding their responses to real stimuli in the physical environment. Thus, the virtualization extends beyond CPSs to encompass their dynamic physical settings, creating a simulation environment denominated as Digital Twins (DTs). These DTs can recreate numerous scenarios and hypotheses that replicate the real behavior of the systems in a virtual way allowing the analysis of different operational conditions in the virtual world.

In this sense, DTs find relevance in contexts like intelligent industrial transportation, where the environment plays a pivotal role in guiding Autonomous Mobile Robots (AMRs) navigation. For this reason, in Chapter 5, a DT was developed to compare times and trajectories between a virtual and a real autonomous vehicle, yielding high similarity. Implementing DTs in industrial transportation enhances decision-making for optimizing key processes critical for the overall performance of the industrial plant.

Moreover, this virtualized environment later incorporates an AMR fleet to scrutinize their behavior under real industrial settings. This allows the understanding of the response of each AMR of the fleet using different navigation algorithms within a dynamic virtualized environment. Particularly, Chapter 6 analyzes the Timed Elastic Band (BET) and Dynamic Window Approach (DWA) navigation algorithms. Additionally, to facilitate the comprehension of the simulations performed, an interface was devised to dynamically modify parameters and visualize real-time simulation data.

However, valuable DT insights aren't seamlessly integrated within Chapters 5 and 6 into the collaborative environment of productive processes, as per the Smart Manufacturing (SM) paradigm. Hence, transmitting DT and other external assets data to industrial architectures and communications protocols demanded the development of an interoperability gateway. This gateway analyzes assets' communications, tailoring them to destination hardware and software needs achieving what is defined in this dissertation as the hyperconnectivity among heterogeneous assets. This specifically applies to the industrial collaborative environment proposed in Chapter 4.

This hyperconnected environment facilitates the convergence of diverse industrial technologies within it for multifaceted applications. For instance, integrating DTs with Virtual Reality (VR) offers a more immersive perception of industrial process virtualization, bridging not only technological but also human assets through immersive experiences. This facilitates the development of numerous industrial applications, including operator training to mitigate costs and risks in real environments, as studied in Chapter 7. In this sense, it is demonstrated that humans can learn to handle industrial machines in a virtual environment nearly as effectively as they do in the real world.

However, the generation of a virtual ecosystem that completely replicates the real environment not only entails the relations between humans and machines but also among humans. Thus, including another human in this virtual environment enables more realistic interactions and collaboration, creating a fully virtual space, the industrial metaverse. Thus, finally, Chapter 8 evaluates performance and user satisfaction by comparing real and virtual environments in collaborative activities involving two humans and an AMR, showing a novel research direction that helps to completely develop the principles of the next industrial revolution, Industry 5.0.

For these reasons, this dissertation particularly explores the virtualization of industrial assets, overcoming technological barriers to develop hyperconnected applications within the Industry 5.0 paradigm, placing humans at the forefront of the factory of the future.

Resumen

La transformación digital está revolucionando la industria manufacturera, fomentando una convergencia entre los mundos físico y virtual a través de los sistemas ciberfísicos (CPS). Estos sistemas, equipados con sensores, actuadores, inteligencia y conectividad, forjan un entorno de colaboración crucial. Sin embargo, superar los retos tecnológicos inherentes a la fusión de diversas tecnologías asociadas a la fabricación inteligente es fundamental para lograr la virtualización industrial. Este cambio digital ha abierto nuevas perspectivas para la simulación de procesos y la formación de operarios, elevando la eficiencia y la colaboración en los entornos industriales.

El desarrollo de estas aplicaciones requiere virtualizar los CPS, lo que exige modelar su comportamiento mediante la comprensión de sus respuestas a estímulos reales en el entorno físico. Así, la virtualización se extiende más allá de los CPS para abarcar sus entornos físicos dinámicos, creando un entorno de simulación denominado Digital Twins (DTs). Estos DTs pueden recrear numerosos escenarios e hipótesis que replican el comportamiento real de los sistemas de forma virtual permitiendo el análisis de diferentes condiciones operativas en el mundo virtual.

En este sentido, los DTs encuentran relevancia en contextos como el transporte industrial inteligente, donde el entorno juega un papel fundamental a la hora de guiar la navegación de los Robots Móviles Autónomos (AMRs). Por esta razón, en el capítulo 5, se desarrolló un DT para comparar tiempos y trayectorias entre un vehículo autónomo virtual y uno real, obteniendo una alta similitud. La implementación de DTs en el transporte industrial mejora la toma de decisiones para la optimización de procesos clave críticos para el rendimiento global de la planta industrial.

Además, este entorno virtualizado incorpora posteriormente una flota de AMR para analizar su comportamiento en entornos industriales reales. Esto permite comprender la respuesta de cada

AMR de la flota utilizando diferentes algoritmos de navegación dentro de un entorno virtualizado dinámico. En particular, el capítulo 6 analiza los algoritmos de navegación Timed Elastic Band (BET) y Dynamic Window Approach (DWA). Además, para facilitar la comprensión de las simulaciones realizadas, se ideó una interfaz para modificar dinámicamente los parámetros y visualizar los datos de simulación en tiempo real.

Sin embargo, los valiosos conocimientos del DT no se integran a la perfección dentro de los capítulos 5 y 6 en el entorno colaborativo de los procesos productivos, según el paradigma de la Fabricación Inteligente (Smart Manufacturing, SM). Por ello, la transmisión de datos de DT y otros activos externos a las arquitecturas industriales y protocolos de comunicaciones exigió el desarrollo de una pasarela de interoperabilidad. Esta pasarela analiza las comunicaciones de los activos, adaptándolas a las necesidades de hardware y software de destino, logrando lo que en esta tesis se define como hiperconectividad entre activos heterogéneos. Esto se aplica específicamente al entorno colaborativo industrial propuesto en el capítulo 4.

Este entorno hiperconectado facilita la convergencia de diversas tecnologías industriales en su interior para aplicaciones polivalentes. Por ejemplo, la integración de las DT con la Realidad Virtual (RV) ofrece una percepción más inmersiva de la virtualización de los procesos industriales, tendiendo puentes no sólo tecnológicos sino también humanos a través de experiencias inmersivas. Esto facilita el desarrollo de numerosas aplicaciones industriales, incluyendo la formación de operarios para mitigar costes y riesgos en entornos reales, tal y como se estudia en el capítulo 7. En este sentido, se demuestra que los humanos pueden aprender a manejar máquinas industriales en un entorno virtual casi con la misma eficacia que en el mundo real.

