Deliverable D 19.1
Workplace analysis and specifications

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Iñaki Díaz	CEIT	Updated changes from internal review

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1. Executive Summary

The aim of this report is to gather all relevant information for the development of successful, innovative, and useful exoskeleton and augmented reality technologies for assistance in railway maintenance operations.

First, the state of the art regarding these technologies is updated. Regarding exoskeletons, existing systems are still conceived for very controlled and clean shopfloors. Current exoskeletons in the market do not have the capacity to be compatible with common protective tools used in outdoors maintenance operations. Besides, they are still quite bulky and heavy. For augmented reality systems, while there are many developments in the market, there is still a huge need to develop tools that ease the content development and the step-by-step instructions and quality checks that are useful in maintenance operations.

With the state of the art in mind, several workplaces from STRUKTON, MERMEC, FSI and PKP have been analysed to evaluate the potential applicability of the technology to assist workers in their daily tasks. This analysis has evolved into the development of two use cases for WP19 where there is a clear need for the technology, and a path for future validation and demonstration of the technology has been defined.

Besides the workplace evaluation, questionnaires have been developed and delivered to railway maintenance workers to gather information from the final end-users' perspective. This information has complemented the specifications and requirements gathered at the workplace evaluation. Ethical considerations, both to develop the project and the technology are also considered.

Final conclusions of the report show the requirements and specifications list necessary to fulfil during the project to develop successful technology for railways maintenance operations.

2. Abbreviations and acronyms

Abbreviation / Acronym	Description
AR	Augmented Reality
MSD	Musculoskeletal Disorder
TGMS	Inertial-Based Track Geometry Measurement System
IMU	Inertial Measurement Unit
IM	Infrastructure Manager
HRI	Human Robot Interaction
XR	eXtended Reality
MR	Mixed Reality
VR	Virtual Reality

3. Background

The present document constitutes the Deliverable D19.1 “Workplace Analysis and Specifications” in the framework of the Flagship Project FP3 – IAM4RAIL as described in the EU-RAIL MAWP. The deliverable is part of the WP19 of the IAM4RAIL project and reports main work and conclusions of Task T19.1.

4. Objective/Aim

The aim of WP19 is the development of novel and smart assistive tools to support workers in their daily railway maintenance tasks. More specifically, in WP19 technology will be developed to improve human safety and skills in workplace through Exoskeleton and Augmented Reality systems.

As a first step of this ambitious goal, Task 19.1 gathers an in-depth evaluation of several workplaces of 4 end-users involved in the WP (STRUKTON, MERMEC, FSI and PKP) to evaluate both the needs and the requirements of applying such technology to railway maintenance tasks. This deliverable gathers the analysis and conclusions of such evaluation.

More specifically, this deliverable reports on the following topics developed within Task T19.1:

- State of the art (covered in section 5): As a first step we have updated and detailed the state of the art in both exoskeleton and augmented reality technology that we evaluated to define the aims of this WP when preparing the proposal.
- Workplace evaluation (section 6): WP19 end-users have identified various potential applications for these technologies within their working sites and workplaces.
- Use Cases Definition (section 7): From the different workplace evaluations 2 UCs have been defined for this WP.
- Questionnaires (section 8): Besides the workplace evaluation carried out, questionnaires have been delivered to end-users' workers that potentially may be users of the technology, to evaluate their point of view regarding several specifications for the technology.
- Ethics (section 9): Ethical considerations for the WP are analysed.
- Specifications and Requirements (section 10): Conclusions of T19.1 serve as the specifications and requirements that the technology to be developed in following tasks and months must comply to be successful with project aims and technology applicability.

5. State of the Art in Exoskeleton and Augmented Reality Technologies

5.1. Exoskeletons

Millions of workers in the EU suffer from musculoskeletal disorders (MSDs), with workplace injuries costing European countries up to 4% of their gross national product. MSDs are particularly prevalent in industries such as agriculture and forestry, construction and demolition, health and social care, transportation, logistics and shipbuilding.

Human-robot collaboration, such as the use of exoskeletons, is becoming more common to improve workflows in such environments. This technology can bridge the gap between unaided human operations and conventional robotics in feasible automation scenarios. Downtime would be reduced, and productivity would increase, while reducing injury rates and the chance of occupational injuries.

Exoskeletons are wearable, external mechanical structures that enhance a person's power. They can be classified as active or passive. The active exoskeletons use actuators such as electric motors, hydraulic actuators and pneumatic muscles to aid human joints and augment their power. Passive exoskeletons store energy using materials, springs, or dampers to store and use energy harvested by human motion. For example, when a person bends forward, the energy can be used to support a posture, like keeping the body erect while lifting an object.

They can also be classified based on their resemblance to human anthropometry, with anthropomorphic exoskeletons having rotational axes aligned with human joint movement and non-anthropomorphic exoskeletons having optimized structures for specific tasks, allowing for more effective energy consumption. Anthropomorphic exoskeletons offer greater freedom of motion but pose design challenges for accommodating natural movements by users of different sizes, while non-anthropomorphic types are generally simpler and more task-specific (*P. de Looze, et al., 2016*).

The strongest growth is expected to come from systems that augment or amplify human capabilities, particularly for industrial tasks that require heavy lifting, extended standing, squatting, bending, or walking in production facilities. Some exoskeletons have also been designed for military applications to help soldiers lift or carry heavy loads (*Bogue, 2019*).

5.1.1. Technology

Actuators and sensors are the main components of any exoskeleton system, either passive or active.

Actuators

Compliance in exoskeleton design is important to ensure proper interaction with the human body.

This compliance is manifested in three aspects: kinematic compliance, static compliance, and dynamic compliance. Kinematic compliance refers to the need for the exoskeleton's movement to be coordinated with the movement of the limb it is attached to, considering the complex anatomical characteristics of human joints.

These characteristics, such as the center of glenohumeral joint translation and the rotation axis of the elbow joint, require designers to consider anatomical joints differently than traditional mechanical joints. Adding passive joints to the exoskeleton in serial or parallel manners or using non-anthropomorphic designs could automatically accommodate joint sliding (Peng & Bu, 2022).

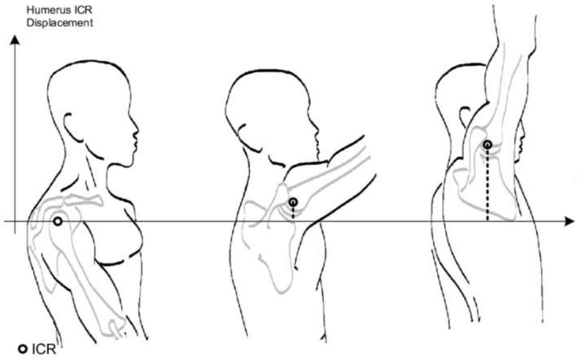


Figure 1. Translation of the Instantaneous Centre of Rotation of the Glenohumeral shoulder joint during shoulder abduction.

In passive devices, the main objective is to compensate gravity by offloading the limb and tool weight during the work task, that usually is achieved with using spring-base systems following different design strategies.

Referring to active devices, estimating the appropriate torque to drive the exoskeleton is needed. There are two main means to actuate an exoskeleton: electric motors, and hydraulic/pneumatic actuators. The parameters considered to design the mechanism are the power-to-weight ratio, torque production, and precision of movement. All these factors are dependent on the targeted application.

Electric actuators are noted for their controllability and power-to-weight ratio, but their high impedance can be problematic. Series Elastic Actuators (SEAs) were developed to mitigate this issue, but the elastic energy stored in the spring can cause unexpected reaction forces. Hydraulic actuators are capable of producing greater torque, but they are complex and heavy, requiring specially designed systems. Pneumatic actuators are lightweight and require low maintenance, but they have limited precision and accuracy. The need for compressed air also limits their mobility, making them more suitable for stationary platforms (Gull et al., 2020).

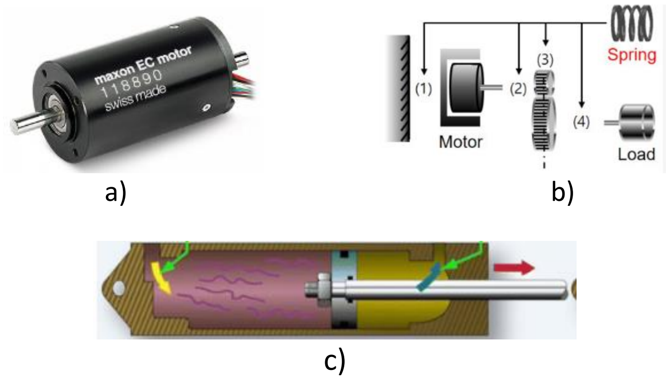


Figure 2. Example of actuators. a) electric motor. b) SEA. c) Hydraulic/pneumatic actuator.

Sensors

In active exoskeletons, sensor are mainly necessary to detect the intention of the user in order to properly command the actuators. The decision-making process relies on cognitive processes influenced by the exoskeleton's impact on the human joints, referred to as human-robot interaction (HRI). There are two types of HRI: cognitive HRI (cHRI) and physical HRI (pHRI). cHRI-based control systems use electric signals from the central nervous system to control the exoskeleton, while pHRI-based control systems use force or position changes resulting from movements by the human musculoskeletal system as control inputs. The main investigation in this field is associated with detecting the user's intention to control the device. The intention detection strategy is a critical component of the exoskeletons, and its impact on usability is rarely evaluated in the context of use.

Different detection strategies have been studied: muscle activation/contraction, upper-limb movement, isometric force generation, brain activity, eye movement, speech and manual triggers among others. The studies show that electromyography was the predominant user input signal associated with IDS (35.6%), followed by manual triggers and isometric force.

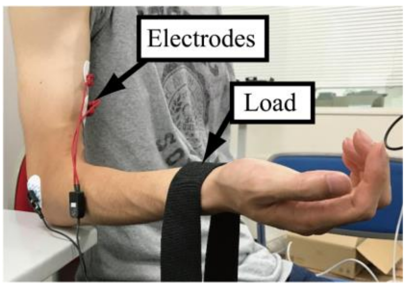


Figure 3. EMG sensor.

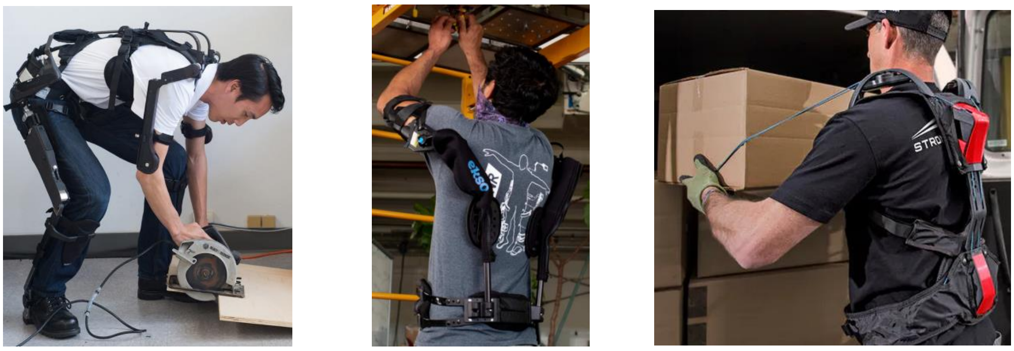
Though, the trade-off between performance and complexity in selecting an optimal IDS and the lack of a systematic way to determine whether the usability of an IDS is sufficiently high for daily life applications, is still a motive of concern (Gantenbein, 2022). Besides, EMG sensors are still too invasive to be applied in industrial workers.

5.1.2. Exoskeletons in Industry 4.0

A brief summary of the most relevant commercial exoskeletons to be applied in industry is presented in this section.

Passive exoskeletons

Three American companies are developing passive devices. ***suitX*** owns three modular exoskeletons: hip, shoulder and leg combinable modules that reduce the activation of the lumbar and spine muscles when lifting loads. Ekso Bionics works on ***EVO***, a passive exoskeleton designed to reduce fatigue from tasks at or above chest level, using mechanical gas spring actuators, providing a portable ergonomic shoulder support solution while maintaining joint alignment. It weighs 4.3 kg, assists between 2.2 kg and 6.8 kg on each arm and is being tested by Ford at its production facilities. Finally, ***StrongArm*** Technologies disposes of V-22 Ergoskeleton that allows ergonomic weight bearing.



a) b) c)

Figure 4. Exoskeleton examples. a) suitX. b) EVO. c) V-22 Ergoskeleton.

Ottobock Shoulder, produced in Germany, is a passive device for work at or above chest height that combines the improvements proposed for the Paexo Shoulder exoskeleton and the know-how of suitX. It is being tested by Volkswagen in its production plants.

The exoskeleton ***CarrySuit*** developed by AUXIVO in Switzerland is a passive exoskeleton that transfers the weight to the hip by hanging it up in two karabiners, alleviating the upper-limbs and trunk. This company also designed ***LiftSuit***, an exoskeleton that supports back and hip elevating weights at heights lower than the user hips or forward leaning positions.

Atlas has been developed by Exomys, Austria. This device is a passive modular exoskeleton that weights 2.3 kg and allows the user to carry until 25 kg. Different end effectors and modules can be installed depending on the final application. (Exoskeleton Report, 2021)

Along the same line, ***Cyber Human System*** in Spain has been working on BESK passive exoskeleton. It consists of two modules permitting the user to work on two different heights, and can assist between 5 kg and 15 kg offloading the arm weight and the hauled load by using gas springs without reducing any degree of freedom from the shoulder. This same company has also developed other two upper-limb devices. The first one, ***Exoshoulder***, assists the shoulder, and the working principle is based on actuators. It compensates gravity, reducing fatigue and avoiding pain. The carried weight can be between 3 kg and 12 kg, and the exoskeleton weights 3 kg itself. The second exoskeleton, ***Exoarms***, assists shoulder and lumbar articulation with artificial muscles that emulates the biceps function. It weighs 1.2 kg and can assist between 5 kg and 10 kg in shoulder articulation and between 7 kg and 15 kg in the lumbar one (*CHS, 2023).*

a) b)

Figure 5. Cyber Human System exoskeletons. a) Exoshoulder. b) Exoarms.

HA EXO-O1 assy exoskeleton developed by Hilti is a passive device designed to relieve stress on the shoulder joint during work at height. The weight of the arms is transferred to the hips via a load transfer mechanism, thus compensating for the wearer's efforts. It weighs less than 2 kg and provides dynamic support of up to 50 N without restricting movement (*Exoskeleton Report, 2023*).

Figure 6. Hilti exoskeleton.

In the Netherlands, ***Laevo*** is a passive device for back support when lifting weights above the shoulders. Here, ***Skelex*** 360 XFR has also been progressing. This passive exoskeleton provides gravity compensation for overhead work augmenting the force gradually as the user raises the arms from the trunk. It weighs 2.5 kg and provides between 1 and 4.9 kg of assistance per arm.

Active exoskeletons

In March 2018, Sarcos Robotics and representatives from various industries formed the Exoskeleton Technical Advisory Group (X-TAG) to identify the key requirements necessary in various sectors to bring powered and quasi-passive, full-body industrial exoskeletons to the market. Sarcos Robotics, a long-time user of robotic exoskeleton technology, is now focused on commercializing the ***Guardian XO MAX***, battery-powered full-body exoskeleton that augments human strength and endurance without restricting movement. This exoskeleton allows the user to carry between 15 kg and 90 kg, reducing the metabolic output and physical strain by offloading all the weight loaded during use.

Figure 7. Guardian XO.

The European development activity has focused on the ***Robo-Mate*** project developing an intelligent exoskeleton based on human-robot interaction for manipulating heavy goods in Europe's future factories. The goal of the project was to create a modular, robotic exoskeleton that can reduce physical strain on workers, especially during assembly and disassembly tasks supporting the arms, back, spine, and legs of workers. These modules were tested in labs and work environments and showed promising results, and the partners are now focusing on commercializing the technology.

Figure 8. Robo-Mate active arms.

Also, in early 2018, German Bionic Systems began production of the ***CRAY X***. It was designed in collaboration with Fiat and intended for use primarily in the automotive industry, but it could also be used in construction and healthcare. The CRAY X weighs 7 kg, is battery-powered, and reduces compression pressure in the lower back while lifting heavy loads until 30 kg. It uses harmonic drives and has a cloud software platform for machine learning and AI functionality.

