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“We are proud to announce the publication of the book “SUN:Social and hUman ceNtered XR - A Horizon Europe Project Paving the Way for the Widespread Adoption of Extended and Virtual Worlds” which provides an overview of the results achieved in terms of research and innovation.”

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Final consideration on the SUN project

We are at the end of the inspiring and ambitious journey of the EU-funded SUN (Social and hUman ceNtered XR) project. The main aim of SUN was to investigate and develop XR solutions that integrate the physical and the virtual world in a convincing and effective way, offering new opportunities for social and human interaction.

SUN identified key limitations hindering the practical adoption of XR and addressed them through a multidisciplinary approach, where research and development were conducted synergistically across several complementary domains.

SUN explored and developed innovative approaches to reconstructing, streaming, and enriching visual content for XR. These advancements include artificial intelligence-based scalable methods for generating and improving 3D environments, objects, and avatars; high-performance solutions for interactive streaming in XR; and the application of artificial intelligence to analyse and enrich 3D assets.

SUN investigated advanced solutions for collaborating and interacting in XR. The project introduced novel techniques for delivering thermal feedback to users, alongside innovative we-

arable haptic devices that enable more natural manipulation of virtual objects. Additionally, the project developed systems that support collaborative interaction among multiple users within a shared XR session.

SUN also explored and experimented with novel paradigms for capturing user input and feedback. Specifically, it proposed and demonstrated the use of electromyography to infer user movement intentions, alongside sensor and computer vision-based techniques for postural assessment and pose estimation. These efforts were complemented by solutions for hand gesture recognition and user emotion detection.

The components and solutions developed within SUN were integrated into the SUN Integrated Platform, an innovative technological framework designed to support the sustainable and secure development of XR applications. The platform incorporates solutions based on non-fungible tokens for managing XR assets, along with advanced techniques for detecting cyber threats in XR applications.

SUN also addressed the sustainability of XR solutions by investigating viable business models and examining the legal, ethical, and societal dimensions of XR. This includes exploring the implications of processing personal and sensitive data collected through wearable devices, 3D acquisition technologies, and human-machine interaction systems.

Over the course of its three-year duration, the SUN project validated its technologies through real-world case studies focused on key application areas: XR for rehabilitation, XR for workplace safety and social interaction, and XR solutions designed to support individuals with mobility and verbal communication impairments. Validation activities were conducted at three distinct sites: the Rehabilitation Unit of Versilia Hospital in Lido di Camaiore (Italy), the shop floor of FACTOR in Valencia (Spain), and the Clinique Romande de Réadaptation of SUVA in Sion (Switzerland). In each case, the validation process actively involved real end-users, ensuring that the solutions were tested in authentic, practical contexts.

SUN has not only advanced the technological frontier of extended reality but has also demonstrated its tangible value in real-world contexts, paving the way for sustainable, ethical,

and human-centered XR solutions. By integrating multidisciplinary research with practical validation, SUN leaves behind a robust foundation for future innovation, collaboration, and adoption of XR technologies across Europe and beyond.

Giuseppe Amato
SUN Project Coordinator

We are proud to announce the publication of the book "SUN:- Social and hUman ceNtered XR - A Horizon Europe Project Paving the Way for the Widespread Adoption of Extended and Virtual Worlds" which provides an overview of the results achieved in terms of research and innovation.

These results were attained through a multidisciplinary approach and thanks to strong collaboration among all consortium members.