Sin embargo, la generación de un ecosistema virtual que replique completamente el entorno real no sólo implica las relaciones entre humanos y máquinas, sino también entre humanos. Así, incluir a otro humano en este entorno virtual permite interacciones y colaboraciones más realistas, creando un espacio totalmente virtual, el metaverso industrial. Así, finalmente, el capítulo 8 evalúa el rendimiento y la satisfacción del usuario comparando entornos reales y virtuales en actividades colaborativas que involucran a dos humanos y un AMR, mostrando una dirección de investigación novedosa que ayuda a desarrollar completamente los principios de la próxima revolución industrial, la Industria 5.0.

Por estas razones, esta tesis explora especialmente la virtualización de activos industriales, superando las barreras tecnológicas para desarrollar aplicaciones hiperconectadas dentro del paradigma de la Industria 5.0, situando a los humanos al frente de la fábrica del futuro.

CHAPTER 1

Objectives and thesis organization

1.1 Objectives

This thesis seeks to develop a virtual industrial ecosystem where the connectivity of assets is integrated considering human presence and participation. Within this general framework, the thesis delineates general and specific objectives. General objectives are outlined here while the specific ones are set out in Chapter 3 and further developed in the research areas of this dissertation spanning from Chapter 4 to Chapter 8.

- Formulation of a novel framework to facilitate seamless communication and integration among systems, assets, and human entities, denominated as hyperconnectivity.
- Creation of an industrial prototype to demonstrate the practical application of hyperconnectivity in a real environment, analyzing the performance of the demonstrator through various industrial protocols.
- Design and validation of a model to assess the behavior of an autonomous mobile robot.
- Creation of a digital environment specifically tailored for simulating vehicle navigation in different scenarios.
- Comparative analysis of trajectories and temporal aspects of the navigation of autonomous mobile robots between the virtual simulation and real-world implementations.

- Integration of diverse industrial technologies in a common framework to facilitate skill development via the inception of a digital platform dedicated to operators' training.
- Quantitative assessment and comparative analysis of skills acquired through diverse digital training methods compared to traditional training, followed by the validation of digital methodologies designed to enhance operators' competencies and improve user experience.
- Proposal of an innovative technological framework for the implementation of the industrial metaverse.
- Develop and implement a functional demonstrator to show its practical application and evaluate user experience and performance metrics during interactions within the metaverse.
- Introduce the industrial metaverse together with human-oriented technologies for the implementation of demonstrators of the Industry 5.0 paradigm.

The achievement of these objectives and technological advances in this thesis has the potential to generate social impact, which is materialized in the following points:

- Mitigation of trainee risk exposure by employing process modeling and virtualization, thereby reducing the likelihood of accidents.
- Substantial reduction in economic expenditures associated with the utilization of physical equipment for operator training purposes.
- Promotion of inclusive learning by leveraging digitalized training methods, fostering widespread access and decentralized learning processes.
- Integration of digitalization and remote training methodologies for industrial operators engaged in collaborative tasks.
- Cultivation of cultural adaptability within industrial labor dynamics, fostering enhanced collaboration and communication.
- Cultivation of novel competencies in social interaction, fostering adaptability in the context of cultural diversity and the evolving landscape of globalization.

1.2 Main contributions

The main contributions of this thesis are summarized below.

i. Development of a technological framework aimed at enhancing connectivity among both internal and external industrial assets, considering the digitalization of human resources.

ii. Implementation of a communication gateway between different communication protocols to ensure interoperability between industrial assets.

iii. Advancement in modeling a non-holonomic, differential-drive autonomous mobile robot through sensor and actuator virtualization, culminating in the creation of a DT.

iv. Integration of the DT within the hyperconnectivity framework, accompanied by the development of intuitive graphical interfaces for result acquisition and visualization.

v. Pioneering convergence between DT technology and VR through hyperconnectivity, facilitating an immersive learning environment for industrial operators.

vi. Comprehensive comparative evaluation of diverse methodologies for skill acquisition, specifically tailored for industrial operator training.

vii. Development of a virtual environment where humans can interact intuitively with the industrial environment and machines.

viii. Evaluation of human behavior, drawing comparative analyses between the virtual and real-world contexts, incorporating both objective and subjective data collected during the experiments conducted.

1.3 Thesis Organization

This section outlines the framework of the thesis. This Chapter 1 defines the main objectives of the thesis, highlights its academic contributions, explains the structure of the document, presents the research funding initiatives, and contextualizes the thesis within the work of the research group.

Chapter 2 provides a general introduction to the digitization and virtualization of industry, including a state-of-the-art. In addition, the existing problems are mentioned, as well as the technological framework in which they are found. Interoperability among heterogeneous industrial assets is presented, as well as its applications and implications defining a new term, hyperconnectivity.

Subsequently, the need of DTs for asset virtualization is introduced, being the intelligent internal transport as an example of integration in a collaborative environment.

Furthermore, the convergence of technologies such as VR and DT through the interoperability of environments for the training of industrial operators is mentioned. In this context, the establishment of human-human interactions within the virtual industrial environment is emphasized. This chapter ends with a reflection on the required technologies for developing the research proposal addressed in this thesis.

In Chapter 3, a review of the research chapters is made to establish an argumentative and connecting thread between them for the development of the doctoral thesis.

Chapter 4 develops the research carried out to improve industrial interoperability by including humans in the digital ecosystem. With this contribution, a framework is developed and implemented where diverse heterogeneous assets are communicated for the development of industrial collaborative activities. In addition, the performance of communication gateways in the industrial environment is evaluated.

Chapter 5 proposes the development of a model for the virtualization of an autonomous mobile robot for industrial internal transportation. For this model, environments for real-time simulation navigation have been recreated for comparison with the real environment.

The joint performance of a fleet of industrial autonomous vehicles is analyzed in Chapter 6. Particularly, the behavior of each AMR by using different navigation algorithms in front of the same virtualized environment is evaluated.