Figure 9. Cray X.

The French company RB3D has developed the ***ExoPush***, a back active exoskeleton that attaches to a hip and leg one. It is designed for levelling asphalt surfaces and aggregates using traditional rakes, manipulating up to 50 kg. It acts as a force amplification system worn by the operator, reducing fatigue and load on their back. It can operate for up to 4 hours on a charge and weighs 8 kg including the battery pack.

In Italy, Agade has elaborated ***AGADEXO Shoulder***, a hybrid exoskeleton for upper limbs. It performs intelligent gravity compensation that adapts to the user's movements and the load carried using electric motors, an elastic mechanism and a network of force and movement sensors. It weighs 4 kg, provides a maximum gravity compensation torque of 20 Nm for each shoulder, and has a long autonomy. The company COMAU in the same country manufactures ***MATE-XT*** a 3 kg exoskeleton with a passive spring mechanism for shoulders and back for work requiring 90-degree flexion/extension overhead. The fact that this exoskeleton is certified as a tool that reduces the biomechanical stress is to be noted (*Bogue*, 2019).

Figure 10. MATE-XT exoskeleton.

Far Eastern nations, including Japan and South Korea, are heavily involved in the development and use of exoskeleton technology particularly for physically demanding industries. Major industrial companies such as Panasonic, Honda, Toyota, Hyundai, Samsung Heavy Industries, Mitsubishi, Kawasaki, and Daewoo are all developing and conducting trials with robotic or passive exoskeletons, as well as a growing number of specialist companies.

The Japanese manufacturer Atoun has designed an active exoskeleton to assist the hip in weight lifting movements. It weights 4.5 kg including the batteries, has 4 hours of autonomy and can embrace users between 150 cm and 190 cm of height.

Innophys is another Japanese industrial exoskeleton manufacturer that was founded in 2013. Its range of exoskeletons is unique in that they are powered by compressed air rather than batteries. The ***Muscle Upper*** back and upper-body exoskeleton weighs 8.1 kg and can exert a force approximately of 140 Nm. It has been used in many industrial applications in civil engineering, construction, logistics sectors.

Japanese agricultural equipment manufacturer Kubota launched ***Assist Suit ARM-1D***, an upper-body exoskeleton aimed at relieving the load on the arms when they are continually raised, for example, while picking fruits such as pears or grapes. It is powered by alkaline or rechargeable Ni-MH batteries and weighs 3.8 kg.

Hyundai Motor Company has developed several prototypes of exoskeletons, including the ***H-LEX***, which was initially aimed at assisting the physically disabled to walk but later presented as an industrial device that gives the wearer extra strength to lift objects weighing hundreds of kilograms. Hyundai has also unveiled the ***H-WEX***, an industrial product intended to provide upper-body and hip support to prevent back injuries for workers conducting repetitive, strenuous tasks or heavy lifting.

Cyberdyne is well known for its ***HAL*** range of robotic exoskeletons, which detect the user's intentions to move by sensing bioelectric signals through electrodes mounted on the skin and initiate appropriate assistance. These exoskeletons are powered by lithium-polymer batteries, weigh 3 kg, and have an operating time of approximately 3 hours. They have been used in several applications involving repetitive load handling, including construction sites and cash transportation by Sumitomo Mitsui Banking Corporation.

DARWING PA-Jacket by Daiya is an active exoskeleton with artificial pneumatic muscles that contract when filled with air and elastic bands providing tension when leaning forward. This mechanism is parallel to the spine and aims to stabilise the sacroiliac joints. It weighs 3.4 kg and has a thumb button to activate the exoskeleton. ***AWN-03*** by ActiveLink, a spin-off of the Panasonic corporation, is also an active technology that weighs 6 kg and can assist up to 15 kg, with autonomy of 8 hours.

5.1.3. Previous SHIFT2RAIL and HORIZON projects

Besides the state of the art, we have searched for previous European projects whose public results can be of relevance for the project, and could be even integrated if feasible:

STREAM (GA 101015418, S2R-OC-IP3-03-2020): Smart Tools for Railway work safEty and performAnce iMprovement

STREAM main objective is to develop innovative technologies to improve rail inspection and maintenance operations in a way that creates benefits in quality of operations, and workers health, safety, and dignity. This is achieved by (i) enhancing current OTMs to create multi-purpose autonomous devices and systems, that increase the level of task execution safety, quality and productivity by applying robotic principles; and (ii) deploying wearable assistive exoskeletons, that use advanced proprioceptive solutions to supply on-demand mechanical power, reducing the risk of injury and related costs. The exoskeleton technology developed under STREAM is focused on lower limb actuation for weight lifting.

BEEYONDERS (GA 101058548, HORIZON-CL4-2021-TWIN-TRANSITION-01): Breakthrough European tEchnologies Yielding cOnstruction sovereigNty, Diversity & Efficiency of ResourceS

The EU-funded BEEYONDERS project will design, develop, and integrate innovative technologies including artificial intelligence and autonomous vehicles to help the sector become more efficient and attractive to young people. These sophisticated tools will also boost safety, productivity, quality, and the environmental impact of construction projects. In collaboration with key stakeholders, BEEYONDERS will develop sophisticated solutions that will ensure the safety, well-being, and training of workers through the testing and validation of case studies focusing on buildings, maritime infrastructures, road maintenance and construction, and tunnels. The work will benefit the workforce, draw in future workers, and support gender equality.

HumanTech (GA 101058236, HORIZON-CL4-2021-TWIN-TRANSITION-01): Human Centered Technologies for a Safer and Greener European Construction Industry.

The aim of HumanTech is the development of intelligent unobtrusive workers protection and support equipment ranging from exoskeletons triggered by wearable body pose and strain sensors, to wearable cameras and XR glasses to provide real-time worker localisation and guidance for the efficient and accurate fulfilment of their tasks.

AGADE (GA 190137729, HORIZON-EIC-2021-ACCELERATOROPEN-01): An Anti-Gravity Active Device for Exoskeletons to Reduce the Impact of Work-Related Musculoskeletal Disorders in the Logistics, Retailing and Manufacturing Sectors.

AGADE aims at erasing work-related muscular disorders through AGADEXO, the first exoskeleton to combine lightness, comfort and low environmental impact with smart compensation of physical fatigue at work. It is conceived of as a modular product (shoulder, low-back and full-body modules) in order to increase customisation and maximise market coverage and penetration in different sectors, such as logistics, retailing and manufacturing. Our innovation disrupts the market by bringing to it high-tech devices so far impossible to commercialise. The innovative wearable robotic system of AGADEXO does not substitute the individual, but it empowers physical abilities, improves efficiency and satisfaction at work.

5.1.4. Standards and Guidelines

We have identified the following standards and guidelines that need to be considered:

- EN ISO 12100:2010 Safety of machinery - Electrical equipment of machines. Part 1: General requirements.
- EN 60204-1:2006 Safety of machinery - Electrical equipment of machines. Part 1: General requirements
- EN ISO 13849-1:2008 Safety of machinery - Safety-related parts of control systems. Part 1: General principles for design
- EN ISO 13849-2:2012 Safety of machinery - Safety-related parts of control systems. Part 2: Validation
- EN ISO 13482:2014 Robots and robotic devices. Safety requirements for personal assistance robot.
- EMC Directive 2004/108 / EC
- Low Voltage Directive 2006/95 / EC

5.1.5. Challenges and Future research

There are several challenges associated with designing exoskeletons that are kinematically compatible with the anthropomorphic parameters of the end-user, like proper alignment between the exoskeleton and the anatomical joints of the wearer.

Wearable exoskeletons are limited in their ability to provide a wide range of motion compared to the human upper-limb torso whose solution ends in a more complex and heavier mechanism. Ultimately, the desired range of motion and workspace depend on the target application and can only be achieved at the cost of a more complex and heavier mechanism.

The issue of singularity arises when two joints of an exoskeleton are aligned, hindering the smooth manipulation of the exoskeleton and human upper limb. It can be resolved with two approaches: including possible situations in the control strategy or incorporating possibilities in the design of the exoskeleton by applying mechanical constraints.

The comfort level of wearable exoskeletons is a major concern. The rotational joint axes tend to change their position during movement, and slippage between the exoskeleton and the human limb can cause misalignment and undesired reaction forces and torques in the human joint.

Various studies have tried to overcome these issues by considering complex human biomechanics and optimizing the mechanical design of exoskeletons. However, designing an active lightweight upper-limb exoskeleton with existing actuators is still a challenging task due to the high power-to-weight ratio of most active exoskeletons supporting shoulder and elbow movements. Furthermore, there are no standards available yet to quantify the comfort level of wearable exoskeletons.

The essential part in controlling active exoskeletons is acquiring human intent through measuring interactions between the human and exoskeleton. The decision-making process relies on cognitive processes influenced by the exoskeleton's impact on the human joints, referred to as human-robot interaction (HRI).

Sensing and estimation in the design of a robotic exoskeleton system is essential. Proprioceptive sensors are used at the lower level to estimate the state of the robotic exoskeleton, while exteroceptive sensors are used at a higher level to interpret sensor data for task-oriented purposes. (Gull et al., 2020)

5.1.6. Conclusion

Most of the commercially available exoskeletons are task specific. The other available products used for therapy and rehabilitation, can only be used under clinical supervision, and are limited in their range of applications.

Also, commercially available exoskeletons are not able to actively support the shoulder glenohumeral movements, shoulder internal/external rotation, forearm supination/pronation, and wrist movements, especially radial/ulnar deviation, since these movements are biomechanically complex and special design efforts are required by considering a comprehensive musculoskeletal model (Gull et al., 2020).

The importance of a user and application-specific selection and evaluation of non-invasive IDS for upper limb exoskeletons is needed, as well as the definition of the parameters considered to design the mechanisms. Selecting an optimal IDS for a given application is highly dependent on various factors such as usage scenario and target user's capabilities, limitations, and preferences and could enhance the device's usability and acceptance by final users (Gantenbein, 2022).

The rise of industrial exoskeletons has also developed the need to test their effectiveness. Various studies have demonstrated corresponding effects on biomechanic or metabolic parameters by wearing an exoskeleton during physically demanding activity, or other parameters like subjectively perceived effort, exoskeleton comfort, and usability in an attempt to normalise this performance evaluation. The physical interaction between humans and robots is also important, and a framework is necessary to quantify the influence of robotic exoskeletons on the human upper limb to account for comfort and compliant interaction (Kopp, 2022).

Existing exoskeletons have not been designed as long-term wearable devices. Therefore, it is required to further improve the ergonomics of the design, which allows the user to wear an exoskeleton for a longer interval of time (Gull et al., 2020).

Summarising, there is still a need for further development of lightweight exoskeletons that are compatible with operators and address key technical issues.

5.2. Augmented Reality

5.2.1. Introduction

The term "Augmented Reality" (AR) was first used in 1992 by Thomas Preston Caudell, a researcher at Boeing. He developed an AR application for industrial use that allowed the viewing of assembly diagrams. Nowadays, there are several definitions of AR, but the most widely accepted one is provided by Paul Milgram and Fumio Kishino, who propose a continuum of different types of reality starting from the real world to a completely virtual one and which they coined it the Reality-Virtuality Continuum (*Milgram, 1994*). The Extended Reality (XR) is an all-encompassing term that includes AR, Mixed Reality (MR), and Virtual Reality (VR).

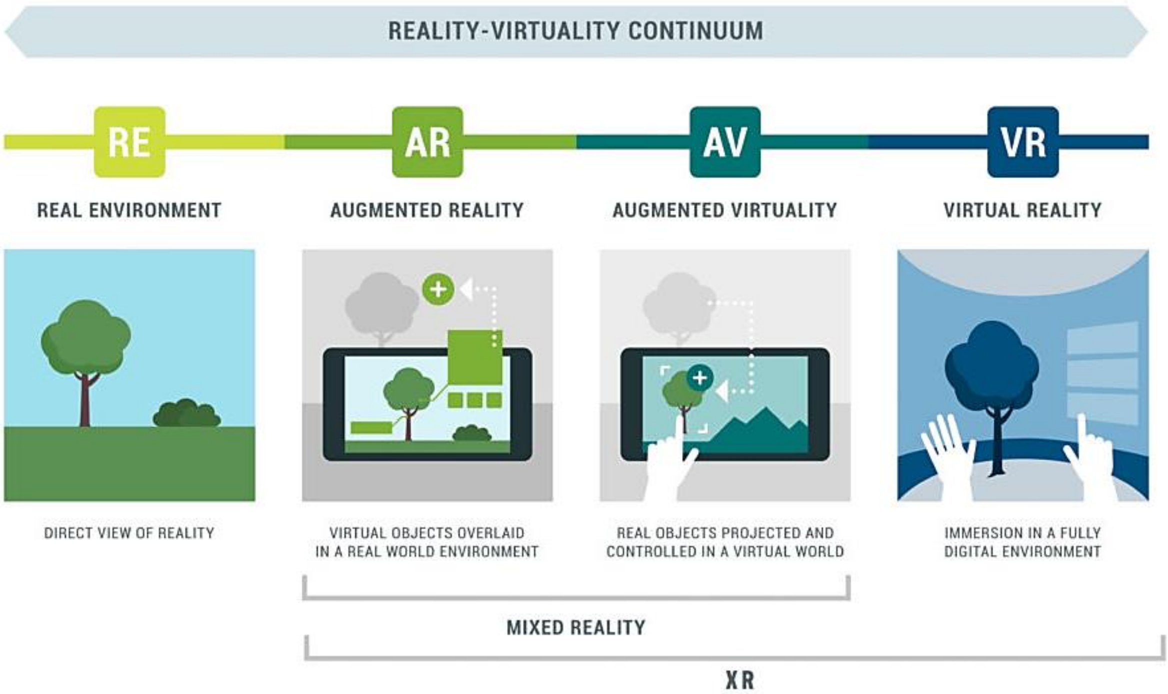


Figure 11. Spectrum of Extended Reality. Source: CreatXR (2022)

In recent years, various industries have begun to use immersive technologies such as AR and VR due to improvements in software algorithms and reduced costs of AR/VR equipment. AR involves superimposing digital information on the user's physical environment in real-time, allowing for an enhanced or "augmented" real-world experience. AR can be delivered through various devices, including smartphones, tablets, smart glasses, and other head-mounted displays (HMD), which besides freeing the user's hands, create more immersive and real experiences.

Although AR and VR are not new, recent advances in computational power, storage, graphics processing, and high-resolution displays have helped overcome some of the constraints that have stood in the way of the widespread use of these immersive technologies in industry. Moreover, further advances are predicted as the worldwide spending on AR/VR reached $13.8 billion in 2022 and is expected to grow to $50.9 billion in 2026, according to the International Data Corporation (IDC) Worldwide Augmented and Virtual Reality Spending Guide (*IDC, 2022*).

5.2.2. Hardware

Hand-Held Devices (HHD)

The use of high-performance hardware is crucial for developing AR applications. Mobile devices such as smartphones have built-in hardware, including accelerometers, high-resolution cameras, and responsive screens, that can support AR applications. However, they have limited internal storage and processing power. To overcome this, some AR applications utilize a client-server design to attain real-time performance. While smartphones are widely used across all user groups, they have smaller screens and may not be the best option for producing complex 3D rendering scenes.

On the other hand, tablets offer larger screens, increased processing power, and better visuals, making them better suited for producing complex 3D rendering scenes. Tablets are often favoured over smartphones, particularly in industrial settings where a larger screen is more beneficial.

Both smartphones and tablets are continuously improving in terms of power and performance with each generation, and there is a growing trend towards the development of AR applications for these devices. Nevertheless, there could be more appropriate hardware options that should be considered for situations where the user may need to use both hands, and at least one, while utilizing AR technology. In such cases, the implementation of head-mounted displays (HMDs) or spatial projection devices should be considered.

Head Mounted Displays (HMD)

Even though, HMDs are a relatively new technology, they are often used in AR applications as they allow users to experience the AR scene at eye-level in real life, creating more immersive and real experiences compared to other devices.