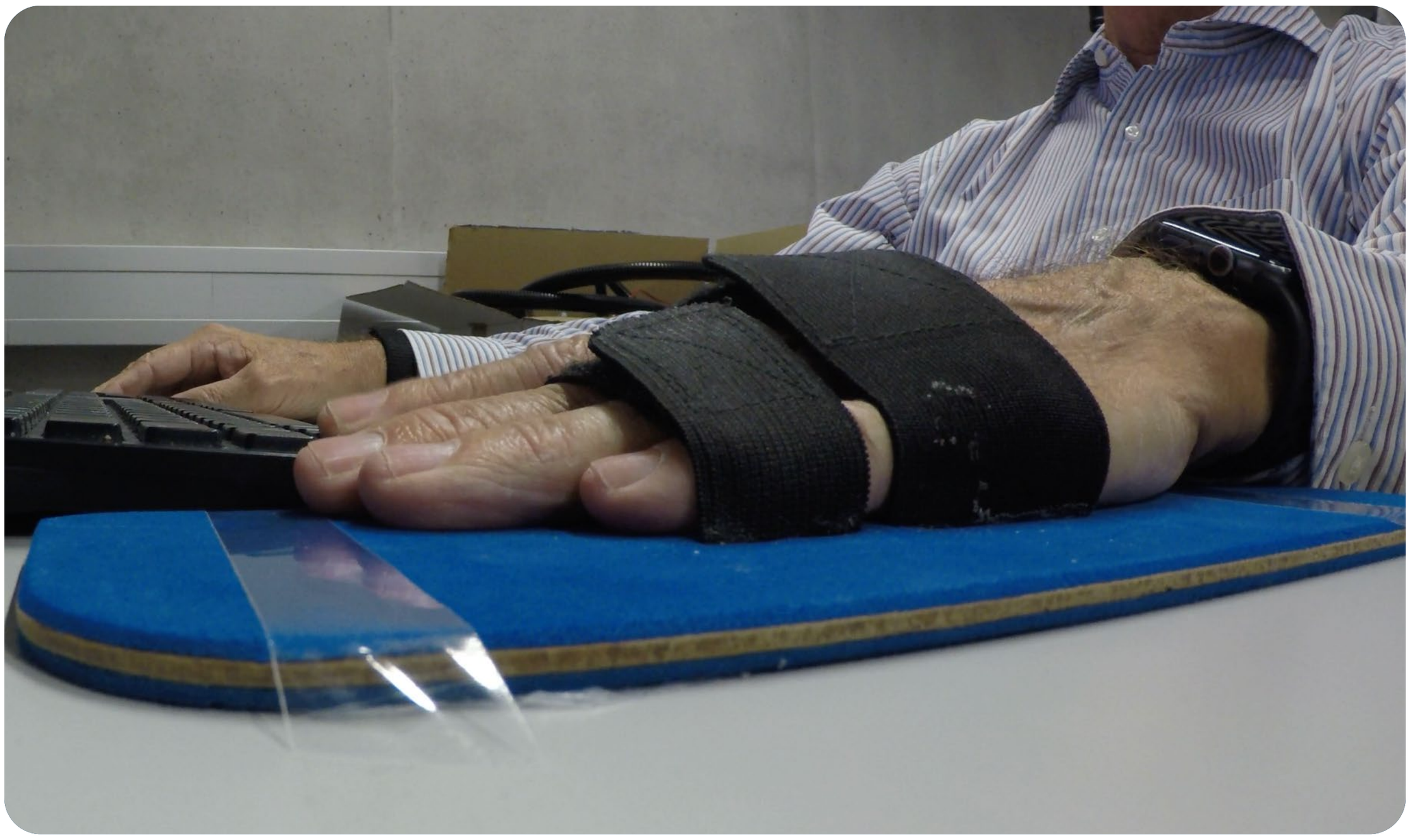
The following paragraphs summarize and preview the contents of the book, which is organized into three main sections: "SUN Technologies", "Human-Centered XR Scenarios and Real-World Case Studies", and "Sustainability, Ethics, and Impact".

Happy reading!

SUN TECHNOLOGIES

The "SUN Technologies" section presents XR as more than a display technology. It is a multisensory, intelligent ecosystem capable of perceiving and responding to users, supporting natural interactions, and upholding privacy and safety. These foundational technologies support subsequent human-centred applications discussed later in the book, setting the scene for XR's role in rehabilitation, workplace safety, and social inclusion.

The section starts with the essentials: the creation and refinement of high-quality 3D content. Through scalable methods for generating, reconstructing, enriching, and streaming assets, SUN enables the development of digital worlds that feel authentic. AI-driven 3D object reconstruction rapidly converts raw scans into semantically rich models, making re-



al-time interaction possible across a wide spectrum, from handheld objects to complex environments. This approach ensures XR scenes mirror both physical and perceptual nuances of the real world.

A significant advancement is the automatic production of realistic avatars. SUN's pipeline transforms user videos into lifelike, animatable avatars within minutes, democratising personalised digital representation. Vision-based capture modules and multimodal pose estimation ensure avatars accurately mirror users' gestures and postures, turning them into social vehicles that convey identity and emotion. Avatars are central to communication, not just decorative elements.