Chapter 7 delves into the creation of a highly realistic virtual environment enabling human interaction with CPS to enhance industrial skills and knowledge. This chapter explores diverse methodologies aimed at evaluating skill transfer in industrial activities.

Chapter 8 addresses the interaction not only between humans and machines in a virtualized environment but also between humans in a natural way as it occurs in real production processes. With this fact, a fully collaborative virtual environment is achieved where the user experience has been measured, as well as the performance compared to the real environment.

Finally, Chapter 9 presents the conclusions highlighting the future work of this thesis.

1.4 Research framework

This work has been developed within the SIMFAB research group (Intelligent Systems for Mechanics and Manufacturing) of the University of León, under the academic supervision of Dra. Hilde Pérez García and Dr. Javier Díez González.

During the development of this doctoral thesis, this research group has led a national project supported by the Ministry of Science and Innovation entitled *Intelligent Manufacturing Systems in Industrial Internet Platforms.* Additionally, financial support has been received from the University of León to promote dissemination and to help in developing the research project. These funds have been essential to promote both the research activities and the dissemination initiatives that make up this doctoral thesis.

Complementary, this thesis acquires an international dimension thanks to the research stays carried out at the Universidade do Minho in Guimaraes, in collaboration with Professor Maria Madalena Teixeira Araujo. During this period, joint research projects have been developed, the results of which are integrated into this international work.

Furthermore, the thesis is part of the doctoral program of the Eureca-Pro alliance of European universities (where the University of León is integrated), focused on responsible production and consumption. This doctoral program is aligned with the Sustainable Development Goals (SDGs) 12 and has facilitated collaboration in outreach and research activities with other European academic partners of the University of León, having the doctoral student play an active role in it.

Furthermore, the dissertation of this thesis is closely linked to SDG 9, which promotes the advancement of industry, innovation, and infrastructure. The research and findings of this dissertation seek to contribute directly to the promotion of innovative technologies and improved infrastructure, aligning with the overarching goal of fostering sustainable, inclusive, and resilient economic growth.

CHAPTER 2

General introduction

The transformation of raw materials into manufactured products improves society's quality of life. To this end, mankind has employed different technologies and techniques to make production processes more efficient, safe, and sustainable. Currently, the industry is immersed in a digital transformation process where the integration of new technologies in a connected environment poses new challenges for the generation of added value [1].

However, this digitization process is usually approached individually for each process promoting the generation of digital islands where connectivity with other processes is limited, thus complicating the joint integration of processes [2]. This is usually due to the diversity of production processes giving rise to different technological solutions which locally meet the needs of a specific process. Nevertheless, the lack of effective communication among industrial assets is a drawback for the global optimization of production [3].

Faced with this lack of a global approach, it is necessary to establish a framework for a comprehensive digitization of production activities along the entire value chain. In this way, connectivity among assets increases the overall operational efficiency by reducing production times, as well as errors, and generating greater added value [4]. Furthermore, the large amount of data that is generated in real-time in each digitized process is key for decision-making, contributing to sustainability by optimizing the use of resources (e.g., energy, raw materials, ...) [5]. Moreover, this global approach should not only be based on the internal assets of the industry but also on the external ones such as the market, suppliers, or customers which are part of the entire value chain [6].

However, these digital assets have heterogeneous characteristics and communication protocols, preventing direct connectivity. To achieve interoperability of industrial assets it is necessary to establish a gateway among the different communication protocols that are used in the industry. Given the different structures and specifications, it is necessary to guarantee both semantic and syntactic interoperability [7], which requires knowledge of all the domains. To address this problem, intelligence is required in an intermediate layer [8] where information is parsed for translation to the target protocols. Moreover, with this centralization, it is possible to complement the information of the protocols with data from other domains, providing greater flexibility and integration. In this way, it is possible to create a collaborative environment where both internal and external assets can communicate, generating a hyperconnected ecosystem [9] that is defined in Chapter 4.

In this context of advanced interconnections, services that require high computational performance, such as simulations to estimate the performance of production processes [10], can be more easily integrated for production optimization. Within these industrial optimization services there are tools such as Digital Twins (DT) which evaluate the behavior of assets in a dynamic virtual environment [11]. Using DTs, simulations can be performed to understand the performance of assets under eventual conditions that reflect an accurate and realistic representation.

One of the industrial assets where it is convenient to use DTs is the internal transportation of materials due to the use of autonomous mobile robots (AMRs) [12]. These autonomous vehicles have a highly environment-dependent behavior, so a DT has been developed by modeling an AMR [13]. In this way, it is possible to know the trajectories and times for the planning of production processes as detailed in chapter 5. With this information and the hyperconnectivity framework, algorithms can be developed to optimize the routes of these vehicles without the need for a real analysis of the cost and implications it has.

Furthermore, in Chapter 6, a study is carried out to evaluate the performance of different navigation algorithms in a given scenario [14]. In this context, it can also be used for the analysis of a fleet of vehicles to evaluate the dynamic behavior of individual vehicles in order to avoid collisions among them [15]. Another application of these environments is the optimization of the navigation parameters for both the global and the closest trajectories to achieve efficient and safe internal transport [16].

The use of these DTs combined with a hyperconnected environment enables the convergence of technologies for the development of industrial applications. Connecting the virtual environments of the DTs with Virtual Reality (VR) glasses enables the integration of the human being. Humans are a fundamental asset for development because, like the CPS [17], they have the ability to perceive the environment with their senses, make decisions, and take action. For this reason, humans must also be part of this transformation through their integration with technologies that allow them to interact with the digital environment in a natural way [18]. Through this consideration, human collaboration is not just limited to the physical world but also to the digital world where interaction between assets is possible [19].

However, to achieve this aim, it is necessary to virtualize the behavior of the machines with the DTs and connect them through hyperconnectivity to the graphics engines, which provide more realism. To increase the immersion of humans in the virtual environment, VR is used [20], which allows them to interact with the elements of their environment in an intuitive and natural way. Therefore, the convergence of DTs and VR enables the coexistence between human and machine in the virtual world reducing the risks and costs associated with its use [21]. One of the applications of the union of these technologies is the training of operators in the acquisition of skills in a delocalized and safe way [22].