The primary focus of current AR studies is mobility, which can be achieved through HHD like smartphones and tablets. However, to fully leverage the potential of the technology, dedicated wearable devices like AR glasses are necessary. AR smart glasses for professional use share common features, including a display for presenting digital content, a camera for spatial orientation and recording the surroundings, microphones and speakers for verbal communication, and convenient mounting. Most glasses can be controlled by voice and gestures, providing users with full mobility while operating machinery or performing demanding tasks.

Industrial-grade AR glasses are particularly important as they do not interfere with safety equipment like protective glasses, gloves, or helmets. Moreover, some models, like the RealWear glasses, are designed for working in demanding environments like high humidity, extreme temperatures, rain, noise, explosive zones, and working at heights.



	REALWEAR NAVIGATOR 520	**MICROSOFT HOLOLENS 2**	**IRISTICK G2**
DISPLAY TYPE	Single LCD monocular	2 x LBS binocular	Monocular display
FIELD OF VIEW	24° horizontal	43° horizontal, 29° vertical and 52° diagonal	117° diagonal
RESOLUTION	1280x720	1440x936 per-eye	426 x 240
WEIGHT	270 g	566 g	157 g
MEMORY AND STORAGE	64 GB internal storage, 4GB RAM	64 GB internal storage, 4GB RAM	Depends on phone's capacities
BATTERY LIFE	8 hours (hot-swappable battery)	3 hours	8 hours (connected to phone's battery, hot-swappable battery)
RESISTANCE	IP66 grade, humidity, dust and water-resistant, -20° C to +50°C temperature range	IP50 grade, resistant to limited dust ingression, 10 °C to 35 °C temperature range	…
MOUNTING	Compatible with helmets, safety glasses, can be worn independently	Headband, compatible with glasses and hardhats (using hardhat adapter)	Smart glasses
EXTRAS	…	Eye and hand tracking	Phone-powered AR
PRICE	$2900 USD	$3500 USD	$2099 USD



	GOOGLE GLASS ENTERPRISE EDITION 2	**VUZIX BLADE 2**	**VUZIX M4000**
DISPLAY TYPE	Single LCoS monocular	Monocular display	Single DLP monocular
FIELD OF VIEW	83° diagonal	20° diagonal	28° diagonal
RESOLUTION	640x360	480x480	854x480
WEIGHT	46 g without headstrap,	90 g	222 g without

	51 g with headstrap		headstrap
MEMORY AND STORAGE	32 GB internal storage, 3GB RAM	40 GB internal storage	64 GB internal storage, 6GB RAM
BATTERY LIFE	8 hours	…	2–12 hours of operation based on external battery choice
RESISTANCE	IP53 grade, resistant to water spray and limited dust ingression, 0 °C to 35 °C temperature range	0 °C to 35 °C temperature range	IP67 grade, humidity, dust and water-resistant, -20° C to +45°C temperature range
MOUNTING	Smart glasses	Smart glasses	Compatible with helmets, safety glasses, can be worn independently
EXTRAS	…	…	…
PRICE	$999 USD	$1299 USD	$2500 USD

In addition to industrial-grade AR devices, there are other designs available that are well-suited for use in less demanding indoor environments. These are also capable of supporting AV and VR applications. Notably, some promising options include the Magic Leap 2, Varjo XR-3, and the Meta Quest Pro.

	MAGIC LEAP 2	**VARJO XR-3**	**META QUEST PRO**
DISPLAY TYPE	2 x LCoS binocular	2 x LCD binocular	2 x LCD binocular
FIELD OF VIEW	44° horizontal, 53° vertical and 70° diagonal	115° horizontal, 90° vertical (peripheral displays. Focal displays: 27°)	106° horizontal, 95.57° diagonal
RESOLUTION	1440x1760 per-eye	2880x2720 per-eye	1800x1920 per-eye
WEIGHT	260 g with headstrap (excludes compute unit)	594 g without headstrap, 980 g with headstrap	722 g with headstrap
MEMORY AND STORAGE	256 GB internal storage, 16GB RAM	Despends on PC's capacities	256 GB internal storage, 12GB RAM
BATTERY LIFE	3.5 hours (sleep mode: 7 hours)	Plugged	1-2 hours

EXTRAS	Eye and hand tracking	PC-Powered AR-VR; Eye and hand tracking	Face, eye and hand tracking
PRICE	$3299 USD with controllers	$5495 USD headset only	$1500 USD with controllers

However, wearing most of these devices for extended periods can lead to discomfort, fatigue and neck pain. To address this last issue, newer HMDs developed in 2020 and beyond are lighter than previous models. Furthermore, upcoming releases of AR glasses are expected to overcome some of the current limitations. For instance, the debut of the 2nd Gen 2D waveguide technology by Lumus at CES 2023 is paving the way for smaller and more advanced AR glasses.

Additionally, industry giant Apple has expressed its interest in entering the AR market with the upcoming release in 2023 of their highly anticipated Apple Glasses. Therefore, it remains to be seen how this technology will evolve in the future.

Spatial projection devices

The usage of spatial projectors by the manufacturing sectors for AR-assisted production activities has eliminated the need for users to wear HMDs to view the augmented virtual scene in real surroundings. This projection-based AR setup is therefore known as spatial augmented reality (SAR) in the industrial context, according to the experts (*Siriwardhana, 2021*).

Based on installation techniques, there are two categories of projector use in augmented reality: permanent installation and portable installation. Permanent installations are ideal for environments where a consistent augmented reality experience is required, such as in manufacturing or training facilities. Portable installations, on the other hand, are more versatile and can be easily moved from one location to another, making them a popular choice for outdoor or temporary events. The choice between permanent and portable installations will depend on the specific needs and requirements of the organization or industry.

5.2.3. Software

AR development frameworks and platforms

Building an AR system from the ground up is challenging and time-consuming. Many AR frameworks and platforms have been created to assist developers focusing on higher-level applications rather than low-level implementations. A summary of a sample subset of the existing platforms and frameworks is provided in the next table.

	Cost	Supported Platforms	Programming Languages	Additional Information
ARToolkit	Free/Open Source	Android, iOS, Windows,	C++, Python, Java, .NET,	+ Supports marker-based and markerless tracking

		macOS, Linux	Unity, Unreal Engine	– Limited functionality compared to other frameworks – Steep learning curve
ARKit	Free	iOS	Swift, Objective-C	+ Native support for iOS devices + Robust image recognition and tracking + Supports marker-based and markerless tracking – Limited to iOS devices – Limited support for older devices – Steep learning curve for beginners
ARCore	Free	Android, Unity, Unreal Engine	Java, C++, Kotlin	+ Native support for Android devices + Robust image recognition and tracking + Supports marker-based and markerless tracking – Limited to Android devices – Limited support for older devices – Steep learning curve for beginners
Vuforia	Free (limited functionality), Paid	Android, iOS, UWP, Unity, Unreal Engine	C#, JavaScript	+ Easy to use and set up + Robust image recognition and tracking + Supports marker-based and markerless tracking – Free version has limited features – Limited support for some platforms
Wikitude	Free (limited functionality), Paid	Android, iOS, Windows, macOS	JavaScript, Unity	+ Easy to use and intuitive + Good support for geo-location-based AR – Limited image recognition capabilities compared to other frameworks – Expensive compared to other options
Kudan	Free (limited functionality), Paid	Android, iOS, Unity, Unreal Engine	C++, Java, Objective-C, Swift, Python	+ Supports marker-based and markerless tracking + High-precision tracking and recognition – Limited documentation and community support

				– Expensive compared to other options – Limited support for some platforms
Unity	Free (limited functionality), Paid	Android, iOS, UWP, macOS, Windows, Linux, WebGL, PlayStation, Xbox, Nintendo Switch	C#, UnityScript (a JavaScript-like language), Boo (a Python-like language)	+ Large user community and extensive documentation + Supports marker-based and markerless tracking + Most of the leading augmented reality frameworks have integrated extensions and tools for Unity – Steep learning curve for beginners – High-quality graphics can cause performance issues if not optimized correctly
Unreal Engine	Free (limited functionality), Paid	Android, iOS, macOS, Windows, Linux, PlayStation, Xbox	C++, Blueprint visual scripting	+ Large user community and extensive documentation + Supports marker-based and markerless tracking + High-quality graphics and rendering – Steep learning curve for beginners – High-quality graphics can cause performance issues if not optimized correctly

AR interaction techniques

Visual Overlays

Visual overlays are the most common feature of augmented reality (AR) applications, and they refer to the graphical elements that are superimposed on the real-world view to create an augmented experience. These visual overlays can take many forms, such as 3D objects, text, buttons, images, videos, and animations. They are created using computer-generated graphics and are displayed on the user's screen, which is usually a HHD or HMD, and enable users to experience a more immersive and interactive world. As AR technology continues to evolve, we can expect even more sophisticated and compelling visual overlays in AR applications.

Audio and Haptic Feedback

Audio feedback involves using sound to provide feedback to the user. For example, a system might play a sound when the user enters a danger-zone or provide audio instructions to guide the user through a task. Audio feedback can be especially useful in situations where the user's visual attention is focused elsewhere, such as when performing a manual task.

Haptic feedback, on the other hand, involves using touch or vibration to provide feedback to the user. Haptic feedback can provide physical cues to help the user locate virtual objects or guide their movements, enabling users to interact with virtual objects in a more realistic way.

In AR applications, audio and haptic feedback are often used in combination with visual feedback, such as text or graphics displayed in the user's field of view. Together, these types of feedback can provide a rich and immersive user experience, allowing users to more easily understand and interact with virtual objects in the real world.

Gesture and Voice Recognition

As previously seen, AR removes the need for a physical interface altogether. Virtual control panels can be superimposed directly on the product and operated via user gestures and voice commands. Voice recognition technology has seen significant advancements and is now 96% accurate, exceeding human performance (*Smith, 2018*). General Electric leveraged this technology to achieve a 34% productivity increase by allowing users to perform complex electrical processes for wind turbines through voice commands (*Kloberdanz, 2017*). Additionally, these advances have made it feasible to operate machinery through voice commands in noisy and chaotic environments, enabling the control of equipment such as lighting and generators. By removing workers from hazardous environments and allowing machinery to be operated at a safer distance, it improves the overall safety of industrial processes.

In addition, advances in facial recognition and retinal tracking could soon allow users to look at or gesture towards a product and open an interface to operate it.

Marker-based object tracking

Fiducial markers are frequently used in AR applications for object tracking and identification. These markers are easily recognizable in a video stream because they include geometric features or distinctive patterns. Marker-based tracking provides a dependable and steady approach in a known environment.

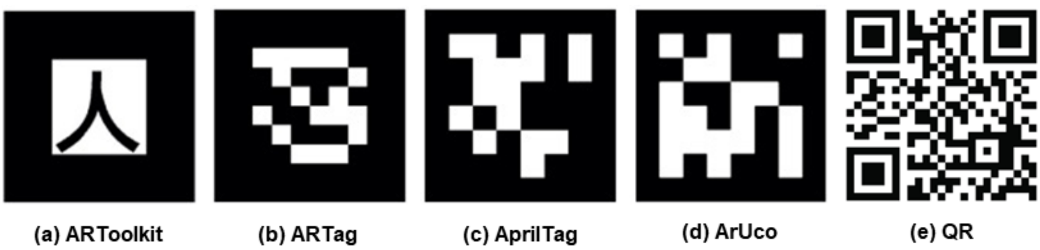


Figure 12 Marker designs of some of the popular fiducial markers.

Overall, the choice of fiducial marker depends on the specific requirements of the AR application, such as the level of accuracy required, the size and shape of the markers, and the available hardware and software resources.

Markerless object tracking

Markerless tracking, is an object tracking method used in augmented reality (AR) applications that does not require the use of physical or fiducial markers. Instead, markerless tracking uses computer vision algorithms to perform the tracking. However, these processes can be computationally intensive, and require algorithms that are robust to changes in lighting, viewpoint, and occlusions.

One of the benefits of markerless tracking is that it allows for greater flexibility in AR applications. With fiducial marker-based tracking, users must point their device at a specific marker to trigger an AR experience. With markerless tracking, however, users can trigger an AR experience simply by pointing their device at an object in the real world. This can lead to a more natural and intuitive user experience.

Here are some widely used markerless tracking techniques:

- **Model-based tracking**: This method involves using a 3D model of an object to recognize and track the object in the real world. This technique requires a digital representation of the object, typically created using computer-aided design (CAD) software or 3D scanning. The system compares the real-time video image of the object to the 3D model and estimates the object's position and orientation based on the best match between the two. One of the main advantages of this tracking method is that it is very accurate and can track objects with high precision. However, it does require a digital 3D model of the object.
- **Template Matching**: This technique involves comparing a real-world image with a stored template image to detect and track objects. This is based on finding the similarity between the features of the two images.
- **Feature-based tracking**: This technique involves identifying and tracking specific points or features on an object, such as corners or edges, and using them as reference points for tracking the object's movement. These features can be detected using computer vision algorithms, and they can be either artificial fiducial markers or naturally occurring features in the environment (then also called natural feature tracking).
- **Deep Learning**: This method involves training a neural network to recognize and track objects in real-world images. The neural network is trained using a large dataset of labeled images and can be fine-tuned for specific object recognition and tracking tasks. There already is an abundance of DL-based object detection techniques by which AR can be accomplished efficiently and almost instantly, including YOLOv3, MobileNet v2 and SSD model.

These are just a few examples of markerless tracking techniques that are used for object recognition and tracking in augmented reality, and there are many variations and combinations of these techniques that can be used in different AR applications.

Geo-Location

Geo-location in augmented reality (AR) refers to the use of location-based services and technologies to provide AR experiences that are anchored to specific geographic locations in the real world. By using GPS, cellular triangulation, or other location-based technologies, AR applications can determine the user's location and provide digital content that is relevant to the user's physical surroundings.

One common use of geo-location in AR is to provide information or digital content about nearby points of interest, such as restaurants, shops, or historical landmarks. AR applications can overlay information about these locations onto the real-world view captured by the camera on the user's device, allowing users to access information about their surroundings in a more immersive and engaging way.

In addition to providing information about nearby points of interest, geo-location in AR can also be used to create location-based games and experiences that are tied to specific geographic locations (for example, Pokemon GO).

Why a Cloud-based architecture - the importance of 5G

One of the main advantages of using the cloud is the ability to access the system from anywhere in the world. This allows for increased scalability and efficient storage of ever-growing data sets, while also ensuring security and regulatory compliance with domestic law.

There are three primary types of infrastructure for cloud-based systems:

- **Sofware as a Service (SaaS)**: SaaS offers great performance with auto-scaling, data encryption and redundancy, auto-failover mechanisms, and high-security measures.
- **Private Cloud**: With a private cloud, company data is physically separated from other clients’ data and the platform can be hosted under its own domain.
- **On-premises**: In this case, the platform is hosted on private company servers. It is chosen mainly by the companies in which security policies don’t allow it to host applications in the cloud.

AR can benefit from the cloud, as it enables easier data transfer and the possibility of remote assistance. However, this requires improvements in the network infrastructure. This is where the 5G network comes in, as it promises faster, more uniform data rates and lower latency required for real-time video interactions, all at a lower cost.

An example of this is the following architecture, which is based on the AVANSANT project previously developed by CEIT. The objective of the project was to create a tool for remote support of maintenance operations using AR as an asset. This was accomplished through a web-based interface (giving the tool cross-device functionality), and where AWS provided the essential infrastructure of the application, including access to databases, log information, shared data, and sessions, among other things.

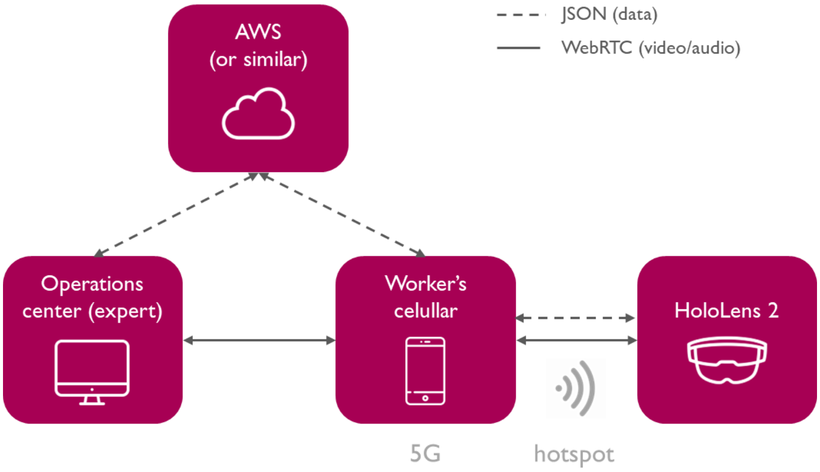


Figure 13 Example of a Cloud-based remote assistance architecture

With download speeds of up to 10 GigaBytes per second (Gbps), compared to the theoretical high of 1 Gbps on the latest 4G LTE-A networks, 5G allows the transfer of high-resolution data in real-time that AR needs. Ultra-low latency is also promised, with an expected drop to under 10ms. All this will enable AR to have a wider reach, allowing for broader mainstream acceptance.

