Human-Centered Intelligent Realities Laboratory

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Figure 1: The Human-Centered Intelligent Realities Laboratory.

Abstract

The "Human-Centered Intelligent Realities" (HINTS) laboratory is a strategic infrastructure project aiming to support research that advances the development of immersive, user-aware, and intelligent digital environments by integrating augmented reality (AR), virtual reality (VR), extended reality (XR), artificial intelligence (AI), and machine learning (ML). By combining virtual reality and communication-computing continuums, the HINTS environment seeks to create innovative concepts, methods, and tools that empower users to engage with digital systems in novel, efficient, and effective ways. Research in the HINTS laboratory focuses on experience assessment, new digital environments and interaction techniques, visual analytics, adaptive AI, and networking. This paper presents the HINTS laboratory, ongoing activities, and opportunities and challenges for the future.

Index Terms: Extended reality, artificial intelligence, intelligent reality, visualization, human-centered.

1 Introduction

Digitalization has become integral to everyday life, influencing how we work, communicate, and spend our leisure time. Over the past decade, technologies such as augmented reality (AR), virtual reality (VR), and mixed reality (MR), collectively referred to as extended reality (XR), have gained traction and become more accessible to a broader audience. Alongside this, there has been a growing focus on the potential of future immersive experiences. The shift toward remote work, driven by the pandemic and sustainability concerns, is expected to accelerate this trend further. The XR market alone was valued at USD 25.84 billion in 2020 and is projected to grow to USD 397.81 billion by 2026 [8]. Additionally, rapid advancements in artificial intelligence (AI) and machine learning (ML), powered by vast data sets, advanced hardware, and improved algorithms, are shaping the future of digital societies.

These developments and the increasing focus on the metaverse—a vision of a fully immersive, interconnected virtual world—are creating new possibilities for an enhanced digital environment. In this space, users engage in an alternative, persistent reality that can be personalized to their desires. The evolving relationship between human-computer interaction (HCI) and new immersive technologies is at the heart of this transformation, with AI playing an increasingly crucial role. Given the current advancements, it is clear that AI will be indispensable in shaping the future of digital, immersive environments. However, with AI comes challenges regarding ethics and privacy, which are fundamental topics in developing human-centred systems [6].

The concept of an *intelligent reality (IR)* has emerged in the last few years [7]. New conferences have emerged, such as the IEEE International Conference on Intelligent Reality (ICIR), first held in 2021, and Visualization Meets AI, which has run since 2020. Similarly, the integration of computer graphics with AI is rapidly gaining traction, exemplified by the 1st EUROGRAPHICS Workshop on Intelligent Graphics, organized in 2022. AI can enhance user experiences by enabling smarter, more personalized, human-centred decisions in future IRs.

At the heart of this evolution is still the human decision-maker. As a result, innovative interaction and visual analytics techniques in these contexts hold great promise for shaping and supporting the decision-making process. Moreover, this process is increasingly becoming bidirectional, where not only does the system learn from

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user trends and make predictions, but users also actively shape and guide the personalization of new, immersive interaction spaces. IRs are more intelligent and responsive to the user needs (e.g., *human-centered*), augmenting human intelligence through technology [7]. This could, for example, be via AR, VR, and MR, all under the umbrella term of XR.

The Human-Centered Intelligent Realities (HINTS) research profile [9] at Blekinge Institute of Technology (BTH) aims at developing novel *human-centered IRs*. The HINTS research profile has been linked to a new infrastructure laboratory where researchers, in collaboration with external partners, focus on developing concepts, principles, methods, algorithms, and tools for human-centered IRs to lead the way for future immersive, user-aware, and smart interactive digital environments. The HINTS project is centered around an ecosystem combining the paradigm of VR and communication and computing to form a new intelligent digital system. The HINTS laboratory (HINTS-lab) is used for research to enhance user interaction with digital realities, enabling more engaging, cognitive, and resource-efficient experiences in real and virtual spaces. Hence, immersive visualization laboratories (IVLs) are needed and this paper presents our initiative relating to this area.

2 The HINTS Laboratory

The HINTS-lab, shown in Fig. 1, is a strategic infrastructure initiative at BTH that aims to create a strong research and education environment in XR and AI. The laboratory is a shared, flexible, and creative space for research, education, and activities with industry and society. Expected synergies via the laboratory have already been seen as new funded project developments. Examples of activities in the laboratory are a collaborative education and research environment, targeted undergraduate and postgraduate courses, student projects, doctoral courses, industry training workshops, regional testbed initiatives, and demo rooms for open days and visits.