In this context, in Chapter 7, a study has been carried out to evaluate the transfer of skills between the real and virtual worlds [23]. This study analyzes how skills acquired or practiced in virtual environments are effectively transferred and applied to the real world, contrasting them with the results obtained through conventional computer applications or learning using real equipment [24]. The aim is to provide a broader and more detailed understanding of the potential of VR in skills' transfer, as well as its relative value in relation to other teaching and practice methodologies [25].

However, this virtual ecosystem focuses on human-machine interaction, but not on the interaction among virtual humans as in real industrial processes [26]. For this reason, it is necessary to develop avatars (i.e., virtual humans) that can communicate not only by voice but also by gestures in the virtual factory [27]. In this way, digitized humans and machines are integrated into a virtual environment called the industrial metaverse [28].

In Chapter 8, a demonstrator of the industrial metaverse is developed in order to analyze the behavior of humans in virtual industrial environments [29]. For this purpose, it is necessary to establish a collaborative challenge where humans not only interact with each other in real time but also with machines. In this way, the objective is to evaluate the user experience in a comparative way between the real and virtual world [30].

In summary, this thesis aims to virtualize industrial assets by integrating human participation in the collaborative framework of smart manufacturing. To achieve this, a DT has been created to simulate the behavior of CPSs in a virtualized environment. This DT has been integrated into the industrial ecosystem, employing hyperconnectivity to establish robust connectivity between various assets.

Subsequently, leveraging this framework, novel applications have emerged through the convergence of DT, hyperconnectivity, and VR. The inclusion of VR technology enables the seamless integration of humans into this digital and virtual environment, opening up new avenues for enhanced interaction and innovation.

The development of these more holistic and collaborative environments makes the human being an actor in the industrial transformation allowing a closer and more immersive approach to digital environments. This fact is closely linked to the Industry 5.0 paradigm where the creative, empathic, and resilient skills of humans complement the capabilities of technology. Consequently, this technological convergence in a hyperconnected environment drives the development of the industrial metaverse, marking the path toward Industry 5.0.

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CHAPTER 3

Evolution of Research and Linking Chapters

The studies presented in this dissertation are part of the development carried out by the researchers of the SIMFAB group at the University of León. In this context, it should be emphasized that the line of research and therefore this thesis is closely linked to a research project. The aim of this chapter is to establish the linkage of the next chapters, as well as the framework and evolution of the activities carried out in recent years.

The research is contextualized in the development of a research project of the Ministry of Science and Innovation entitled *Intelligent Manufacturing Systems in Industrial Internet Platforms* belonging to the 2019 call. This project with code PID2019-108277GB-C21 has had funding of over 130,000 euros with a duration of 3 years.

The project is framed within the context of the digitalization of manufacturing industries, with the aim of reducing production costs through the introduction and development of innovative technologies. In this line, it seeks to align with Sustainable Development Goals (SDGs) numbers 9 and 12, focused on industry, innovation, and sustainable infrastructure, as well as responsible consumption and production. This initiative is strategically linked to global efforts to promote technological adoption in the manufacturing industry, ensuring a link with the international goals of sustainability and economic progress.

To achieve this main objective, specific challenges have been identified that include the development of hyperconnected environments, the virtualization of production processes, materials logistics management, the implementation of collaborative robotics, positioning systems, cybersecurity, and systems integration. These objectives represent a challenge because they require combining various technologies in an industrial environment. In addition, a broad multidisciplinary knowledge is needed to address them effectively.

However, all the objectives set out are within the framework of the digitization of industrial processes, in order to collect data and information both internally and externally. This approach is essential for decision-making at the production level and for the development of business strategies. To achieve this, it is imperative to develop an Industrial Internet Platform (IIP) based on the Industrial Internet of Things paradigm. In this context, Smart Manufacturing technologies must collaborate in a cohesive manner to achieve the overall purpose outlined by the project.

In the execution of this project, a variety of specialized equipment for the transport and handling of industrial materials has been acquired. Among this equipment are an Autonomous Mobile Robot (AMR), which displays autonomy in its movements, and a collaborative robot (Cobot), designed to interact safely with workers in the industrial environment. In addition, as a fundamental part of the development of the IIP, various networking and communications equipment has been acquired. This equipment has been specifically designed to facilitate communication between the different assets integrated in the IIP, thus ensuring an efficient and secure exchange of data and processes among the different components of the industrial system.

The AMR was used in the first phase of research, where a Digital Twin (DT) was developed to simulate the behavior of the autonomous vehicle. This DT [1, 8] allowed comparing trajectories and mission times between the virtual model and the real vehicle, detailed in Chapter 5. The accuracy of the model was remarkable, which opens a wide range of applications in the industrial field, especially for process planning and decision making thanks to its high reliability and accuracy.

Furthermore, a fleet of AMRs was introduced in this virtual environment where they had to navigate together in order to evaluate the performance. With the fleet of AMRs, a study was carried out comparing different navigation algorithms, which is developed in Chapter 6. This work was presented at the Ibero-American Congress of Mechanical Engineering in 2022 and later published [13] as a valid method for the evaluation of algorithms in different scenarios and dynamic environments.

However, DTs require connectivity with the assets involved in the production processes in order to have greater applicability. For this reason, it was necessary to develop a connectivity framework between physical and virtual assets in order to create a collaborative production environment whose proposal is detailed in Chapter 4. This published research [3] it is intended to establish a demonstrator of industrial asset integrations that will serve as a basis for the following works of the research line.

One of these works was the integration of a manual borescope which was digitized and connected to the IIP for the inspection of machined elements automatically. Automation is not enough because this system must be coordinated with collaborative robots for the precise positioning of the parts. This work was presented at the 2023 Manufacturing Engineering Society International Conference (MESIC) [4] where the technological challenges were addressed.

Another work on asset integration in the hyper-connected environment is AMR access control for special industrial rooms (e.g., cleanrooms, whiterooms). This work addresses the necessary communications between vehicles and automatic doors where the heterogeneity of technologies and protocols is addressed from hyperconnectivity. However, this problem presents another challenge, to know the position of the autonomous vehicles with sufficient accuracy for the opening and closing of the doors. In this work published [2] and presented at the responsible consumption conference organized by the Eureca-Pro alliance of universities in 2022, Bluetooth Low Energy (BLE)-based communications were used to find out which vehicle is near the door.