Furthermore, incidents such as the Sandilands Junction tram derailment in November 2016 (*Rail Accident Investigation Branch, 2017*) could have prevented by providing drivers with hands-free AR technology and updated information in real-time.

5.2.4. AR Technology in Industry

Industry 4.0 is a term used to describe the current trend of automation and data exchange in manufacturing technologies. Thanks to the integration of Information Technology (IT) with traditional manufacturing, it has become possible to better manage company resources and accelerate a variety of processes.

In particular, the contribution of IT in the form of Artificial Intelligence (AI), Internet of Things (IoT), machine-to-machine communication, big data analysis, and augmented reality has revolutionized the manufacturing sector.

Mainly, the implementation of AR technology has been found to have two benefits: providing step-by-step instructions and remote assistance for manual tasks. Moreover, AR technology has demonstrated to solve many common issues, such as high employee training costs, lack of standardization in knowledge transfer, time-consuming access to information, and human errors.

Many companies have reported significant improvements in quality, productivity, and cost reductions through the implementation of AR technology. Some examples include Boeing's implementation of AR for hands-free step by step instructions for airplane wiring assembly, which led to a 25% decrease in the time required to complete tasks and a 40% increase in worker productivity (*Boeing, 2018*). Or, Siemens case, where AR was used to perform quality control of printed circuit boards and improved quality by 20-25% (*Cohen, 2018*).

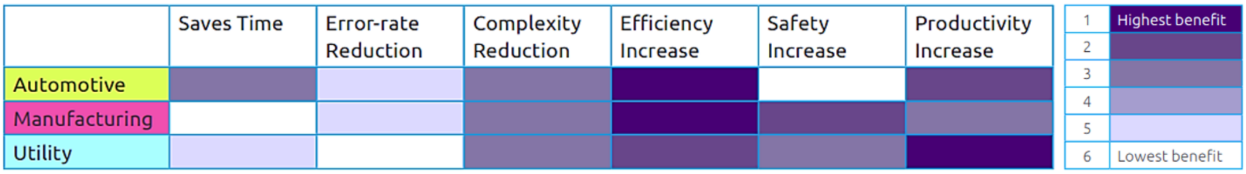


Figure 14 Benefit per sector - AR. Source: Capgemini Research Institute, AR/VR Survey; May–June 2018, N=709 organizations

Commonly, AR technology can support knowledge transfer at crucial manufacturing stages such as training, assembly and maintenance by enabling:

- Remote consultations with experts (remote support)
- Interactive checklists and service procedures
- Instructions for resolving common failures and breakdowns
- Permanent and easy access to documentation
- Presentation of data from other systems, e.g. SCADA, MES, ERP, CRM, PLM...
- Remote inspection and maintenance of machines
- Verification of the quality of tasks performed by the system
- Predictive maintenance of machines
- Digital twins

Many companies already use AR technology to streamline workflows and remotely collaborate with experts for any troubleshooting guidance, leading to higher productivity and efficiency. According to the head of Digital Services at Fingrid, a Finnish electricity transmission grid operator, AR technology could also provide added value for employees in high-risk situations[8].

Training

The use of Augmented Reality (AR) is revolutionizing training and coaching in the modern workplace, particularly in asset-heavy industries such as rail. With extensive infrastructure and a complex network spanning over 16,000 kilometers, it is crucial that training practices keep up with the growing demands. Traditional training methods are expensive, time-consuming, and often do not provide satisfactory results. For example, written instructions can be cumbersome, videos are non-interactive, and in-person training can be logistically challenging and expensive, especially in a geographically dispersed workforce with shift-based schedules.

AR technology provides an effective solution to these challenges by offering real-time, on-site, and interactive visual guidance. This includes equipment assembly, maintenance, and operation, providing workers with step-by-step instructions that supplement the physical world directly, reducing ambiguity and improving safety and productivity.

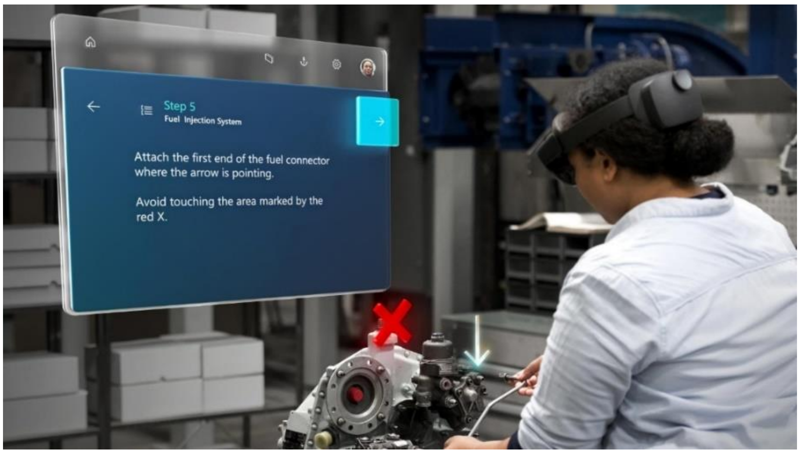


Figure 15 Example of step-by-step instructions with HoloLens 2. Source: Dynamics 365 Guides

For instance, Toyota Motor Corporation utilizes AR to develop interactive work instructions aimed at assisting workers in executing intricate procedures, including the assembly of engine components (*Microsoft, 2021*). The instructions are displayed on a Microsoft HoloLens 2 headset, allowing workers to see the instructions overlaid onto the real-world objects they are working on, and they can use voice commands to progress through the instructions hands-free. Toyota has reported significant improvements in efficiency and quality since implementing the system.

Furthermore, if the aforementioned system is integrated with cloud technology, it would be ensured that instructions are always up-to-date and allowing employees and businesses to adapt quickly to changes.

Assembly

The assembly process in the manufacturing industry is a critical component that requires assembly workers to have a thorough understanding of the equipment, assembly activities, and collision prevention. Although there is a wealth of information on virtual assembly planning, it cannot be accessed instantly on the shop floor. To address this issue, researchers have explored the latest advancements in visual representation, user cognition, interaction approach, and ergonomics to create AR-assisted assembly guidance.

AR technology enables effective communication with users through AR guidelines, which can facilitate manual assembly tasks by incorporating assembly information into the cyber-physical universe as virtual objects.

Many studies have shown that AR-assisted activities can improve assembly processes by reducing cognitive task load, increasing flexibility, and minimizing the risk of errors compared to paper-based instruction manuals. C. V. Martin and T. L. Smith-Jackson found that displaying part models in actual scenes improves spatial reasoning and reduces assembly mistakes (*Martin, 2008*)**.**

For instance, TNO, Bronkhorst High Tech, Omron, and TE Connectivity developed an operator support system using LightGuide Systems AR projected work instructions to assist with assembly work (*LightGuide, 2017*). This system has been shown to reduce cycle time and pick time while also reducing workload and errors. In addition, it has been found useful for both new and experienced operators and can be easily integrated with other systems.

AR technology can also capture information from sensors, asset management tools, and automation systems during the fabrication stage, enabling operators to make monitoring and diagnostic decisions at each stage of the process. This helps to detect efficiency and defect rates early, allowing technicians to proactively (rather than reactively) make corrections and prevent downtime, increasing the likelihood of on-time delivery.

Maintenance and Repair

The maintenance system in the industrial sector is a crucial and challenging task where technicians need to ensure optimum machine availability and reliability. However, workers in the repair and maintenance stage face technological barriers due to the variance of product design according to demand and customer requirements. Adopting AR technology can eliminate this problem and improve product life by supporting technology transfer at various stages.

AR technology expands the maintenance and repair system by providing audio and visual instructions to workers, unlike traditional maintenance methods that rely on manuals for guidance. Researchers suggest an immersive AR/VR technology-based machine servicing system to enable maintenance tasks. The proposed system involves three steps: compiling failure reports, diagnosing the issue with AR, creating maintenance instructions, and finally performing maintenance and evaluation. With this system, the onsite technician can document machine failure in various formats and send failure reports to the chief mechanic or other experts via a cloud platform. Experts can then provide guidance to the on-site technicians using step-by-step AR instructions, reducing the need for physical appearance specialists.

Manufacturers such as Ford have recently adopted AR technology for challenging maintenance tasks (*Teamviewer, 2021*). Their See What I See (SWIS) headset enables remote specialists to guide local technicians using step-by-step instructions in real-time, resulting in improved service efficiencies and a reduction in maintenance costs.

Figure 16 Example of remote assistance with HoloLens 2. Source: Dynamics 365 Remote Assist

However, HMDs are not the only alternative. Siemens has developed a new AR software application for smartphones, tablets and data glasses called "Comos Mobile Worker" in cooperation with Augmensys GmbH (*Siemens, 2021*). The Comos Mobile Worker app has an easy-to-use interface that allows users to visualize and process all necessary data, including data from ERP systems, engineering data, and live data from the process control system. The app also allows for real-time collaboration with experts who can provide remote support, reducing the need for on-site visits and increasing efficiency.

Overall, adopting AR technology in the repair and maintenance stage of the manufacturing sector can significantly improve productivity, reduce maintenance costs, and enhance service efficiency.

5.2.5. Previous Shift2Rail and Horizon Projects

Besides the state of the art, we have searched for previous European projects whose results can be of relevance for the project, and could be even integrated if feasible:

AssAssiNN (GA 886977, H2020-CS2-CFP10-2019-01): Development of a multifunctional system for complex aerostructures ASSembly, ASSisted by Neural Network

The main objective of the ASSASSINN project is to develop and validate a robust multifunctional assembly cell able to assist manual activities as the installation of typical fuselage systems and equipment, including cabling through the cabin structures or the application of sealant. This cell will guide the worker using Mixed and Augmented Reality during the assembly and inspection processes.

XR4ALL (GA 825545, H2020-ICT-2018-20): eXtended Reality for All

XR4ALL is set to risk through 6 objectives that correspond to the 6 work packages. Together, they will create a thriving European XR community: 1) unite the XR community through the XR Forum (community and supportive portal for knowledge exchange and visibility); 2) provide access to XR solutions on the XR Platform; 3) increase XR innovation through funding of sub-projects, to be integrated in the XR Platform; 4) monitor trends, visions and developments to create a SRIA; 5) boost the take-up of XR through a technology transfer strategy and VC involvement; and 6) carry out efficient dissemination activities to pave the way towards sustainability.

CORTEX2 (GA 101070192, HORIZON-CL4-2021-HUMAN-01): COoperative Real-Time EXperiences with EXtended reality

The EU-funded CORTEX² project will bridge the divide between widespread video conferencing tools and innovative XR-based solutions to democratise the adoption of next-generation eXtended Reality tele-cooperation by industrial sectors and SMEs. The initiative will use and extend the widespread Rainbow teleconferencing solution from Alcatel Lucent Enterprise to allow for fully interactive XR-based cooperation. This will be demonstrated in three pilots: industrial production, business meetings, and remote training respectively.

EMIL (GA 101070533, HORIZON-CL4-2021-HUMAN-01): European Media and Immersion Lab

The EU-funded EMIL project will help to make Europe a leader in the next digital development revolution, focussing on XR for media and funding promising innovators as part of the Financial Support to Third Party (FSTP) Action.

INDEXAR (GA 889719, H2020-EIC-SMEInst-2018-2020): Developing a Scalable Mobile AR Browser

The EU-funded INDEXAR project is developing a web platform aimed at disrupting the current market and making AR technology affordable for SMEs. It is also working to provide a faster SaaS solution. Eventually, this new platform will allow SMEs to create AR experiences through a free iOS and Android mobile app.

5.2.6. Challenges and Future Research

Implementing AR technology in Industry 4.0 also presents several challenges that need to be addressed to ensure its success. Some of the key challenges are:

- **Integration with existing systems:** One of the biggest challenges of implementing AR in Industry 4.0 is integrating it with existing systems. This challenge is amplified when we desire to monitor other devices through AR technology. Incompatibility issues can arise due to differences in hardware components, software architectures, protocols, or programming languages. Achieving compatibility and a smooth integration of AR technology with existing systems may require significant investments in software and hardware upgrades. Middleware systems, acting as intermediaries between the AR devices and existing systems, could also help to translate and transfer data between different systems.

- **Content availability:** A well-functioning system requires a repository of content and data that is readily available in the appropriate format. However, aggregating and collating data from operational and repair manuals can be a daunting task, requiring complex coding to create work instructions for a given procedure. Replicating workers' tribal knowledge into a database is an additional challenge. To address some of these issues, an authoring tool could be employed to allow users to create, edit, and publish augmented reality experiences without requiring extensive programming knowledge. However, creating such an authoring tool is a complex task itself.
- **Data security:** AR systems can capture and process sensitive data, which may pose a security risk if not handled properly. This includes the potential for cyberattacks and breaches of personal and proprietary data. Companies must implement robust security measures to protect against these risks.
- **User adoption:** For AR to be successful, workers must be trained and comfortable using the technology. This requires a change in the work culture and may take time to implement, especially for workers who are resistant to change. To overcome this challenge, it is important to provide sufficient training and support to the users. Organizations can gamify the AR/ VR experience to engage their workforce and reward them for making use of immersive tools. For instance, Light Guide Systems, an enterprise AR technology provider, turns a set of manufacturing tasks into a sequence of challenges where employees can score points and effectively track key metrics (*LightGuide, 2017*). This provides positive motivation and a competitive environment for completing those tasks. The inclusion of worker's opinions and inputs in the design and development phase of the AR solution can also be a beneficial approach to improve adoption.
- **Cost:** Implementing AR technology can be expensive, especially for smaller companies with limited budgets. Factors that can influence the cost of AR implementation include the type and number of devices required, as well as the development and maintenance of the software and applications, which can also prove to be a time-consuming process. Additionally, there may be costs associated with training employees to use the technology, as well as potential costs for technical support and troubleshooting. Companies must weigh the costs and benefits of AR and determine if it is a viable investment for their business.
- **Technical limitations:** AR technology is still in its early stages, and there are limitations to what it can do. For example, AR devices may have limited battery life or field of view, and the accuracy of AR tracking may vary depending on the environment. In addition, some HMDs can be ergonomically poor: heavy, uncomfortable to wear for long periods, and can cause neck and eye strain. Companies must be aware of these limitations when implementing AR technology and find a suitable solution for their use case.

Efforts are being made in research and development to advance AR technology for manufacturing applications. This includes enhancing the virtual interface for reality, identifying worker behaviours, and enabling sharing and collaboration between multiple streams in an industrial context. To enhance immersive technology, upgrades to the optical and visual system interface, 3D auditory system, haptic multichannel devices, and marker-less tracking techniques are necessary. Recognizing worker activity is crucial for assessing employee performance. And collaboration and sharing are becoming increasingly challenging, thus, solutions must be developed, such as generating AR instructions, enhancing adaptability in AR/VR immersive environments, enabling distant work, and constructing effective approaches for simultaneous collaborations and concurrent interfaces between stakeholders in an immersive system. Cloud-based collaboration strategies should also be further studied to enable workers to share their relevant expertise and experience across various workshops and sectors in different locations.

5.2.7. Conclusions

Augmented Reality has emerged as a rapidly growing field that promises to revolutionize the way we interact with digital information and the world around us. AR technology has made significant strides in recent years, driven by advances in computer vision, graphics, and machine learning, as well as the widespread availability of powerful mobile devices.

However, the adoption of AR in Industry 4.0 is not without its challenges, such as the need for seamless integration with existing systems, the necessity of establishing standardization of knowledge and procedures, the need for a workforce that is willing and able to work with this technology, and the technical limitations that inevitably arise from introducing a new and emerging technology into an industrial setting.