The SUN project also pioneers autonomous systems for real-time digitisation of physical environments. These systems scan and map spaces like hospitals, homes or industrial zones, ensuring XR experiences are anchored in actual contexts. High-performance rendering architectures facilitate interactive streaming, adapting to hardware limitations and network conditions to keep even complex scenes fluid and responsive on headsets.

Beyond visual fidelity, SUN tackles the challenge of understanding and interpreting XR scenes. Using open-vocabulary object recognition and scene analysis, the system gives semantic meaning to 3D environments. This enables XR applications to adapt instructions, recognise user intent, and improve safety and decision-making, particularly in workplaces or clinical settings.

SUN advances multisensory interaction through wearable haptics devices that let users “feel” virtual objects, temperatures, and forces. Fingertip and wrist-worn actuators provide fine-grained, distributed feedback, restoring tangibility to virtual manipulation. Experiments with thermal feedback further enrich the sensory experience, aiming for XR where temperature cues enhance realism and convey critical information.

Collaboration is also central: gaze-based interaction and multi-user environments let people cohabitate, share perspectives, and cooperate within the same virtual scene. These developments shift XR from a solitary activity to a socially meaningful space, where communication and joint action are key. Extending this idea, XR is also used to support coordination in complex work settings, where immersive cues and intelligent task prioritisation can ease decision-making and reduce workload.

The technological suite extends into user perception and monitoring. SUN’s wearable and vision-based systems interpret users’ physiological and emotional states. Electromyography decodes hand and wrist movements for gesture control; postural modules track joint angles and movements, supporting rehabilitation and safety. Gesture recognition and affective computing allow XR to adapt dynamically adjusting difficulty, feedback, or support according to user fatigue, frustration, or confidence.

Holding these innovations together is the SUN Integrated Platform: an open, modular, and secure framework for XR application development and deployment. It manages data streaming, component integration, dynamic scene updates, and cybersecurity. Noteworthy is its tokenised asset management system, supporting persistence and traceability, and complementary cybersecurity functions that safeguard against threats, ensuring trustworthiness where safety is critical.

The unifying message is clear: XR’s future depends on understanding humans, responding to their needs, and making the virtual world accessible, empowering, and profoundly human.

HUMAN-CENTERED SCENARIOS & REAL-WORLD CASE STUDIES

The“Human-centered scenarios and real-world case studies” illustrate how XR technology finds true value when shaped around human needs, emotions, and social realities. This section moves beyond technical innovation, focusing on how XR transforms lives by being empathetic, safe, and inclusive.

The narrative begins with a foundational reflection on the need for humanity and ethics in XR design. SUN’s approach emphasizes safety (not just physical, but also emotional) and insists that users feel supported and respected. Empathy guides the design: avatars interact gently, feedback remains non-intrusive, and systems avoid overwhelming users. These principles set the ethical groundwork for the major pilot scenarios explored next.

The first case study spotlights a rehabilitation pilot in an Italian hospital. Here, XR technology reinvents therapeutic exercises for patients recovering from orthopedic injuries, neurological disorders, or cancer surgeries. Using head-mounted AR, patients interact with virtual objects and avatars, supported by haptic feedback that simulates touch. For example, upper limb rehab patients grasp virtual bottles and place them on shelves, while glove-based actuators reinforce the sense of movement. Sensors monitor joint angles and compensatory movements, allowing therapists to intervene or the system to offer real-time corrections.

Patient reactions highlight the transformative power of well-designed XR. Many reports increased motivation, fascination with avatars that mirror their movements, and a sense of fun that replaces the monotony of traditional rehab. Clinical results show tangible improvements, such as reduced swelling and improved range of motion. However, the narrative also acknowledges limitations: XR supports but does not replace therapists, and technical challenges like glove fit or gesture accuracy prompt ongoing refinement.