However, the positioning of these vehicles with BLE systems lacked the necessary accuracy to perform other object manipulation tasks. In this context, the SIMFAB research group has modeled positioning systems based on UltraWideBand technology (UWB) for indoor scenarios such as industrial environments. In this sense, several works have been carried out and published [9, 10, 12] where the location of the sensors of the architecture deployed is optimized based on mathematical models for the calculation of the uncertainty of the positioning calculation whose results indicate centimeter error bounds.

Although this is a breakthrough, there are industrial activities that require higher accuracy, such as AMR positioning for a cobot to perform pick-and-place or assembly tasks. For this reason, a research work has been carried out where an AMR and a Cobot are coordinated within hyperconnectivity to perform precision tasks. To this end, a novel method was designed to adjust the reference systems of both the cobot and the AMR through contact to accurately know the pose (i.e. position and orientation). This work has been published in a scientific journal [5] offering accuracies of the order of magnitude of millimetres.

Hyperconnectivity is not only based on the collaboration among machines and digital assets but also is human-centric in order to integrate into the digital ecosystem. In this context, wearables are being employed in order to generate stimuli (i.e., visual, haptic), make decisions, and trigger actions that can be digitized. One of the most immersive wearables for humans is Virtual Reality (VR) where visually only a fully digitized environment is perceived.

In this context and within the perspective of hyperconnectivity, we are working on the union of VR and DTs, which would allow humans to perceive the simulation environment with greater realism. In this way, humans can see in an immersive way the AMR simulations as well as the dynamic environment of the DT. The technological convergence between the DTs and the development of applications for VR glasses was presented at the 2023 National Congress of Mechanical Engineering.

Given the potential of the technological convergence of DTs and VR, a study was initiated to evaluate the transfer of skills with different methodologies (i.e., computer applications, VR, real environment). For this purpose, a challenge of driving a commercial vehicle was established in order to complete a route in the shortest possible time and with the least possible failures. The experimentation was performed with a random population where skills were evaluated before and after training in order to measure the performance of the different methodologies. The results of this experimentation have been published in 2023 in the International Journal of Human-Computer Studies [11] as well as in Chapter 7 of this thesis.

In view of the results obtained, the study continued focusing on the teaching of university practices where the acquisition or manipulation of industrial equipment is costly or requires many human resources. For this reason, a teaching platform was developed where the practices can be tutored using VR glasses, which was presented and published [6] in the 2023 International Congress on European Transnational Education (ICEUTE).

However, these works of convergence of DT and VR only addressed the interaction between humans and machines, but not between humans as it happens both in industry and in educational spaces. For this reason, the scope of these works has been expanded by creating a new technological framework where the human is the protagonist according to the paradigm of Industry 5.0.

Virtual environments where humans can interact with the rest of the assets in the digital environment are known as metaverses. The creation of a hyperconnectivity framework where enabling technologies (e.g., DTs, VR) are connected facilitates the creation of an industrial metaverse. This fact makes it possible to train and evaluate operators remotely and in safer environments, as well as to simulate production processes where humans are involved.

To showcase the potential of virtual environments within the industrial sector, a comprehensive study was undertaken to assess individual performance and user experience. The evaluation involved replicating an actual industrial setting in a virtual realm, specifically designed for collaborative industrial operations. Addressing the challenge, participants interacted with both human counterparts and autonomous vehicles. This experiment was conducted in both virtual and real settings, allowing for a comparative analysis of performance and user experience across both environments. The findings of this research have been submitted to the international journal Robotics and Computer-Integrated Manufacturing for publication consideration.

Therefore, the results of this dissertation have culminated in the development of an industrial collaborative environment where humans are integrated into the digital environment. These results have led to the following scientific publications:

A.1 A. Martínez-Gutiérrez, J. Díez-González, R. Ferrero-Guillén, P. Verde, R. Álvarez, and H. Perez, "Digital twin for automatic transportation in industry 4.0," 2021

A.2 A. Martínez, J. Díez, P. Verde, R. Ferrero, R. Álvarez, H. Perez, and A. Vizán, "Digital twin for the integration of the automatic transport and manufacturing processes," in *IOP Conference Series: Materials Science and Engineering*, vol. 1193, p. 012107, IOP Publishing, 2021

A.3 A. Martínez-Gutiérrez, J. Díez-González, P. Verde, R. Ferrero-Guillén, and H. Perez, "Analysis of navigation algorithms for a fleet of mobile robots by means of digital twins," in *Ibero-American Congress of Mechanical Engineering*, pp. 412–417, Springer, 2022

A.4 A. Martínez-Gutiérrez, J. Díez-González, R. Ferrero-Guillén, P. Verde, J.-M. Alija-Pérez, and H. Perez, "Wireless industrial access control systems for autonomous transportation," in *EURECA-PRO Conference on Responsible Consumption and Production*, pp. 298–305, Springer, 2022

A.5 A. Martínez-Gutiérrez, J. Díez-González, P. Verde, R. Ferrero-Guillén, and H. Perez, "Hyper-connectivity proposal for smart manufacturing," *IEEE Access*, 2023

A.6 J. Díez-González, P. Verde, R. Ferrero-Guillén, R. Álvarez, N. Juan-González, and A. Martínez-Gutiérrez, "Evaluation of the skills' transfer through digital teaching methodologies," in *Computational Intelligence in Security for Information Systems Conference*, pp. 340–349, Springer, 2023

A.7 A. Gil-Cuadrado, A. Martínez-Gutiérrez, J. Díez-González, P. Verde, R. Ferrero-Guillén, and H. Perez, "Full automation of a manual inspection unit for industrial borescopy," *Advances in Science and Technology*, vol. 132, pp. 140–146, 2023

A.8 I. Sánchez-Calleja, A. Martínez-Gutiérrez, R. Ferrero-Guillén, J. Díez-González, and H. Perez, "Contact system method for the precise interaction between cobots and mobile robots in smart manufacturing," *International Journal of Precision Engineering and Manufacturing*, pp. 1–16, 2023

A.9 A. Martínez-Gutiérrez, J. Díez-González, P. Verde, and H. Perez, "Convergence of virtual reality and digital twin technologies to enhance digital operators' training in industry 4.0," *International Journal of Human-Computer Studies*, vol. 180, p. 103136, 2023

Furthermore, with the publication of these works and the achievement of the objectives of the research project, a positive impact is expected not only in the scientific field but also in the industrial manufacturing, improving its competitiveness and resilience in the market.