Despite these challenges, AR has gained significant momentum in Industry 4.0, with many companies investing in the technology and developing innovative use cases for their operations. As AR technology continues to advance, it has the potential to transform the industrial landscape, creating new opportunities for innovation and growth, and driving improvements in productivity, efficiency, and safety.

6. Workplace Evaluation

STRUKTON, MERMEC, PKP and FSI carried out a workplace evaluation in many of their sites to search for the applicability and needs of these technologies to assist their workers. This in-depth evaluation showed multiple applications of the technology as well as many requirements for their use. In this section, main points of this analysis are presented.

6.1. Exoskeletons

FSI concluded that exoskeletons can support the operator in the execution of manual tasks in the railway industry with significant improvement of working conditions and safety, cost reduction, improved quality and higher accuracy of service.

An exoskeleton specifically developed for the worker support during on track operations, that can reduce gravity load of tools and reduce vibrations transmitted during manual handling of tools such as manual tamping tools, so overall reducing the risk of onset of Work-related Musculoskeletal Disorders (WMSDs) can be of great relevance during the execution of the most important maintenance tasks for the lower and upper part of the railway infrastructure such as cutting and grinding of rail tracks, ballast tamping, bolt screwing/unscrewing and catenary maintenance; all these tasks are repetitive and include two main phases: moving the tool between two locations, and performing the task.

Figure 17. Example of manual heading of heavy tools

Exoskeletons can enable to account three main goals:

- Ergonomics for usability, feasibility of using the device in the task and comfort;
- Safety for risk reduction as capability of the exoskeleton to make load and vibrations bypass the critical districts of the user's body;
- Robustness.

The exoskeleton should be "transparent" to the user though providing assistance and to make it easy for the user to switch tasks. What should be kept in mind as the Project evolves is that the exoskeleton should not, for one reason or another, itself be a cause of risk to the operator.

As an infrastructure manager, FSI is interested in evaluating the use of the exoskeleton in all areas related to infrastructure maintenance and bringing real benefit to the sector operators' work.

MERMEC concluded four workplaces where exoskeletons could really make a different to their workers:

- Use for work with arm positioning at shoulder-height, e.g., when specialized operators weld some elements on the ceilings of the rolling stock, the fatigue resistance of the operator is extremely solicited.
- Use for material positioning activities on shelving, in fact warehouse operators every day carry out repetitive operations of material busting and positioning of the same on the shelves of the department warehouses.
- Use for handling heavy materials (> 2 kg), very often operators transport, albeit for a few meters (max 10-15 cca), heavy material to be assembled on the rolling stocks.
- Auxiliary use for operators with certain restrictions and physical limitations; they should not move loads of more than 3 kg or have postural alternation.

STRUKTON identified two main points of action for exoskeletons:

- Building railway overhead lines & constructions creates heavy physical load on human body (shoulders & elbows in particular)
- At great heights in rail platforms "above your head" and "in front of your body" – continuously.

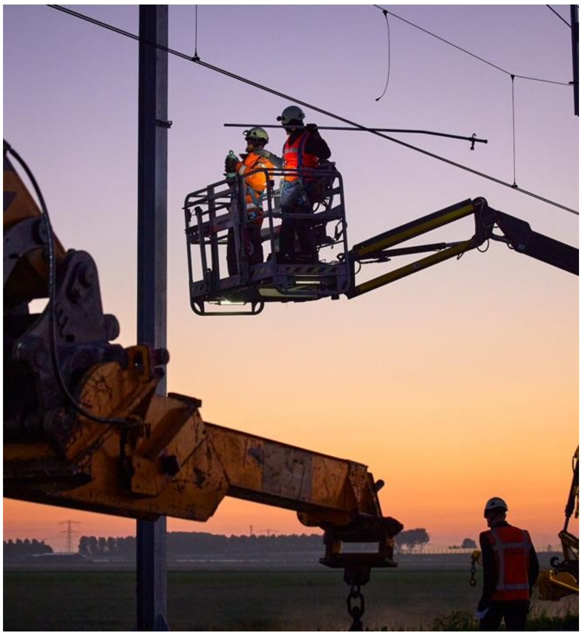


Figure 18. Example of application for exoskeletons evaluated by STRUKTON

STRUKTON also evaluated some of the exoskeletons already available at the market, developing the following observations (for working on the catenary):

- Arms are in special 'cups' and once the worker starts lifting beyond power, springs of exoskeleton come into effect.
- Exoskeleton gives kind of weightlessness, which causes less stress in arms and shoulders (2 – 8 kg)
- When working at height, on railway-platform, fall harness and leash is required
- Practical tests also showed that it is hard to wear exoskeletons together with fall protection (fall harness and leash)
- It is important that the total weight of both personal protective equipment does not become so heavy that this creates physical problems for the worker.
- Great “hook danger” on top of shoulder of exoskeleton. Dangerous because workers work and walk on moving train, under catenary-components.
- Too much resistance/friction with downward movement with current exoskeletons. This takes extra energy in some cases (e.g., when picking up tools or components on floor of basket).
- No investigation has been done into what happens in case someone falls (include leash) with fall harness and exoskeleton.
- Building in into materials that do not conduct electricity.

These observations yielded to the following requirements:

- Design exoskeleton with less resistance / friction during downward movements of arms; Joint in elbow must be movable in both vertical plane and horizontal plane (ball joint); No “hook danger” on top of shoulder of exoskeleton.
- Approved combination exoskeleton + fall harness / leash (including low weight).
- Light integrated exoskeleton with fall harness (including leash) that is then integrated into reflective orange workwear

PKP has identified a potential application for exoskeleton technology within their maintenance operations:

The cleaning of glass surfaces (windows, divider panels, advertising, or information panels) requires a great frequency, because the glass in differences needs to be clean with a regularity. The cleanness of glass surfaces is very important not only to the comfort of the station, more also to “windows” to bring lighter to the interior and in the interior to bring more brilliance.

Depending on the height or dimensions of glass surface, apart from the cases needs lift platform or basket, for the higher positions the operator needs to make more effort raising your arms and for the lower bending the body to uncomfortable position. Also, for the cases that needs lift platform or basket, the operator can use the exoskeleton, avoiding making big efforts for more distant positions. This can contribute to an easy and effortless task, reducing the musculoskeletal disorders and reducing the causes for sick leaving or also work accidents.

The cleaning of glass surfaces is two subproblems (at low heights make necessarily makes it necessary to bend the body to an uncomfortable position main during prolonged periods and at high heights forcing them to stretch your arms and/or use instruments to increase the field of action). Also results in additional efforts and loss of comfort resulting in problems cited above.

More specifically, the targeted objectives can be defined as:

- Develop an exoskeleton for work with arm positioning at low-height, e.g., when it is necessary clean the surface glass at bottom,
- Develop an exoskeleton for work with arm positioning at high-height, e.g., when it is necessary clean the surface glass at top,
- Develop an exoskeleton ergonomic and compatible with two requirements at same time to allow to clean the allow cleaning of the entire glass (from the top to the bottom).

The first or main objective of use of exoskeleton technology should reduce the physical effort carried out by the worker in over-shoulder operations, compared to the current manual operation, without reducing the feeling of comfort.

6.2. Augmented Reality

FSI identified the following areas of application for AR so that it has a real impact on the railway industry; the areas of application are as follows:

- Training;
- Support for complex activities;
- Asset maintenance history.

The tools to accomplish this would be glasses or other devices equipped with screen and camera. The images that follow are extracted from application examples already on the market.

Many technical operations performed by the maintenance team are primarily driven by experience gained in the field, and there are not always procedures that allow for easy detection of a failure.

Augmented Reality technology would provide support of a technical nature by overlaying the operator's actual vision with digital data such as:

- Providing, when requested by the operator, electrical and mechanical schematics;
- Guide troubleshooting by indicating a list of checks;

- Providing a list of checks required before declaring the fault resolved and the asset re-commissioned.

Where it is not practicable to develop technology capable of providing automated support for the resolution of a complex failure scenario, Augmented Reality would allow a remote operator real-time interaction with operators in the field to teleguide them in troubleshooting.

This vision can be extended to larger-scale applications such as combining "paper model" with Augmented Reality that would allow all information to be given to operators in an immediate way for both training purposes and real-world activities.

The information that could be shown is many, for example: aspects of signals, type of tracks, buildings, type of assets, allowed speed, joints, limit crossings, TE, routes.

The proposed implementation of augmented reality includes the possibility of being able to integrate in the viewer or directly on the device, supplied to the crews, a database containing historical maintenance orders performed on each individual asset. This development is achievable by uniquely tagging each individual entity, i.e., assigning to each of them a distinct tag, capable of providing the information fully automatically whenever it enters the field of view of the detection system.

Figure 19. Concept example of solution for AR

MERMEC has identified a potential application of AR (Augmented Reality) systems within their operations, in the maintenance of optoelectronic diagnostic systems for the automatic control of the conditions of railway infrastructures.

The output of the process is to provide a maintenance service to a remote maintainer, using specific visual AR technologies (AR glasses and tablet) for the transfer of information and simultaneously exploiting Internet connectivity (remote assistance).

The AR System will represent a simple work tool able to facilitate, in the context of assembly activities, the correct assembly of each component of the diagnostic systems, without errors and in increasingly short times, while in the field of maintenance, the AR System can be of support to maintenance personnel in all those processes that involve the calibration of the system, the replacement of worn parts and/or components of the diagnostic systems being inspected.

In particular, the applicability of the AR System for the assembly and subsequent maintenance of the inertial system for measuring track geometry (TGMS) will be verified. This system essentially consists of the assembly of optical units and inertial sensors. The optical units, consisting of lasers and cameras, are contained inside sealed optical boxes. Inertial sensors are contained in an Inertial Measurement Unit (IMU) specifically designed to operate in a railway environment for track geometry measurement applications. The optical units and the IMU are assembled on a rigid beam designed to facilitate specific installation, on trolleys or under the vehicle body, depending on the customer's requests and the type of vehicle. Below inertial track geometry measurement system (TGMS) layout is reported.

Figure 20 - Inertial-Based Track Geometry Measurement System (TGMS)

TGMS allows an accurate evaluation of railroad track geometry in a variety of operational conditions. The system integrates an inertial measuring unit - incorporating accelerometers and solid-state rate gyroscopes - with optical-gauge boxes and provides measurements of all critical track geometrical parameters from 0 km/h up to 400 km/h.

The complete assembly of the system takes 8 person-months. Below is the breakdown of person months by components.

Components	Person Months (pms)
Optical components	3,50
Inertial Measurement Unit	2,00
Power Supply - UPS	2,00
Assembly	0,50
Total	8,00

For each part of the system, an analysis of the reliability expressed in terms of MTBF (Mean Time Between Failures) measured in hours [h] has been carried out, which in this preliminary phase was estimated on the basis of the failure history of similar components already installed by MERMEC in the same environmental and operating conditions. Below are the values obtained.

Components	MTBF [h]
Laser Box	8.000
Camera Box	40.000
Inertial Measurement Unit	50.000
Power Supply - UPS	6.000

The results also showed that the system meets approximately 3.000 operating hours and subsequently requires corrective/periodic maintenance. Periodic maintenance can be classified into:

- First level maintenance: includes all routine maintenance operations.
- Second level maintenance: includes corrective maintenance operations to resolve anomalies within 24 hours if spare parts are in stock.
- Third level maintenance: includes corrective maintenance operations to solve faults.

An estimate of the time required to perform periodic maintenance on each component of the system was carried out, always considering the historical maintenance data. The values were expressed in terms of MTTR (Mean Time to Repair) measured in minutes.

The followings table indicates the maintenance activities that can be carried out with AR System support:

ID	Ordinary Maintenance Activities	Level	MTTR (minutes)
1	Visual inspection and cleaning of protective glass	1	10
2	Optical box integrity check	1	20
3	Control of electrical connections for optical boxes	2	60
4	Control of mechanical fixings	2	20
5	Dehumidifier replacement	2	15
6	Functional control of optical boxes	2	15
7	Functional verification of the cleaning system	2	40
8	Laser unit and camera power control	3	15
9	Calibration control	3	120

In addition, since the system technology is constantly evolving, often the level of competence of the operators involved in installation and maintenance is not immediately adequate, and therefore requires continuous updating by the personnel involved.

The AR System, providing the operator step by step with the sequence and type of operations to be performed, will be able to assist him during the assembly / maintenance of each component of the system and to make it operational in the shortest possible time. This will therefore allow you to:

- reduce the time and cost of preliminary training on assembly operations;
- reduce maintenance times;
- reduce the costs of travel of maintenance staff;
- create truly usable manuals.

STRUKTON has identified several applications for AR technology:

- Process acceleration: AR can support in making processes in the field more uniform and then more efficient. By projecting clear instructions for employees, processes can be accelerated.
- Error reduction: By projecting clear instructions for employees, errors are reduced during processes. In addition, an expert can be called in via the Remote Assistant function if an employee cannot figure it out himself. An expert watches with the employee via a video connection and can give instructions.
- Improve security: Due to the aforementioned instructions and dial-in from experts, the chance of accidents is significantly reduced. In addition to these functions, warnings can also be projected or real live data about, for example, the pressure in a pipe or the voltage on a cable (is not measured by the glasses themselves). Furthermore, the HoloLens has a role to play in raising awareness in the field of safety.
- Train employees: Through AR systems, new employees can be trained faster, safer, more enthusiastic, more flexible and cheaper. For example, employees are more likely to get excited about interactive and structured training.
- Attract new employees: AR systems can serve as a powerful tool in the search for new personnel for the rail industry. This can be done through demonstrations at trade fairs and workshops at schools.
- Futureproofing from Strukton: In addition to the practical advantages that the HoloLens can offer in the technical field, AR systems have a positive effect on the future-proofing organization itself. Setting up and conducting an innovation study such as the HoloLens within the organization, the company learns how to deal with any future innovations. Despite the rail industry being a relatively conservative sector, there is a lot of change in the current working climate such as digitisation, employee shortages and sustainability.

7. Use Cases Definition

From the workplace evaluation of the companies involved in WP19, several potential applications for exoskeletons and AR technologies have been identified. Section 6 has described the most relevant ones, and it has also pointed out many requirements for both technologies. A more integrated analysis of all potential applications has yielded to the development of two use cases for this WP covering most technological demands presented in previous section and developing a framework for the validation and demonstration of the technology to be developed withing this WP19.

7.1. UC19.1: Upper-body exoskeleton for worker's support in railway industry

This Use Case will focus on developing a novel exoskeleton that will be able to support the operator upper body during the execution of the most physically demanding maintenance tasks of the railway infrastructure.

Rail system maintenance activities often involve the use or handling of heavy technology or objects or repeated activities that can lead to excessive operator fatigue. Musculoskeletal disorders in the work environment (WMSD) are the leading cause of sick leave in work accidents and occupational diseases. Overexertion, the leading cause of WMSD, is directly linked to the physical workload. More specifically, in railway maintenance operations, WMSD is related to:

- Building railway overhead lines & constructions creates heavy physical load on human body (shoulders & elbows in particular).
- At great heights in rail platforms "above your head" and "in front of your body“.
- Most important maintenance tasks for the lower and upper part of the railway infrastructure such as cutting and grinding of rail tracks, ballast tamping, bolt screwing/unscrewing and catenary maintenance.

It is a serious problem that generates a high social, health, business and economic cost in general:

- Personal and family: the affected worker loses personal autonomy for their activities of daily living, must undergo various clinical processes and, in certain cases, also affects their future employability.
- Socio-sanitary: The rehabilitation of musculoskeletal disorders represents a significant burden for health systems, and a significant cost for public health systems and labor mutual companies.
- Business: companies bear an economic cost that is generally higher than what is reflected, due to the large number of hidden costs that are unknown, also called indirect or uninsured costs (first aid, lost time, interference in production, conflicts labor, loss of image and market, sanctions, legal proceedings, etc.).

Possible solutions can be found around specific machines & special tools to reduce physical load.