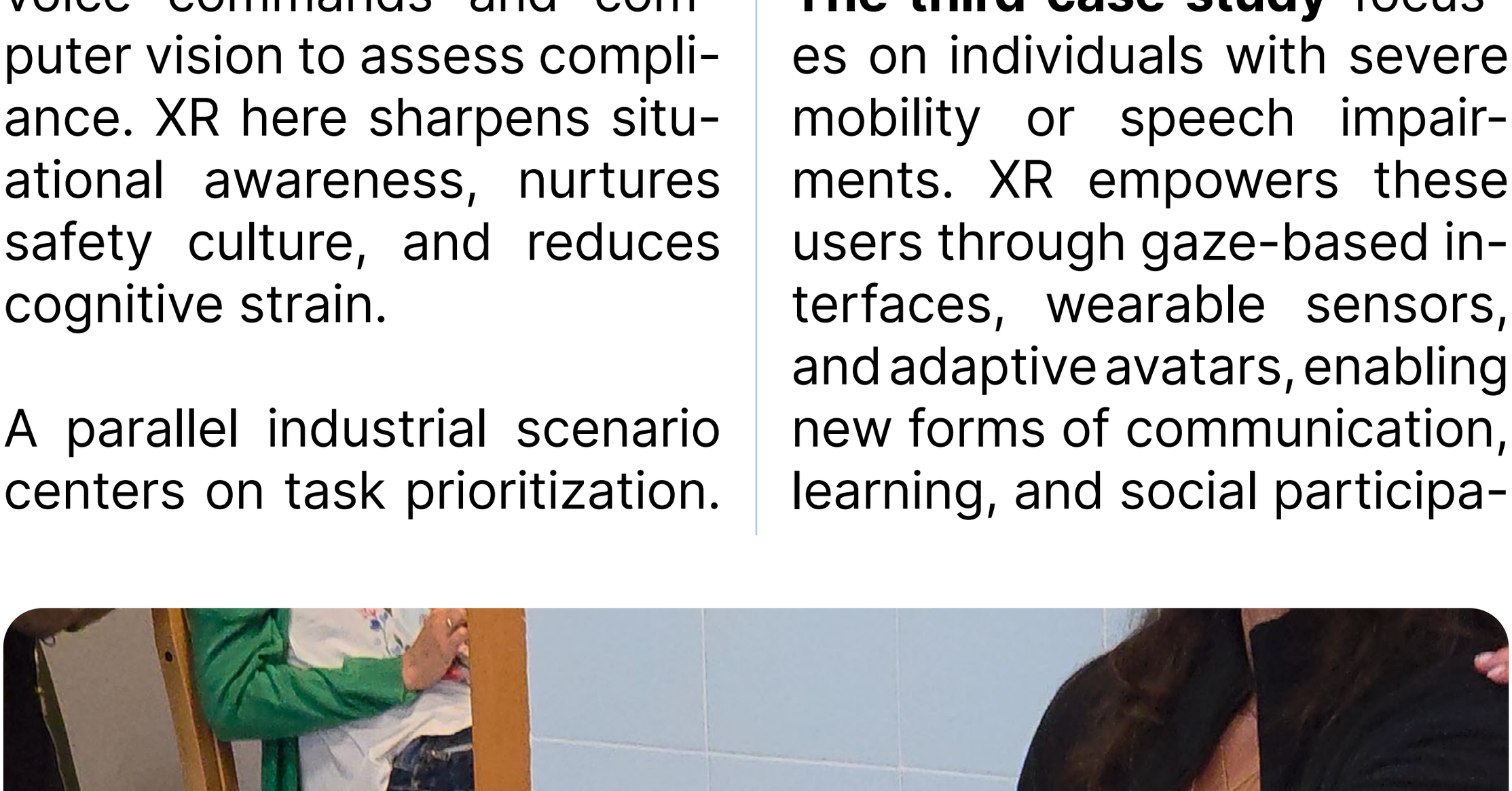
The lower limb rehabilitation scenario adds complexity, guiding patients through squats, knee extensions, and gait exercises. Wearable EMG sensors and inertial units track muscle activity and posture, while the system provides

feedback on alignment and joint angles. The narrative stresses the need for adaptable design: older or inexperienced patients benefited from careful onboarding and empathetic interfaces, demonstrating that XR is most effective as a supportive extension of clinical care.

The second case study shifts to an industrial setting in Spain, where XR enhances workplace safety and workflow coordination. In safety training, AR headsets deliver interactive modules on personal protective equipment, guided by avatars. In real-world use, workers tour the factory, using voice commands and computer vision to assess compliance. XR here sharpens situational awareness, nurtures safety culture, and reduces cognitive strain.

A parallel industrial scenario centers on task prioritization. XR systems monitor factory conditions, displaying dynamic task lists in workers' headsets. Gesture-based interaction allows workers to make decisions autonomously, while XR adapts task priorities as situations evolve. Feedback from workers reflects enthusiasm for practical guidance and improved coordination, though initial hesitancy over gesture recognition and new interfaces is addressed through iterative refinement. The key to success is deep integration with existing workflows, respect for worker autonomy, and transparent handling of data.