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CHAPTER 4

Hyperconnectivity proposal for Smart Manufacturing

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Abstract

Smart Manufacturing is characterized by the digitization and massive communication of Cyber-Physical Systems under the Industrial Internet of Things paradigm. However, the heterogeneity of communication protocols hinders connectivity among assets due to lack of interoperability. Moreover, the decomposition of the classical production hierarchy towards decentralized self-organization makes the implementation of interoperability in industrial environments key to help decision-making. In this sense, the interoperability of heterogeneous assets (e.g., external, internal, and human) has been defined as hyperconnectivity and supposes a technological challenge in the scientific literature. To prove this novel hyperconnectivity definition, the authors propose and develop a novel hyperconnected demonstrator where all types of assets are interconnected in a case study consisting of the automation of an inspection process. For this purpose, an industrial internet

platform has been used for connecting industrial equipment creating a collaborative environment through the use of interoperability. In this regard, it has been possible to communicate assets among the cloud, humans, and CPS with a processing time of less than 10 ms, which demonstrates that the technological challenge of implementing the hyperconnectivity concept of this paper has been successfully addressed.

CHAPTER 5

Digital twin for automatic transportation in industry 4.0

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Abstract

Industry 4.0 is the fourth industrial revolution consisting of the digitalization of processes facilitating an incremental value chain. Smart Manufacturing (SM) is one of the branches of the Industry 4.0 regarding logistics, visual inspection of pieces, optimal organization of processes, machine sensorization, real-time data acquisition and treatment, and virtualization of industrial activities. Among these tecniques, Digital Twin (DT) is attracting the research interest of the scientific community in the last few years due to the cost reduction through the simulation of the dynamic behaviour of the industrial plant predicting potential problems in the SM paradigm. In this paper, we propose a new DT design concept based on external service for the transportation of Automatic Guided Vehicles (AGVs) which are being recently introduced for the Material Requirement Planning satisfaction in the collaborative industrial plant. We have performed real experimentation in two different sce-

narios through the definition of an Industrial Ethernet platform for the real validation of the DT results obtained. Results show the correlation between the virtual and real experiments carried out in the two scenarios defined in this paper with an accuracy of 97.95% and 98.82% in the total time of the missions analysed in the DT. Therefore, these results validate the model created for the AGV navigation, thus fulfilling the objectives of this paper.

CHAPTER 6

Analysis of navigation algorithms for a fleet of mobile robots by means of Digital Twins

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Abstract

Industrial handling is undergoing a process of digitalization and automation through the use of Industry 4.0 technologies. For instance, digital twins allow the virtualization of assets such as the fleet of Autonomous Mobile Robots (AMR). In this digitized environment, two local navigation algorithms are analyzed; Dynamic Window Approximation (DWA) and Time Elastic Band (TEB). For this purpose, a Digital Twin is implemented in the ROS ecosystem where an industrial environment is virtualized. On this environment, a mission of a fleet of three AMRs is simulated where they will navigate simultaneously in order to compare the behavior of the algorithms in dynamic industrial environments. As results, the trajectories and times of each AMR are analyzed, which are key for the planning of production costs. Furthermore, in this work a web server is developed to interact with the digital twin, facilitating its use.

CHAPTER 7

Convergence of virtual reality and digital twin technologies to enhance digital operators' training in industry 4.0

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Abstract

Industry 4.0 technologies enable the generation of added value throughout the production process. Among them, Digital Twins (DT) allow the modelization of cyber-physical systems in the virtual world and Virtual Reality (VR) allows an immersive perspective of the behavior of industrial equipment in a digitized environment. The combination of DT and VR can generate a digital platform for operators' training where the industrial operator can perceive a more realistic environment for digital learning. In this paper, we introduce the convergence of DT and VR to enhance the digital learning process of driving an industrial mobile robot. To validate this proposal, an experimental methodology looking for measuring the transfer of skills from digital training into the real world has been set. This experiment consists of handling a mobile robot in a predefined course looking

for committing the lowest number of failures in the minimum possible time. The experiment has been carried out by defining three different training methods: training with real equipment as the control group and two different experimental groups following digital training (VR and computer application-supported techniques). The abilities of their subjects have been measured in the initial and final stages of the experiment showing an improvement of 47% through real training, 38% through VR and 28% through the computer application. Results demonstrate the utility of using DT to attain significant digital learning and validate the initial hypothesis demonstrating the enhancement of digital learning through VR-supported training.

CHAPTER 8

Towards Industry 5.0 through Metaverse

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Abstract

The digital transformation of the industry allows the optimization of resources through enabling technology that virtualizes the behavior of Cyber-Physical Systems (CPS) along the entire value chain. However, these virtual environments characterized by machine-to-machine interactions lacked the presence of humans who are at the center of the next defined industrial revolution, Industry 5.0. The goal is for humans to be actively integrated into these virtual environments called metaverses where interactions with environmental digital assets are possible. To achieve this human-centered industrial metaverse perspective, it is necessary to provide humans with technologies that allow them to reach a more immersive and realistic conception of the production processes. For this purpose, we present in this paper, a framework based on hyperconnectivity where several enabling technologies (e.g., Digital Twins, Virtual Reality, Industrial Internet of Things (IIoT)) are integrated in order to converge towards the industrial human-centered metaverse. To validate our framework, a demonstrator has been developed enabling the evaluation of the behavior of humans in virtual environments when facing collaborative tasks that require human-to-human interaction. Within

the evaluation of this demonstrator, an experiment based on an assembly that requires interaction with an autonomous vehicle has been carried out both in reality and in the virtual world. The results obtained indicate that the avatars' metaverse performance is closer to reality when individuals have previous experience with VR goggles, even proving, in this case, the effectiveness of metaverse for industrial operators' training. In addition, the performance of the application has been evaluated with technical parameters and the perception of the users has been analyzed by conducting a survey receiving very positive feedback and results. Therefore, the industrial metaverse, blending cutting-edge tech with a human-centric approach for Industry 5.0, is now a reality.