IMs have already tested several exoskeletons available on the market. However, none of the existing solutions satisfies the requirements of the railways maintenance sector, as they are conceived for other “cleaner” industrial environments such as manufacturing or logistic repetitive operations. More specifically, the disadvantages found on current systems can be summarized as:

- When working at height, on railway-platform, fall harness and leash is required

- Practical tests also showed that it is hard to wear exoskeleton together with fall protection (fall harness and leash)
- The total weight of both personal and protective equipment cannot become so heavy that this creates physical problems
- Great “hook danger” on top of shoulder of exoskeleton. Dangerous because of work can be walking on moving trains and under catenary-components
- Too much resistance/friction with downward movement with current exoskeleton. This takes extra energy in some cases (e.g., when picking up tools or components on floor of basket).
- No investigation has been done into what happens in case someone falls (include leash) with fall harness and exoskeleton
- Building in into materials that do not conduct electricity.

Technology will be developed to improve human safety and skills in workplace through Exoskeleton systems. A novel exoskeleton with a passive structure, designed to be mean and lean, and compatible with other protective tools will be developed. Besides, the exoskeleton will have the option to be scaled with active modules (compact devices with integrated actuators, energy source and electronics) that will easily snap in the passive structure to assist workers in managing heavy loads. The passive and active parts of the exoskeleton will result in the first hybrid exoskeleton specifically designed for railway-related operations.

More specifically, the targeted objectives can be defined as:

- Develop an exoskeleton for work with arm positioning at shoulder-height, e.g. when specialized operators weld some elements on the ceilings of the rolling stock, the fatigue resistance of the operator is extremely solicited.
- Develop an exoskeleton for handling heavy materials (> 2 kg), very often operators transport, for a few meters heavy material to be assembled on the rolling stocks.
- Develop an exoskeleton ergonomic and compatible with other protective outfit common in railway maintenance.

There is still uncertainty regarding some aspects for the final TRL8/9 implementation of the exoskeleton in certain issues such as the analysis of the impact of the exoskeleton in case of worker falls and the materials use and the impact of active systems (batteries, actuators) on the working environment.

Definition of KPIs: KPI1 - < Cost reduction of the interventions by at least 10%>

The use of exoskeleton technology will reduce the physical effort carried out by the workers in over-shoulder operations compared to the current manual operations. The use of an exoskeleton will improve ergonomics and overall workers’ safety, thus reducing the incidence of WMSD on IM’s employees, contracted consultants and contractors while at work at IM’s premises and trackside. Both parameters, improved task performance due to fatigue reduction and reduction of workers' sick leaves and injuries, directly influence on the cost of the intervention.

Validation of the new exoskeleton system in 4 testing scenarios (Strukton-Netherlands, Mermec-Italy, FSI-Italy, PKP-Poland) and KPI measurement compared with current manual process. We will carry out real maintenance task with and without the exoskeleton. A minimum of 2 workers in 4 different working scenarios will participate in the validation phase (8 workers in total). A subjective evaluation by the workers that will test and validate the exoskeleton will be carried out in order to evaluate their satisfaction when using the exoskeleton mainly regarding physical effort reduction, safety, ergonomics and usability. Questionnaires will be developed and Liker-type scales will be used for quantitative measures.

$$KP1 = \frac{Value_{traditional\_method} - Value_{new\_method}}{Value_{traditional\_method}} \times 100$$

- For the traditional method the value represents the answer of the operator to the questionnaire (rate scale) in relation to the traditional method (without the exoskeleton).
- For the new method the value represents the answer of the operator to the questionnaire (rate scale) in relation to the innovative method (with the exoskeleton).

If KP1 is positive: Indicates that the new method is more satisfactory for the operator than the traditional method.
If KP1 is negative: Indicates that the traditional method is more satisfactory for the operator than the new method.

7.2. UC19.2: Augmented Reality tools to help and guide railway workers in maintenance operations

This Use Case will focus on developing Augmented Reality technology to provide railway maintenance workers with assistance during the assembly / maintenance procedures reducing time and cost of these operations.

The railway infrastructure, as a complex system, integrates several assets with different technologies. The infrastructure must follow the continuous and growing technological upgrading without losing its safety and robustness.
To achieve these goals the maintenance has a primary importance, and the operators have to combine the past experience with the needs of the innovative technologies.

Currently, many technical operations performed by the maintenance team are primarily driven by experience gained in the field, and there are not always procedures that allow for easy detection of a failure.

In this scenario, the augmented reality technology should be developed to provide technical support such as:

- Providing, when requested by the operator, electrical and mechanical schematics;
- Guide troubleshooting by indicating a list of checks;
- Providing a list of checks required before declaring the fault resolved and the asset re-commissioned.
- Providing remote assistance in real-time by an expert.

The Use Case addresses the need of technology to assist workers on complex and remote maintenance operations to reduce process cost, time and improve safety. More specifically, the following objectives are targeted:

- Process acceleration: Augmented Reality can support in making processes in the field more uniform and then more efficient. By projecting clear instructions for employees, processes can be accelerated.
- Error Reduction: By projecting clear instructions for employees, errors are reduced during processes. In addition, an expert can be called in via the Remote Assistant function if an employee cannot figure it out himself.
- Improve Security: Due to the aforementioned instructions and dial-in from experts, the chance of accidents is significantly reduced. In addition to these functions, warnings can also be projected or real live data about, for example, the pressure in a pipe or the voltage on a cable (is not measured by the glasses themselves).
- Train employees: Through this technology, new employees can be trained faster, safer, more enthusiastic, more flexible and cheaper. For example, employees are more likely to get excited about interactive and structured training.
- Attract new employees: As mentioned earlier, the experience of using this technology has an enthusing effect. With this in mind, it can serve as a powerful tool in the search for new personnel for the rail industry. This can be done through demonstrations at trade fairs and workshops at schools.

There is still uncertainty regarding some aspects for the final TRL8/9 implementation of the exoskeleton in certain issues such as dependence of good internet connectivity, battery live, compatibility with common glasses, etc…

Definition of KPIs: KPI1 - < Cost reduction of the interventions by at least 10% >

The use of the proposed Augmented Reality technology will reduce the time to complete a complex maintenance task. Thus, the cost of the maintenance operation is also reduced. The use of the proposed Augmented Reality technology will also reduce the number of errors in these operations as the system can make a quality check of the process. Ideally, the errors should approach to cero. This in turn, also derives in a cost reduction and improved safety of the operation. The combination of these parameters will achieve the target KPI1 goal.

This KPI has also relation with the CAPACITY KPI from PRIME "Planned possessions (ID.43)", percentage of a network's available main track-km- days which are planned to be blocked possessions for IM's activities included in the yearly timetable, including maintenance, enhancement, and renewals.

We will carry out real maintenance operations with and without the proposed Augmented Reality technology. A minimum of 2 workers in 3 different working scenarios (Strukton-Netherlands, Mermec-Italy, and FSI-Italy) will participate in the validation phase (6 workers in total).

We will measure the time needed to accomplish the tasks and the number of assistance requests (mainly in the case without the technology) to an expert worker. We will compare both time and cost (taking into account also the hour/cost of the expert worker) to carry out the operations with and without the proposed Augmented Reality system. We will also measure the number of errors carried out by the operator with and without the proposed technology.

For computing KP1, it's possible to estimate time (hour/ man referred to the activity) to perform the activity and post-processing data and compare it with traditional methods to establish the time saving ratio that could be achieved with the application of this technological system. Errors will be taken into account by the additional time and cost required to amend the task.

To evaluate this KPI we can use the following formula.

$$KP1\ (\%\ time\ savings)\ = \frac{Time_{traditional\_method} - Time_{new\_method}}{Time_{traditional\_method}} \times 100$$

- Traditional Method Time is the time required to perform an inspection by the traditional method.
- New Method Time is the time required to perform an inspection by the new method.

If KP1 is positive: Indicates that the time for the new method is less than the time required for the traditional method. In this case, a positive value indicates a time saving or a reduction in the time required to complete the task, however, if KP1 is negative: Indicates that the time for the new method is greater than the time required for the traditional method. In this case, a negative value indicates that the new method would require more time compared to the traditional method.

Therefore, the cost of personnel (h/m. referred to activity on singular bridge span) is indicated below:

$$KP1\ (\%\ cost\ savings)\ = \frac{Cost\ _{traditional\_method} - Cost_{new\_method}}{Cost_{traditional\_method}} \times 100$$

- Traditional Method Cost is the cost required to perform an inspection by the traditional method.

- New method Cost is the cost required to perform an inspection by the new method.

If KP1 is positive: Indicates that the estimated cost for the new method is less than the cost required for the traditional method. In this case, a positive value indicates a time saving or a reduction in the cost required to complete the task, however, if KP1 is negative: Indicates that the estimated cost for the new method is greater than the cost required for the traditional method. In this case, a negative value indicates that the new method would require more cost compared to the traditional method.

8. Questionnaires

Beyond the analysis of the workplaces, it is very important to properly gather the perspective and requirements for the technology from the potential final worker. Their opinion is usually essential to measure the applicability of the developments and to detect needs and specifications from early designs. Therefore, in WP19 we designed two questionnaires, one for exoskeletons (see Appendice I) and one for AR (see Appendice II) to gather the workers' perspective over a set of issues.

The questionnaires were digitalized and delivered by the EUSurvey tool to a set of volunteer workers from the four end-user companies involved in WP19. The questionnaires were translated into the official language of the workers. Prior to deliver them, an Ethics Committee Approval was requested to the Research Ethics Committee of the University of Navarra in Spain https://en.unav.edu/research/our-research/etica-para-la-investigacion#comitedeetica. The Committee delivered a favourable report (see Appendice III).

The participation in the study was voluntary. The answers to the questionnaires were totally anonymous and treated in an aggregated way. No identifying information could be linked to the responses. No personal data was collected. The data collected is only used as information of interest for the development of design requirements that the Augmented Reality tools and the exoskeleton to be developed must meet. The data collected within the framework of the surveys are stored securely and confidentially in digital form on a medium in the possession of CEIT. They will be destroyed within 5 years of termination of the project. The data are protected by statistical secrecy and therefore cannot be communicated or externalised except in aggregate form, so that no individual reference can be made to it and can only be used for statistical purposes. The data is processed in compliance with the General Data Protection Regulation 2016/679 (GDPR) which is fully applicable in all EU Member States as of 25 May 2018.

8.1. Exoskeletons

21 participants took part in the survey.

The first technical question was related to a list of functions that the exoskeleton can have and their degree of usefulness. The answer of the participants to the usefulness of each one of these functions was the following:

	Not Useful	Slightly Useful	Useful	Very Useful	Necessary
Assist me transporting heavy goods	4.76%	0.00%	28.57%	**33.33%**	**33.33%**
Assist me working on above shoulders postures	0.00%	4.76%	4.76%	**47.62%**	42.86%
Assist me to reduce the weight of the equipment	0.00%	9.52%	19.05%	33.33%	**38.10%**
Reduce fatigue by repetitive tasks	0.00%	14.29%	19.05%	28.57%	**38.10%**
Possibility to add another protective outfit integrated in the exoskeleton	4.76%	23.81%	9.52%	23.81%	**38.10%**
Possibility of integrating auxiliary working tools (communications, small equipment, maintenance equipment)	4.76%	28.57%	**33.33%**	28.57%	4.76%
Possibility of integrating physiological sensors to monitor my health and ergonomics	4.76%	28.57%	23.81%	**33.33%**	9.52%
Possibility of integrating sensors to identify hazardous environments (gas, temperature, etc.)	4.76%	14.29%	**38.10%**	28.57%	14.29%
Possibility of correcting a posture to be ergonomic	0.00%	14.29%	**38.10%**	28.57%	19.05%
Robust but light structure, lightweight	0.00%	4.76%	14.29%	**47.62%**	33.33%
Reduce vibrations transmitted during manual handling of tools	4.76%	23.81%	**33.33%**	23.81%	14.29%
Take up little space when not in use	0.00%	4.76%	28.57%	**38.10%**	28.57%

Overall, most functions listed are believed as useful by the workers. Regarding the primary need for assistance is seems that working above the shoulder operations have a greater relevance over transporting weights or reducing the weight of the equipment. Integrating protective outfit is also well ranked, as well as the requirement of developing a lightweight system.

Regarding the range of weight that workers would tolerate for an exoskeleton, the following question was presented to them:

	< 0.5 kg	0.5 – 1 kg	1 – 1.5 kg	1.5 – 2 kg	> 2 kg
In your opinion, how much should be the maximum weight of the exoskeleton?	14.29%	14.29%	**38.10%**	23.81%	9.52%

It seems that an exoskeleton with a range of weight between 1 and 1.5 kg can be accepted by workers If it meets the functions listed above.

Finally, a final question was presented to the participants asking to scale the usefulness of an exoskeleton for their work.

To what extent do you think that the use of the exoskeleton to be developed could be useful for your work? Indicate your opinion on a scale of 0 to 10 where 0 is not helpful at all and 10 is totally helpful.

0 Not helpful at all	1	2	3	4	5	6	7	8	9	10 Totally helpful
4.76%	4.76%	0.00%	0.00%	0.00%	4.76%	4.76%	**28.57%**	**28.57%**	14.29%	9.52%

The results to this question (higher marks for options 7 and 8) present an optimistic point of view from the workers surveyed to the usefulness of the technology to be applied.

8.2. Augmented Reality

35 participants took part in the survey.

The first technical question was related to a list of functions that the AR system can have and their degree of usefulness. The answer of the participants to the usefulness of each one of these functions was the following:

	Not Useful	Slightly Useful	Useful	Very Useful	Necessary
Provide specific operating and maintenance step-by-step instructions	0.00%	2.86%	14.29%	**65.71%**	17.14%
See general information of an object whenever it enters the Field of View	11.43 %	8.57%	**37.14%**	34.29%	8.57%
Have access to and visualize in real-time a database containing e.g. manuals, schematics, datasheets, historical maintenance orders/reports… of an object	0.00%	11.43%	**45.71%**	34.29%	8.57%
See live data of an object whenever it enters the Field of View	5.71%	8.57%	22.86%	**42.86%**	20.00%
Allow remote communication with an expert center that will give real-time tele-assistance	0.00%	2.86%	11.43%	**60.00%**	25.71%
Provide a list of checks required before declaring a task completed	0.00%	8.57%	**40.00%**	**40.00%**	11.43%
Automatically create maintenance operation reports whenever a task is completed	5.71%	17.14%	28.57%	**37.14%**	11.43%

Overall, most functions listed are believed as useful by the workers, being the functionality of providing specific operating and maintenance step-by-step instructions the most valuated one.

The following questions intended to gather further information related to the particular application of the AR systems. This question gathered information for the specifications to be considered when developing the technology.

	Never - 1-	Sometimes - 2-	Often - 3-	Usually - 4-	Always - 5-
Both hands are required to perform the task	0.00%	22.86%	31.43%	**40.00%**	5.71%
The location of the maintenance is outdoors	8.57%	28.57%	**31.43%**	25.71%	5.71%
The location of the maintenance is remote (no internet access)	11.43%	**37.14%**	31.43%	14.29%	5.71%
The environment is wet or hot or extreme (storms, dust, more than 30ºC, less than 0ºC…)	14.29%	**48.57%**	28.57%	2.86%	5.71%
The task involves liquids	20.00%	**54.29%**	14.29%	5.71%	5.71%
The operation requires gloves	11.43%	**25.71%**	17.14%	20.00%	**25.71%**
The operation requires a helmet	8.57%	25.71%	8.57%	25.71%	**31.43%**
The operation requires protection glasses	2.86%	**34.29%**	25.71%	20.00%	8.57%
Markers such as QR could be placed on objects	11.43%	**28.57%**	20.00%	20.00%	8.57%
CAD of the objects to maintain are fully available	0.00%	22.86%	31.43%	**40.00%**	5.71%

Results are of high interest for the development phase as for example it is important to note that most operations require gloves and helmets, which conditions how AR is provided to the worker.

An additional question inquired about the preference of users when providing AR information, confronting glasses and phones.

Would you prefer using AR glasses or smartphones/tablets? Glasses tend to be less comfortable, but they allow hands free operations. Indicate your opinion on a scale of 0 to 10 where 0 is I totally prefer using glasses and 10 is I prefer using mobile phone/tablets.

0 ☐ **Glasses**	**1** ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐ **Phone/Tablet**
2.86%	11.43 %	11.43 %	**20.00 %**	5.71 %	14.29 %	5.71 %	11.43 %	8.57 %	5.71 %	2.86%

From the results it can be seen that there is not a clear preference for one system or the other to display AR information.