The third case study focuses on individuals with severe mobility or speech impairments. XR empowers these users through gaze-based interfaces, wearable sensors, and adaptive avatars, enabling new forms of communication, learning, and social participa-



tion. Traditional XR systems often exclude such users; SUN's approach, grounded in co-design and ethical sensitivity, transforms XR into a medium for agency and dignity.

Several cross-cutting themes emerge throughout the case studies. Co-design is crucial: therapists, patients, workers, caregivers, and individuals with disabilities actively participate in shaping technology. Barriers such as technical complexity, physical limitations, trust, or resistance are treated as vital feedback, guiding SUN's iterative adaptation and improvement.

In summary, the section underscores XR's true strength not in immersion alone, but in creating meaningful, personalized experiences. Whether it's helping a patient regain movement, supporting a worker in complex tasks, or giving a nonverbal user a voice, XR serves as a bridge between the physical and digital, between challenge and opportunity. The human-centered approach is clear: technology achieves its fullest potential when it is anchored in human values, developed collaboratively, and sensitive to real-world contexts.

SUSTAINABILITY, ETHICS AND IMPACT

The concluding section of the SUN Book move focus from technical innovations and pilot deployments to broader questions of sustainability, ethics, and impact in XR (Extended Reality) systems. Instead of viewing sustainability as a purely technical challenge, the narrative frames it as a dynamic, human-centered ecosystem that connects patients, workers, caregivers, institutions, and communities. To push XR beyond research phases, it must adapt to varied real-world settings and build trust through transparent governance. SUN's participatory approach involves end-users as long-term partners, promoting shared ownership of innovation rather than focusing solely on hardware longevity.

The SUN Integrated Platform stands at the center of this vision: an open, modular XR ecosystem integrating wearable sensors, AI-driven analytics, haptic devices, secure asset management, and cybersecurity tools. Rather than being a one-size-fits-all product, the platform is designed for flexibility enabling integrators, developers, and hardware providers to customize it for industry, healthcare, or assistive applications. SUN adopts an "open core" business model: essential components are freely accessible, encouraging community adoption and extension, while advanced modules offer commercial opportunities for professional services and industry deployment. This hybrid strategy supports sustainability by balancing community involvement with commercial viability, and the platform's validation across rehabilitation, industrial safety, and assistive technology showcases its adaptability and market relevance.