CHAPTER 9

Conclusions and outlook

9.1 Conclusions

THIS dissertation presents a technological development for the creation of a collaborative environment among industrial assets including humans. For this purpose, several technologies such as Digital Twins, Virtual Reality, or the Industrial Internet of Things have been implemented in order to generate new applications. Operator training, behavioral analysis of autonomous vehicle fleets or immersive human-human interaction are some of the applications implemented in this thesis when integrating several technologies.

The main remarks of this thesis on the development of a collaborative environment for industrial assets are presented below.

- An architecture has been implemented to improve interoperability between internal and external digital assets for heterogeneous communication protocols achieving acceptable response times for the industrial sector.

- The term hyperconnectivity has been defined to refer to the syntactic and semantic interoperability to display and structure information according to the characteristics of each asset optimizing production.

- A digital model has been developed for the virtualisation of the navigation of a non-holonomic autonomous mobile robot (AMR) with differential traction in order to determine its behavior and to optimize process planning.

- The DT performance has been validated with a correlation of more than 97% between the DT simulation for AGV trajectory planning and AGV navigation in the real environment, confirming the effectiveness of the proposed DT ecosystem for industrial applications.
- A fleet of AMRs has been integrated in the DT in order to analyse the parameters as well as the navigation algorithms for different industrial virtual environments.
- The DWA and TEB algorithms have been compared revealing that TEB demonstrates shorter times, particularly excelling with dynamic obstacles, while DWA is more adaptable to less smooth cost functions due to its velocity sampling approach.
- TEB has also been shown to present trajectories closer to optimal solutions, although compliance with the constraints depends on the application of penalties, lacking a satisfaction guarantee.
- A web interface has been developed for the visualisation of simulation parameters as well as the assignment of parameters for the navigation algorithms in the ROS ecosystem, which has facilitated interaction by non-expert users.
- Digitised training techniques have been implemented through the technological convergence of DTs and Virtual Reality (VR), demonstrating their potential to reduce the risks and costs associated with the training of industrial operators compared to learning with real equipment.
- The effectiveness of different training methods (real equipment, VR and computer applications) in the training of industrial operators has been evaluated and compared, revealing a significant improvement of 38% with the VR methodology compared to 28% with the computer applications.
- According to the survey of the study population, it has been determined that the perception and realism between the virtual and real model motivate users to employ this methodology as a technique for the acquisition of skills and knowledge.
- In accordance with the current state of the art, a blended approach is advocated combining digital methodologies with training on real equipment, proposing a compromise solution to balance costs, risks, and efficiency, ultimately optimizing the training process of industrial operators in the context of Industry 4.0.

- A technological framework has been established to integrate humans into virtual environments within the context of Industry 5.0, where hyperconnectivity and enabling technologies such as DT, VR, and IIoT are fundamental to the generation of added value.
- A comprehensive evaluation of a demonstrator that integrates several enabling technologies and evaluates human behavior in virtual environments through collaborative challenges has been carried out and it has been concluded that with the current performance of the devices, the implementation of the metaverse is possible.
- Performance patterns in the VR goggles of tasks within the metaverse have been analyzed, determining a minimal increase in resources during certain interactions with avatars and objects.
- User experience insights validated by the experimental subjects of the experiments conducted have shown the potential implications beyond workforce training by revolutionizing production, remote operations, and collaborative efforts, marking a significant step towards Industry 5.0.

9.2 Future works

The pursuit of an industry where all assets exist in a virtual realm represents an ambitious objective. Therefore, the thesis and its research trajectory offer avenues for expansion through the incorporation of novel applications or the integration of emerging technologies. The following points outline potential research directions derived from this thesis.

- The implementation of intelligence in the hyperconnectivity gateway involves the creation and improvement of algorithms that enable automatic adaptation of data representation. This involves considering human sensory capabilities, such as sight, touch and hearing, to improve communication between humans and digital assets. This could involve advanced signal processing techniques, machine learning and neural networks to interpret and translate data efficiently.
- Evaluating navigation algorithms in dynamic environments and in the face of potential failures in embedded vehicle systems involves using methods to determine which parameters are most appropriate. This requires a deep understanding of vehicle dynamics, sensor fusion techniques and decision making algorithms to ensure safe and efficient navigation in variable industrial environments.

- ❖ The development and integration of artificial intelligence-based optimization algorithms involves the application of reinforcement learning techniques to dynamically manage fleets of autonomous vehicles. This may include route optimization, efficient energy management and adaptation to changing environmental conditions.

- ❖ To understand the relationship between user discomfort and technical parameters, it is necessary to conduct a detailed study. This involves collecting data related to system performance and communications, as well as measuring user response in terms of discomfort, disorientation, etc. This analysis may require statistical analysis tools and data processing techniques to identify meaningful patterns.

- ❖ Analyze human behavior in virtual environments by observing and measuring user responses to specific situations, such as reflexes, dangerous situations, and psychological reactions. This may require the use of eye-tracking devices, motion sensors, and behavioral analysis techniques to understand how users interact and respond in a virtual environment.

- ❖ To enhance avatar movement and achieve greater realism, motion capture techniques, such as motion sensors or tracking cameras, can be used. In addition, the implementation of physics- and biomechanics-based animation algorithms can help avatars move more naturally and accurately reflect the measurements and behaviors of real humans in the virtual world. This involves an advanced technical approach to computer animation and physical simulation.

CHAPTER 10

Conclusiones y Líneas Futuras

10.1 Conclusiones

ESTA disertación presenta un desarrollo tecnológico para la creación de un entorno colaborativo entre los activos industriales incluyendo a los humanos. Para ello se ha implementado diversas tecnologías como Gemelos Digitales, Realidad Virtual o el Internet Industrial de las Cosas con el fin de generar nuevas aplicaciones. La formación de operadores, el análisis del comportamiento de flotas de vehículos autónomos o la interacción entre humanos de forma inmersiva son algunas de las aplicaciones implementadas en esta tesis cuando se integran varias tecnologías.

Las principales observaciones de esta tesis sobre el desarrollo de un entorno colaborativo para los activos industriales se presentan a continuación.

- Se ha implementado una arquitectura para mejorar la interoperabilidad entre activos digitales internos y externos para protocolos de comunicación heterogéneos logrando tiempos de respuesta aceptables para el sector industrial.

- El término hiperconectividad se ha definido para referirse a la interoperabilidad sintáctica y semántica para mostrar y estructurar la información según las características de cada activo optimizando la producción.