Finally, a final question was presented to the participants asking to scale the usefulness of an AR tools for their work.

To what extent do you think that the use of an AR tool would be useful for your work? Indicate your opinion on a scale of 0 to 10 where 0 is not helpful at all and 10 is totally helpful.

0 ☐ **Not helpful**	**1** ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐ **Totally helpful**
2.86 %	0.00 %	2.86 %	8.57 %	5.71 %	14.29 %	8.57 %	14.29 %	**20.00 %**	11.43 %	11.43 %

The results to this question (higher mark for option 8) present an optimistic point of view from the workers surveyed to the usefulness of the technology to be applied.

9. Ethics

In this section we cover ethical issues foreseen for the development of WP19.

The utilization of exoskeleton and AR technology in railway maintenance tasks has the potential to improve worker safety, increase efficiency, and enhance overall productivity. However, the implementation of such technology in this context introduces various risks that need to be carefully assessed and mitigated.

First of all, we list potential hazards we have evaluated and identified during the development of the workplace evaluation. With this information, we have also performed an exercise of developing a risk classification assessment. The aim is not to have a definitive risk assessment for the application of the technology in a particular workplace, but to identify and enrich the specifications and requirements of this report. Therefore, quantitative values are just an exercise developed by the partners of WP19 in order to discuss each risk identified. The risk assessment methodology has followed the method use in Robo-Mate European project (*Van der Vorm, 2016*). Risk classification was done using Fine/Kinney method originally developed in 1971 by W. Fine (later publication in 1976 by G.H.F. Kinney). It breaks down the risk/failure rate into two components:

- Failure rate:
    - Likelihood or probability (P) - the probability of occurrence of the unwanted event during the activity concerned

- Exposure (E) - the frequency or duration of the activity concerned from which the unwanted event may result

- Consequences (C) - the possible consequences of the accident, incident and other unwanted event

The three aspects P, E and C are provided with value descriptions and factors allowing a numeric risk score calculation R = E x P x C.

The following values have used by project partners in order to carry out the exercise:

Score criteria					
Probablility		Exposure		Consequense	
score		score		score	
0.1	Absolutely impossible	0.5	Very rarely	1	Meaninful
0.2	nearly impossible	1	Several times a year	3	important
0.5	Very unlikely	2	Monthly	7	considerably
1	only on long term	3	Weekly or incidentally	15	very serioua
3	unusual, but possible	6	daily during work	40	Disaster
6	possible	10	Constantly	100	catastrophy
10	very likely				

9.1. Risk Assessment for exoskeletons

Physical Risks

- Musculoskeletal Injuries: While exoskeletons are designed to support and protect workers, improper fit or incorrect usage may still result in musculoskeletal injuries. Assessing ergonomic factors, providing proper training, and ensuring the correct adjustment and fit of exoskeletons are essential for mitigating this risk.
- Tripping and Falling Hazards: The additional weight and restricted mobility imposed by exoskeletons may increase the risk of tripping or falling, especially in challenging railway maintenance environments. Ensuring proper training, maintaining clear walkways, and implementing fall prevention measures can help minimize these risks.

Safety Risks

- Impaired Visibility and Auditory Cues: Exoskeletons may limit workers' peripheral vision, obstruct their hearing, or impede their ability to detect warning signals in the railway environment. Raising awareness through training, implementing safety protocols, and incorporating appropriate signalling systems can mitigate these risks.

- Interference with Safety Equipment: The integration of exoskeletons with existing safety equipment, such as harnesses or protective gear, may pose challenges. Ensuring compatibility, conducting risk assessments, and modifying safety equipment accordingly are crucial for minimizing safety risks.

Cognitive and Psychological Risks

- Increased Cognitive Load: The use of exoskeletons may impose additional cognitive demands on workers, potentially leading to distractions or errors in railway maintenance tasks. Providing comprehensive training, allowing sufficient acclimation time, and implementing clear communication protocols can help mitigate these risks.
- Psychological Impact: Workers may experience psychological effects related to wearing exoskeletons, such as increased stress or reduced job satisfaction. Promoting open communication, providing psychological support, and monitoring worker well-being contribute to risk reduction in this regard.

Environmental Risks

- Restricted Mobility and Evacuation: In emergency situations, the use of exoskeletons may impede workers' mobility or hinder their ability to evacuate quickly. Developing emergency response protocols, conducting drills, and ensuring that workers are trained to safely remove or disable exoskeletons in emergencies are crucial risk mitigation measures.
- Environmental Hazards: Railway maintenance tasks may expose workers to various environmental hazards, such as extreme temperatures, electrical risks, or hazardous materials. Exoskeleton design and material selection should account for protection against these hazards, and workers should receive appropriate training and personal protective equipment to mitigate associated risks.

Training and Education

- Insufficient Training: Inadequate training on the proper use, adjustment, and maintenance of exoskeletons may lead to errors or misuse. Implementing comprehensive training programs, incorporating regular refresher courses, and conducting performance evaluations can minimize this risk.
- User Competency: Workers must possess the necessary competence to operate exoskeletons effectively and safely in railway maintenance tasks. Evaluating user

competency, providing ongoing support, and addressing skill gaps through targeted training contribute to risk reduction.

Equipment Reliability and Maintenance

- Technical Malfunctions: Exoskeletons may experience technical failures or malfunctions during railway maintenance tasks, potentially endangering workers. Regular maintenance, inspections, and adherence to manufacturer guidelines are critical for mitigating this risk.
- Power and Energy Supply: Exoskeletons rely on power sources or energy storage systems that may pose risks, such as electrical hazards or limitations in power availability. Implementing robust power management systems, ensuring backup power sources, and conducting safety checks are essential for risk mitigation.

Regulatory Compliance and Standards

- Compliance with Railway Safety Regulations: Adhering to railway safety regulations and standards is crucial for ensuring the safe use of exoskeletons in railway maintenance tasks. Collaborating with regulatory bodies, conducting regular audits, and implementing necessary modifications contribute to compliance and risk mitigation.

Risk nr	Risk	Probability	Exposure	Consequence	Total Risk score
1	Compatibility of safety equipment and personal protective equipment cannot be guaranteed.	5	6	15	450
2	Insufficient observation of unsafe situations, with elements under voltage as an example	1	1	40	40
3	Hazards presented by electric currents (damaged wiring insulation, use of electrical equipment, catenary, etc.)	0.5	0.5	40	10
4	Employees not fitted correctly with the exoskeleton (exoskeleton unsuitable for the work process)	2	1	3	6
5	Loss of exoskeleton assistive support (material or power faillure, exoskeleton not fitted properly to worker)	0.5	0.5	3	0.75
6	Loss of exoskeleton stability (mobility, center of gravity, wet floor)	0.5	0.5	7	1.75
7	Risks of falls. The exoskeleton give rise to particular falls hazards (ladders, steps, elevated workplaces)	0.5	0.5	15	3.75
8	Operator not protected from dangerous situations (material covering, hot/cold surfaces, electrostatic phenomena, etc.)	0.5	0.5	40	10
9	Non robustness of critial exoskeleton parts (corrosion, lubrication, vibrations, etc.)	0.5	0.5	3	0.75
10	Operator not scaping from dangerous situations (exoskeleton hinder and not allowing quick or free movement)	0.2	0.5	100	10
11	Exoskeleton being caught and dragged by moving parts in its vicinity	0.2	0.5	15	1.5
12	Discomfort due to weight, ergonomics, and other stressing factors leads to loss of acceptance of exoskeleton	0.5	0.5	7	1.75
13	Physical stresses caused by the exoskeleton (additonal loads upon the body, unfavourable body postures)	1	0.5	15	7.5
14	Facility for adjustement / ergonomics (poor adaptation, loose/sliping)	0.5	0.5	3	0.75
15	Instructions (Possible failure to provide employees with the necessary workplace-specific instructions)	0.5	0.5	1	0.25
16	Part with dangerous surfaces (corners, sharp points)	3	2	40	240

9.2. Risk Assessment for AR technology

Technical Risks

- Equipment Malfunctions: AR devices, such as smart glasses or headsets, may experience technical failures or malfunctions, impacting workers' ability to access real-time information or navigate through the AR interface. Regular maintenance, software updates, and adherence to manufacturer guidelines are crucial for minimizing these risks.
- Data Accuracy and Reliability: The accuracy and reliability of the information presented through AR interfaces are critical. Inaccurate or outdated information may lead to errors in maintenance tasks. Ensuring data integrity, validation processes, and implementing quality control measures contribute to risk reduction.

Safety Risks

- Impaired Vision and Auditory Cues: The use of AR devices may restrict workers' peripheral vision or hinder their ability to hear auditory cues in the railway environment, potentially

leading to accidents or hazards going unnoticed. Implementing safety protocols, providing clear visibility guidelines, and incorporating audio alerts can mitigate these risks.
- Distractions and Reduced Focus: The introduction of AR technology may divert workers' attention or reduce their focus on essential safety procedures or environmental hazards. Developing training programs, establishing clear guidelines, and fostering a culture of mindfulness can help address these risks.

Cognitive and Psychological Risks

- Increased Cognitive Load: AR interfaces may impose additional cognitive demands on workers, potentially leading to increased mental workload, distractions, or information overload. Providing comprehensive training, incorporating user-friendly interfaces, and optimizing the presentation of information can help mitigate cognitive risks.
- Psychological Impact: The use of AR technology may have psychological implications, such as increased stress, decreased job satisfaction, or anxiety related to technology adoption. Providing adequate psychological support, promoting a positive work environment, and facilitating user feedback can help address these risks.

Environmental Risks

- Impaired Spatial Awareness: AR interfaces may interfere with workers' perception of their physical surroundings, leading to a reduced awareness of environmental hazards or obstacles. Comprehensive training, establishing clear safety zones, and maintaining situational awareness protocols are essential for mitigating these risks.
- Compatibility with Safety Equipment: The integration of AR devices with existing safety equipment, such as personal protective gear or communication devices, may present challenges. Ensuring compatibility, conducting risk assessments, and modifying equipment accordingly contribute to risk reduction.

Training and Education

- Insufficient Training: Inadequate training on the proper use, navigation, and interpretation of AR interfaces may lead to errors or misuse. Implementing comprehensive training programs, incorporating practical exercises, and providing ongoing support are critical for minimizing these risks.
- User Competency: Workers must possess the necessary competence to interact with AR interfaces effectively and safely in railway maintenance tasks. Evaluating user competency,

providing refresher training, and addressing skill gaps through targeted programs contribute to risk reduction.

Regulatory Compliance and Standards

- Compliance with Railway Safety Regulations: Adhering to railway safety regulations and standards is crucial when implementing AR technology in railway maintenance tasks. Collaborating with regulatory bodies, conducting regular audits, and implementing necessary modifications contribute to compliance and risk mitigation.

Data Security and Privacy

- Privacy and Data Protection: AR technology may involve the collection and processing of sensitive data, potentially compromising worker privacy. Implementing robust data protection measures, user consent protocols, and compliance with privacy regulations are essential for mitigating data security risks.

Risico nr	Risk	Probability	Exposure	Consequence		Total Risk score
1	Increased risk of tripping/falling incidents when moving due to reduced visibility	3	2	7		42
2	Increased risk of collision/being in an active danger zone due to reduced visibility	0.2	0.5	40		4
3	The user has less or no hearing for the environment/signals of safety personnel due to the speakers/sound system emitted by the device	1	2	15		30
4	Neck muscles are strained by prolonged use of AR Device.	1	2	7		14
5	Hearing damage due to nearby loud equipment/work	1	2	15		30
6	Rail safety- personnel are unable to perform their primary duties due to distractions while operating the AR-device.	0.5	2	15		15
7	Personnel using the AR-device have limited sensory perception of the work location and therefore run the risk of not being alert to a variety of occupational health and safety risks	1	2	15		30
7	Damage to the AR-device from dropping, impact or neglect	3	2	3		18
8	Damage to AR-device due to water intrusion	3	2	3		18
9	compatibility of safety equipment and personal protective equipment cannot be guaranteed.	3	2	3		18
`10	Insufficient observation of unsafe situations, with elements under voltage as an example	1	2	40		80
11	Safety instructions cannot be properly received/understood using the AR-device	6	2	15		180
12	Reception and aftercare in case of calamities/accidents when using the an AR-device	0.2	0.5	15		1.5
13	Operating installations and machines	3	2	40		240

9.3. Ethical considerations for the development of the project

In addition to the ethical considerations for the development of the technology itself, for the development of the project there is a need to involve potential workers from the beginning. This involvement enriches considerably the focus on the acceptability of the technology on the final real users. To that end, we have identified two main points during the project where workers involvement is essential. First, in the evaluation of the workplace by delivering questionnaires to gather specifications from workers. This was already explained in Section 8. Ethics committee approval was requested for this action, and data privacy was properly managed and guaranteed. Another critical point of action will be after M34 of the project were validation and demonstration of the technology in TRL6 will be performed. This implies the need of workers to validate the technology. Again, appropriate ethics committee approval, informed consents and coordination with end-user companies' safety departments will be seek. Testing protocols will be developed to guarantee worker safety. Finally, it is worth to mention that an External Ethics Advisor will be contracted to look out for the proper execution of all actions carried out on WP19 from an ethical perspective.

9.4. Conclusion

A thorough risk analysis is essential for the successful implementation of exoskeletons and AR technology in railway maintenance tasks. By identifying and evaluating potential risks related to physical safety, equipment reliability, cognitive factors, environmental considerations, training, and compliance, the list of specifications and requirements can feed with very relevant information. Continuous monitoring, feedback mechanisms, and ongoing risk assessments are necessary to adapt to changing circumstances, improve safety measures, and ensure the responsible and beneficial integration of exoskeleton and AR technology in railway maintenance tasks.

10. Specifications and Requirements

10.1. Exoskeletons in railways maintenance operations

Workplace evaluations yielded to a UC description for the application of exoskeleton technology in railways maintenance. Questionnaires and state-of-the-art also poses several functional requirements to build a successful and proper system. Risk analysis carried out also points out many critical issues that must be tackled from early design.

Main potential tasks for exoskeleton support have been selected to be above shoulder operations. Thus, the focus will be on the development of an upper-limb exoskeleton for above shoulder operations that also meet the following general requirements:

- GSR1: The exoskeleton must be compatible with other protective outfit used in the use case scenarios.
- GSR2: The target weight for the exoskeleton will be of 1.5 kg maximum (only considering the passive system). Dangerous surfaces must be avoided (corners, sharp points).
- GSR3: The exoskeleton needs to be easy to put on and off. Easy and safe emergency put off should be considered.

- GSR4: A very ergonomic design is needed to allow worker comfort for a full shift.
- GSR5: Hybrid exoskeleton. Active modules should be designed to provide extra assistance only on demanding tasks.
- GSR6: Proper detection of user intention is necessary (for the active system).
- GSR7: Nonconductive materials or other protection means need to be included in the first stages of design.
- GSR8: Minimal temperature range should be between -10ºC and 30ºC.

10.2. AR-based support tools for maintenance in railways

10.2.1. Hardware Requirements

The solutions developed should provide the following benefits:

- Enable training of operators using virtual reality or mixed reality.
- Support and guide operators through complex maintenance operations such as assembly/disassembly of components.
- Enable the interaction with IoT devices and other automated systems (e.g., the exoskeletons above), providing for a flexible interface.
- Enable support by experts using bidirectional audio and video communication.

These objectives must be supported by the devices supporting the applications. As described in the state of the art we can identify three main families of XR devices:

- Virtual Reality headsets such as the Meta Quest or HTC Vive families, provide support for VR applications and in some cases limited Mixed Reality capabilities. For this function, the headsets project the user a video stream captured from on-device sensors (video through). The quality of this stream is however not suitable for extended usage. This mode is typically only used for security. Once the user steps out of the designated safe space the device automatically exits VR-mode and allows the users to see their environment.
- Augmented reality headsets and glasses present the user a small screen where additional information can be seen. This information is however not integrated into the environment. The screens are also small and require one eye to focus on an image very close to it. This makes its usage uncomfortable.
- Mixed reality headsets integrate virtual contents into the real world, enabling for example objects to be fixed in a local spatial position. There are two different approaches to this. 1) Some devices (Microsoft HoloLens 2 and use transparent screens and laser guides to generate virtual images between the eyes and the real world. 2) Other devices use an

approach similar to the one used in VR headsets: cameras capture the environment and present it to the user through a screen including the virtual environments.