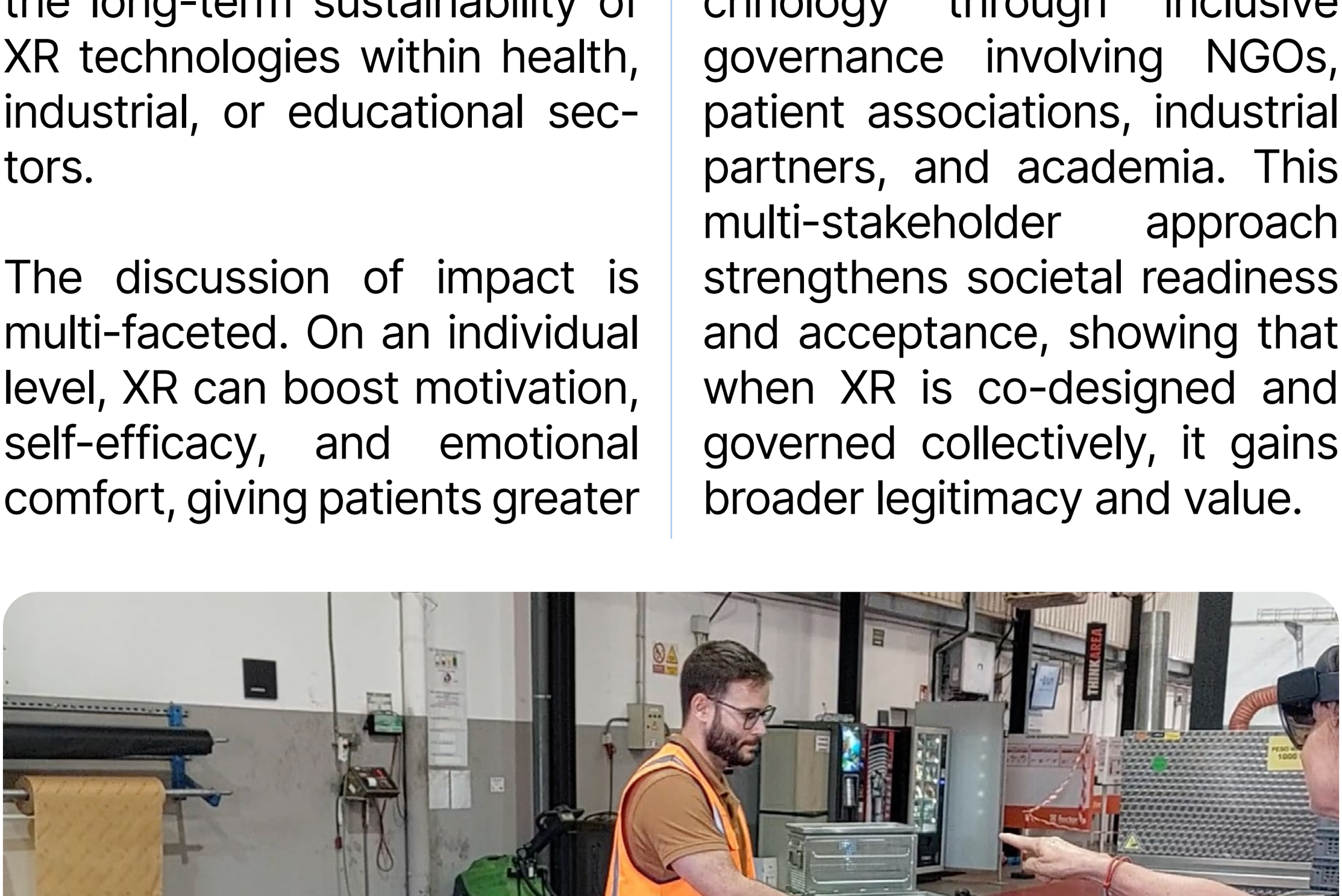
A significant portion of the narrative addresses ethical considerations. XR systems gather highly sensitive data, including movement, biometrics, emotional states, and environmental models. The book highlights the necessity of privacy-by-design, informed consent, and transparent AI, especially when engaging vulnerable users. Throughout real-world pilots, ethical questions are woven into the scenarios: XR should enhance autonomy in rehabilitation without becoming prescriptive; in industrial settings, it must avoid fostering surveillance; and for people with disabilities, it should empower rather than patronize. Striking a balance between assistance and autonomy is essential, as overwhelming feedback or excessive automation can undermine user trust and engagement. SUN's methodology emphasizes adaptive control,

letting users adjust feedback and interaction styles, reinforcing that respecting autonomy is both an ethical requirement and crucial for adoption.

Data protection and legal compliance are explored through the lens of GDPR and broader European regulations. Managing diverse data types, such as 3D scans and emotional analytics, while ensuring users retain control of their digital identity is a complex challenge. Legal rigor and ethics-by-design are presented as keys to building trust, institutional acceptance, and the long-term sustainability of XR technologies within health, industrial, or educational sectors.

The discussion of impact is multi-faceted. On an individual level, XR can boost motivation, self-efficacy, and emotional comfort, giving patients greater control in rehabilitation, supporting workers in their roles, and providing people with disabilities new avenues for communication and participation. At the organizational level, SUN helps hospitals adopt personalized rehabilitation tools, factories to strengthen safety cultures, and care institutions to foster autonomy and engagement. These transformations help integrate XR into lasting institutional practices.

From a societal perspective, SUN positions XR as a trustworthy and ethically grounded technology through inclusive governance involving NGOs, patient associations, industrial partners, and academia. This multi-stakeholder approach strengthens societal readiness and acceptance, showing that when XR is co-designed and governed collectively, it gains broader legitimacy and value.



A distinctive feature of SUN's impact assessment is its innovation monitoring methodology. Rather than focusing solely on technical metrics, SUN incorporates emotional, ergonomic, ethical, and usability factors into its evaluation framework. Continuous feedback, interviews, and iterative adjustments ensure that XR development remains closely aligned with users' real needs and lived experiences.

The section concludes with a forward-looking vision: SUN's ethical models, technological innovations, and human-centered, participatory governance provide a blueprint for the future of XR in Europe. The project envisions deeper integration with European digital infrastructures, evolving XR avatars into secure digital identities, and seamless blending of physical and digital environments. Ultimately, the long-term impact of XR, SUN argues, will be determined not by technology alone, but by its capacity to empower, respect, and resonate with the people it serves.

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