- Se ha desarrollado un modelo digital para la virtualización de la navegación de un robot móvil autónomo (AMR) no holonómico con tracción diferencial con el fin de determinar su comportamiento.

- Se ha validado el rendimiento del DT con una correlación superior al 97% entre la simulación del DT para la planificación de la trayectoria del AGV y la navegación del AGV en el entorno real, confirmando la eficacia del ecosistema DT propuesto para aplicaciones industriales.
- Se ha integrado una flota de AGVs en el DT con el fin de analizar los parámetros así como los algoritmos de navegación para diferentes entornos virtuales industriales.
- Se han comparado los algoritmos DWA y TEB revelando que TEB demuestra tiempos más cortos, destacando particularmente con obstáculos dinámicos, mientras que DWA es más adaptable a funciones de coste menos suaves debido a su enfoque de muestreo de velocidad.
- También se ha demostrado que TEB presenta trayectorias más cercanas a las soluciones óptimas, aunque el cumplimiento de las restricciones depende de la aplicación de penalizaciones, careciendo de garantía de satisfacción.
- Se ha desarrollado una interfaz web para la visualización de los parámetros de simulación, así como la asignación de parámetros para los algoritmos de navegación en el ecosistema ROS, lo que ha facilitado la interacción de usuarios no expertos.
- Se han implementado técnicas de formación digitalizada mediante la convergencia tecnológica de DTs y Realidad Virtual (RV), demostrando su potencial para reducir los riesgos y costes asociados a la formación de operarios industriales en comparación con el aprendizaje con equipos reales.
- Se ha evaluado y comparado la eficacia de diferentes métodos de formación (equipos reales, RV y aplicaciones informáticas) en la formación de operarios industriales, revelando una mejora significativa del 38% con la metodología de RV frente al 28% con las aplicaciones informáticas.
- De acuerdo con la encuesta realizada a la población objeto de estudio, se ha determinado que la percepción y el realismo entre el modelo virtual y el real motiva a los usuarios a emplear esta metodología como técnica para la adquisición de habilidades y conocimientos.
- De acuerdo con el estado actual de la técnica, se aboga por un enfoque mixto que combine metodologías digitales con formación en equipos reales, proponiendo una solución de compromiso para equilibrar costes, riesgos y eficiencia, optimizando en última instancia el proceso de formación de operarios industriales en el contexto de la Industria 4.0.

- Se ha establecido un marco tecnológico para integrar a los seres humanos en entornos virtuales en el contexto de la Industria 5.0, donde la hiperconectividad y las tecnologías habilitadoras como DT, VR e IIoT son fundamentales para la generación de valor añadido.

- Se ha realizado una evaluación exhaustiva de un demostrador que integra varias tecnologías habilitadoras, evaluando el comportamiento humano en entornos virtuales a través de retos colaborativos, revelando la viabilidad de alcanzar el metaverso industrial con la tecnología actual.

- Se han analizado los patrones de rendimiento en las gafas de RV de tareas dentro del metaverso, determinando un incremento mínimo de recursos durante ciertas interacciones con avatares y objetos.

- Las percepciones de la experiencia del usuario validadas por los sujetos experimentales de los experimentos realizados han mostrado las implicaciones potenciales más allá de la formación de la mano de obra al revolucionar la producción, las operaciones remotas y los esfuerzos de colaboración, marcando un paso significativo hacia la Industria 5.0.

10.2 Trabajos futuros

La búsqueda de una industria donde todos los activos existan en un entorno virtual representa un objetivo ambicioso. Por lo tanto, la tesis y su trayectoria de investigación ofrecen caminos para la expansión a través de la incorporación de nuevas aplicaciones o la integración de tecnologías emergentes. Los siguientes puntos esbozan posibles direcciones de investigación derivadas de esta tesis.

- La implantación de la inteligencia en la pasarela de hiperconectividad implica la creación y mejora de algoritmos que permitan la adaptación automática de la representación de los datos. Esto implica tener en cuenta las capacidades sensoriales humanas, como la vista, el tacto y el oído, para mejorar la comunicación entre los seres humanos y los activos digitales. Esto podría implicar técnicas avanzadas de procesamiento de señales, aprendizaje automático y redes neuronales para interpretar y traducir los datos de forma eficiente.

- Evaluar los algoritmos de navegación en entornos dinámicos y ante posibles fallos en los sistemas integrados de los vehículos lo que implica utilizar métodos para determinar qué parámetros son los más adecuados. Para ello es necesario conocer a fondo la dinámica del vehículo, las técnicas de fusión de sensores y los algoritmos de toma de decisiones para garantizar una navegación segura y eficiente en entornos industriales variables.

- El desarrollo e integración de algoritmos de optimización basados en inteligencia artificial implica la aplicación de técnicas de aprendizaje por refuerzo para gestionar dinámicamente flotas de vehículos autónomos. Esto puede incluir la optimización de rutas, la gestión eficiente de la energía y la adaptación a condiciones ambientales cambiantes.

- Para entender la relación entre la incomodidad del usuario y los parámetros técnicos, es necesario realizar un estudio detallado. Esto implica recopilar datos relacionados con el rendimiento del sistema y las comunicaciones, así como medir la respuesta del usuario en términos de incomodidad, desorientación, etc. Este análisis puede requerir herramientas de análisis estadístico y técnicas de procesamiento de datos para identificar patrones significativos.

- Analizar el comportamiento humano en entornos virtuales observando y midiendo las respuestas de los usuarios ante situaciones específicas, como reflejos, situaciones de peligro y reacciones psicológicas. Esto puede requerir el uso de dispositivos de seguimiento ocular, sensores de movimiento y técnicas de análisis del comportamiento para comprender cómo interactúan y responden los usuarios en un entorno virtual.

- Para mejorar el movimiento del avatar y lograr un mayor realismo, se pueden utilizar técnicas de captura de movimiento, como sensores de movimiento o cámaras de seguimiento. Además, la aplicación de algoritmos de animación basados en la física y la biomecánica puede ayudar a los avatares a moverse con más naturalidad y reflejar con precisión las medidas y comportamientos de los seres humanos reales en el mundo virtual. Esto implica un enfoque técnico avanzado de la animación por ordenador y la simulación física.