The devices used for evaluation of XR technologies in IAM4RAIL need to fulfil the following technical and usability requirements for hardware:

- HR1. Avoid eye strain and suitable for continuous extended periods of use (above 1h).
- HR2. Compatible with prescription glasses required by operators.
- HR3. Battery-life should enable completing relatively complex tasks (above 1h).
- HR4. The device should be lightweight and with good ergonomics.
- HR5. The devices should provide means for intercommunication applications with other devices.
- HR6. The device should minimize the risk of nausea by providing either direct view of the exterior or low latency in both headset positioning and graphics.
- HR7. To avoid hardware lock-in the devices must support open programming frameworks such as OpenXR.

If we take requisite HR1 into account, we can discard most pure augmented reality devices. As mentioned above, these devices present a small screen close to the eye which can lead to sever strain specially for older workers.

In the case of some Mixed Reality devices such as the Magic Leap, it is uncomfortable to wear the headset with prescription glasses (HR2).

These requirements lead to Microsoft's HoloLens 2 as the only device that meets all the technical requirements proposed at the time of writing this document.

10.2.2. Software Requirements for Mixed Reality support applications

The development of mixed reality applications to support railway workers during maintenance operations opens a series of questions:

- How do we generate the contents (sequence of steps, images, 3d models, etc.) for the assistance/training tools?
- How do we capture reality do that it can used to assist during the process?
- How do we structure a procedure to present it to the operator?
- How much information do we present? If we present too much information the operator can feel overwhelmed and if we present too few information, he can feel lost.
- How do we improve the acceptance of XR technologies in this context?
- How do we capture information (esp. vision) while respecting the privacy of the workers?

These questions lead to a series of general requirements for the development of software:

- GSR1: The software must be able to extract as much information as possible from existing sources of data such as 3D CAD models of the structures to be maintained.
- GSR2: The software must be able to capture relevant information from reality using specific sensors.
- GSR3: The software must be able to organize a work order into an equivalent "Digital Work Order" that includes additional tasks and activities relevant to a digitalizes activity that where not possible with traditional approaches (such as using the device to run an automated inspection of the results of a maintenance operation).
- GSR4: The software must be able to adapt the amount of information presented to various types of operators from new employees that require extensive training to more experienced workers that only need support in specific points.
- GSR5: Operators and other stakeholders need to be involved during the decision process that will fix the actions and functionality of the software. It is also important that they are trained to understand the capabilities and limitations of the technologies involved as to be able to understand what is possible and what not with current devices.
- GSR6: The operator needs to be aware of what kind of information is being captured, what is its purpose and be able to control it.

11. Conclusions

This deliverable aimed to analyse the general specifications and requirements to develop exoskeleton and augmented reality technology to assist workers in railways maintenance operations. This analysis will be the starting point for task T19.2 aimed at developing a concept design of a novel exoskeleton and the architecture for AR tools and systems, and a roadmap in general for all WP19 tasks.

First, the state of the art for both technologies has been reviewed in detail. With existing art in mind, several potential workplaces have been identified and analysed among WP19 partners (STRUKTON, MERMEC, PKP, FSI). This evaluation has yielded to the definition of two use cases covering the needs of multiple maintenance operations. Future developments of WP19 will be tested, validated, and demonstrated on these use cases showcasing the potential application of these technologies and the innovativeness of the solutions to be developed within this WP19.

Besides this workplace evaluation process, questionnaires have also been delivered to potential users and managers of the technology, and a preliminary risk and hazard analysis has been carried out, with the objective of better approaching to the definitive specifications and requirements list. Ethical considerations to the application of the technology and development of the project have also been considered from the beginning.

While the conclusion of the deliverable is the specifications and requirements list shown in Section 10, the knowledge acquired, and discussions held when developing the deliverable are of utmost importance for the design and development phases that follow this study. Overall, the list of specifications and requirements points out the right directions, but it is still a live document that will be improved with further inputs from all partners as the project evolves and thus it has to be considered as the minimum list of requirements that the technology to be developed has to cover.

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13. Appendice I

IAM4RAIL – WP19

QUESTIONNAIRE ABOUT PERCEPTION, REQUIREMENTS AND ASSESSMENT OF FUNCTIONALITIES DEMANDED BY THE IAM4RAIL AUGMENTED REALITY TOOLS

The aim of the IAM4RAIL European project is the development of novel Augmented Reality technology to support workers in their daily railway maintenance tasks. This work is carried out in WorkPackage 19 (WP19).

Certain construction and maintenance operations can be of high complexity mainly for unskilled or new workers. The project aims to develop smart assistive tools, based on Augmented Reality Technology, to provide assistance to workers and reduce task complexity and errors.

To develop the new Augmented Reality Tools, it is essential to understand and take into account the demands and needs of the potential users of the system to be developed. For this, this small questionnaire has been prepared to collect key information for the initial development of the tools.

It is a simple questionnaire that will not take you more than 10 minutes.

The answers to this questionnaire are totally anonymous and will be treated in an aggregated way. No identifying information will be linked to your responses. The data collected will only be used as information of interest for the development of design requirements that the Augmented Reality tools to be developed must meet.

Your participation in this study is voluntary, and you may choose to withdraw at any time without any consequences or the need to provide an explanation. Once you have started the questionnaire you can decide to stop it and resume from the point of interruption at any time.

All the information collected will be used exclusively for scientific research purposes by the Research Centre leader of the WP19 CEIT (Paseo Manuel Lardizábal 15, 20018 Donostia, Spain), and the EU-funded project IAM4RAIL. The responsible researcher of CEIT and WP19 leader is Dr. Iñaki Díaz (idiaz@ceit.es). The data collected within the framework of this survey will be stored securely and confidentially in digital form on a medium in the possession of CEIT. It will be destroyed within 5 years of termination of the project. The data are protected by statistical secrecy and therefore cannot be communicated or externalised except in aggregate form, so that no individual reference can be made to it and can only be used for statistical purposes. The data will be processed in compliance with the General Data Protection Regulation 2016/679 (GDPR) which is fully applicable in all EU Member States as of 25 May 2018.

By clicking the 'Next' button, I confirm that:

- I have read the information provided above and fully understand the purpose of this research and my involvement in it.
- I voluntarily agree to participate in this study.
- I understand that I can withdraw from the study at any time without giving any reason.
- I have read and understood the information provided above regarding data privacy and GDPR compliance.
- I agree to the collection, storage, and use of my personal data in accordance with the information provided.

Thank you very much in advance for your collaboration since your answers will be of great help to us.

  - **Next**

Q.1 ¿What is your Age?

____

Q.2 ¿To which gender do you most identify?

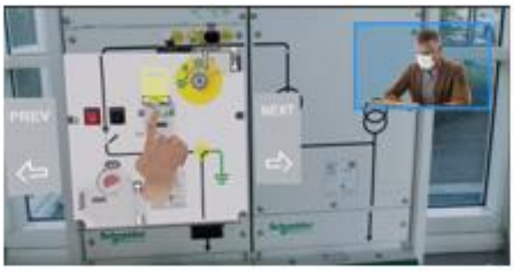
1. Male
2. Female
3. Non-binary
4. Prefer not to answer

____

Now we are going to briefly show you some illustrative images about some AR devices and tools that could be used and developed so that you can get a little idea and reflect on it in the questions that we will ask you next; There could be images of existing AR tools, but we do not intend to make a copy of them, but to develop new tools and systems that exceed the benefits of the existing ones, taking into account all your contributions.

- <u>**Augmented Reality Wearables**</u>

- <u>**Augmented Reality Info**</u>



After showing you some images of what an AR system could look like, we would like you to assess how interesting the possible functionalities are for you in relation to different types of service and tasks.

Q5. From this list of functionalities that the AR tool could have and thinking about the different tasks that you perform, indicate the degree of usefulness that each of them would have.

	Not Useful - 1 -	Slightly Useful - 2 -	Useful - 3 -	Very Useful - 4 -	Necessary - 5 -
Provide specific operating and maintenance step-by-step instructions	☐	☐	☐	☐	☐
See general information of an object whenever it enters the Field of View	☐	☐	☐	☐	☐
Have access to and visualize in real-time a database containing e.g. manuals, schematics, datasheets, historical maintenance orders/reports... of an object	☐	☐	☐	☐	☐
See live data of an object whenever it enters the Field of View	☐	☐	☐	☐	☐
Allow remote communication with an expert center that will give real-time tele-assistance	☐	☐	☐	☐	☐
Provide a list of checks required before declaring a task completed	☐	☐	☐	☐	☐
Automatically create maintenance operation reports whenever a task is completed	☐	☐	☐	☐	☐

Q.6. Determining which device is more suitable for our case can be challenging. Therefore, knowing a little bit more about the work you intend to perform while using the AR tool can help us find a fitting option.

	Never - 1 -	Sometimes - 2 -	Often - 3 -	Usually - 4 -	Always - 5 -
Both hands are required to perform the task	☐	☐	☐	☐	☐
The location of the maintenance is outdoors	☐	☐	☐	☐	☐
The location of the maintenance is remote (no internet access)	☐	☐	☐	☐	☐
The environment is wet or hot or extreme (storms, dust, more than 30ºC, less than 0ºC...)	☐	☐	☐	☐	☐
The task involves liquids	☐	☐	☐	☐	☐
The operation requires gloves	☐	☐	☐	☐	☐
The operation requires a helmet	☐	☐	☐	☐	☐
The operation requires protection glasses	☐	☐	☐	☐	☐
Markers such as QR could be placed on objects	☐	☐	☐	☐	☐
CAD of the objects to maintain are fully available	☐	☐	☐	☐	☐

Q.7. However, it is also interesting to know what you prefer. Would you prefer using AR glasses or smartphones/tablets? Glasses tend to be less comfortable, but they allow hands free operations. Indicate your opinion on a scale of 0 to 10 where 0 is I totally prefer using glasses and 10 is I prefer using mobile phone/tablets.

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Glassess										Phone/Tablet

Q.8. Finally, to what extent do you think that the use of an AR tool would be useful for your work? Indicate your opinion on a scale of 0 to 10 where 0 is not helpful at all and 10 is totally helpful.

0	1	2	3	4	5	6	7	8	9	10
☐ Not helpful	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐ Totally helpful

We have finished. Thank you very much for your collaboration.

14. Appendice II

IAM4RAIL – WP19

QUESTIONNAIRE ABOUT PERCEPTION, REQUIREMENTS AND ASSESSMENT OF FUNCTIONALITIES DEMANDED BY THE IM4RAIL EXOSKELETON

The aim of the IAM4RAIL European project is the development of novel exoskeleton technology to support workers in their daily railway maintenance tasks. This work is carried out in WorkPackage 19 (WP19).

Construction and maintenance are strongly based on human work. Workers' effort on joints/muscles in prolonged tasks can result in musculoskeletal disorders. Many commercial passive exoskeletons for logistics and assembly are available. However, existing systems are only conceived for very "clean" environments and specific tasks.

IM4RAIL aims to develop a novel upper-limb exoskeleton to provide physical assistance to workers when working in non-ergonomic postures, mainly above shoulder.

To develop the exoskeleton prototype, it is essential to understand and take into account the demands and needs of the potential users of the exoskeleton to be developed. For this, this small questionnaire has been prepared to collect key information for the initial development of the exoskeleton.

It is a simple questionnaire that will not take you more than 10 minutes.

The answers to this questionnaire are completely anonymous and will be treated in an aggregated way. No identifying information will be linked to your responses. The data collected will only be used as information of interest for the development of design requirements that the exoskeleton to be developed must meet.

Your participation in this study is voluntary, and you may choose to withdraw at any time without any consequences or the need to provide an explanation. Once you have started the questionnaire you can decide to stop it and resume from the point of interruption at any time.

All the information collected will be used exclusively for scientific research purposes by the Research Centre leader of the WP19 CEIT (Paseo Manuel Lardizábal 15, 20018 Donostia, Spain), and the EU-funded project IAM4RAIL. The responsible researcher of CEIT and WP19 leader is Dr. Iñaki Díaz (idiaz@ceit.es). The data collected within the framework of this survey will be stored securely and confidentially in digital form on a medium in the possession of CEIT. It will be destroyed within 5 years of termination of the project. The data are protected by statistical secrecy and therefore cannot be communicated or externalised except in aggregate form, so that no individual reference can be made to it and can only be used for statistical purposes. The data will be processed in compliance with the General Data Protection Regulation 2016/679 (GDPR) which is fully applicable in all EU Member States as of 25 May 2018.

By clicking the 'Next' button, I confirm that:

- I have read the information provided above and fully understand the purpose of this research and my involvement in it.
- I voluntarily agree to participate in this study.
- I understand that I can withdraw from the study at any time without giving any reason.
- I have read and understood the information provided above regarding data privacy and GDPR compliance.
- I agree to the collection, storage, and use of my personal data in accordance with the information provided.

Thank you very much in advance for your collaboration since your answers will be of great help to us.

- ○ **Next**

Q.1 ¿What is your Age?

____

Q.2 ¿To which gender do you most identify?

1. Male
2. Female
3. Non-binary
4. Prefer not to answer

____

Now we are going to briefly show you some illustrative images about the exoskeleton that is going to be developed so that you can get a little idea and reflect on it in the questions that we will ask you next; They are images of existing exoskeletons for industry, but we do not intend to make a copy of them, but to develop a new model of exoskeleton that exceeds the benefits of the existing ones, taking into account all your contributions.

- <u>**Passive exoskeletons for above shoulder operations**</u>

- <u>**Passive exoskeletons for load lifting**</u>

After showing you some images of what the exoskeleton would look like, we would like you to assess how interesting the possible exoskeleton functionalities are for you in relation to different types of service and tasks.

Q3. From the list of functions that the exoskeleton can have and thinking about the different tasks that you can perform in the field, indicate the degree of usefulness that you have for having the help of the exoskeleton for each of them.

	Not Useful -1-	Slightly Useful -2-	Useful -3-	Very Useful -4-	Necessary -5-
Assist me transporting heavy goods					
Assist me working on above shoulders postures					
Assist me to reduce the weight of the equipment					
Reduce fatigue by repetitive tasks					
Possibility to add another protective outfit integrated in the exoskeleton					
Possibility of integrating auxiliary working tools (communications, small equipment, maintenance equipment)					
Possibility of integrating physiological sensors to monitor my health and ergonomics					
Possibility of integrating sensors to identify hazardous environments (gas, temperature, etc.)					
Possibility of correcting a posture to be ergonomic					
Robust but light structure, lightweight					
Reduce vibrations transmitted during manual handling of tools					
Take up little space when not in use					

Q4.

	< 0.5 kg	0.5 – 1 kg	1 – 1.5 kg	1.5 – 2 kg	> 2 kg
In your opinion, how much should be the maximum weight of the exoskeleton?					

Q5. Finally, to what extent do you think that the use of the exoskeleton to be developed could be useful for your work? Indicate your opinion on a scale of 0 to 10 where 0 is not helpful at all and 10 is totally helpful.

0 Not helpful at all	1	2	3	4	5	6	7	8	9	10 Totally helpful

We have finished. Thank you very much for your collaboration.

15. Appendice III

Universidad de Navarra

Comité de Ética de la Investigación

Dña. MARÍA DEL CARMEN BERASAIN LASARTE, Secretaria Técnica del Comité de Ética de la Investigación de la Universidad de Navarra,

CERTIFICA: Que, en la sesión ordinaria celebrada el día 27/04/2023, el Comité examinó los aspectos éticos del proyecto **2023.075,** presentado por el **Dr. IÑAKI DÍAZ GARMENDIA** como Investigador Principal, titulado:

HOLISTIC AND INTEGRATED ASSET MANAGEMENT FOR EUROPE'S RAIL SYSTEM (IAM4RAIL). W19

Se emitió un informe favorable para la realización de dicho proyecto, dado que el Comité ha considerado que se ajusta a las normas éticas esenciales y a los criterios deontológicos que rigen en este centro.

Y para que así conste, expide el presente certificado en Pamplona, a 28 de abril de 2023.

Dña. MARÍA DEL CARMEN BERASAIN LASARTE

Secretaria Técnica

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