The HINTS-lab features a small collection of state-of-the-art books related to immersive environments, available for all staff and students as a more sustainable solution. In addition, it consists of two rooms: a prep room for flexible equipment storage and a main room with a spacious, adaptable surface designed for working with XR technologies, minimizing the risk of getting hurt by the surroundings. The main room has curtains to block distractions and adjust to varying lighting conditions that could impact recordings.

2.1 Hardware

In the HINTS-lab, there is diverse equipment for MR, VR, and AR experiences, with a strong focus on integrating eye-tracking technologies into various devices for enhanced user interaction and data collection. Examples of present MR Smartglasses include two setups of the HoloLens 2 and a Varjo X-3 (on loan from an external project partner). Examples of available VR headsets are Meta Quest 2, HTC VIVE (one with the HTC VIVE wireless adapter), HTC VIVE Pro Eye, Samsung Gear VR, and Oculus Rift DK2. Examples of VR headsets with incorporated eye tracking include the Tobii Pro VR Integration (based on HTC VIVE), FOVE Eye Tracking VR Headset, and HTC VIVE Pro Eye. Additional eye tracking equipment are three Tobii Eye Tracker 5, Tobii T60 Eye Tracker, two Tobii EyeX Eye Tracker, and two Tobii Pro X2-30 Eye Tracker. These devices are crucial for conducting experiments and research on user experience, cognitive interaction, and data-driven insights in both real and virtual environments, with a particular emphasis on how eye tracking can enhance the immersion and responsiveness of digital systems. In addition, the laboratory also has AR technology, including a Samsung Galaxy Tab S7, which shows digital 3D models overlayed on the real world.

During the COVID-19 pandemic, running user studies was challenging for all organizations working with people. In this process, the experimental protocol for running user studies was adjusted. The laboratory was equipped with Cleanbox technology for each experiment using MR/VR technology, CX1 (Cone A/Cone B), a cleaning technology used for HMD devices. Using this technology between each study participant, we want to reduce and minimize the risk of spreading disease.

In addition to HMDs, the HINTS-lab is equipped with various wearable sensors designed to record implicit responses from different parts of the body. These include the EMOTIV Epoc+ electroencephalogram (EEG) headset, which records brain activity in high resolution through 14 channels and two reference points, with electrodes positioned according to the international 10-20 system standard. Another notable sensor is the Shimmer3 GSR+, which measures Galvanic Skin Response (GSR) to track the skin's electrical conductance. Both wearable sensors provide information on implicit responses related to evaluation tasks, capturing reactions such as brain activity or the degree of emotional arousal induced by visual stimuli. Other sensor devices in the lab include different controllers for interaction, including hand gesture interaction.

The HINTS-lab compute environment consists of four nodes designed to emulate a high-end gaming setup from 2022, combining AMD and Intel CPUs alongside AMD and NVIDIA GPUs. The setup aims to include nodes from at least three different generations, updating every cycle with the latest technologies. Each node is equipped with 32GB RAM and 1TB NVME storage, with specific configurations including AMD Ryzen 9 5950X and 12th Gen Intel Core processors i9-12900K as well as Radeon RX 6900XT and RTX GeForce 3080Ti GPUs. The robust network features two 10GbE network interfaces per node, with high-speed connections to two different Dell PowerSwitch S4112T, each using a dedicated fiber connection to the core network. This allows network connectivity with two broken links and one broken switch. The environment also utilizes PiKVM for management, converting typical consumer hardware into features such as keyboard video mouse (KVM) control. Monitoring tools are in place for energy consumption and performance visualization. Concerning challenges, to name a few, we can refer to potential PiKVM and monitor integration issues and the need for improved external storage access and authentication services. The setup, in general, aims to provide a high-performance infrastructure for educational purposes.

2.2 Software

Examples of software are Tobii Pro Studio Software (for eye-tracking analysis) and the iMotions software platform for additional biometric research. The iMotions platform also includes the VR eye tracking module, which allows us to gather eye movement data when watching VR stimuli in HMDs.

The HINTS-lab is designed with flexibility and reusability in mind. Being controlled by metal as a service (MAAS), setting up the lab environment with a desired operating system and software relevant to studied scenarios within a few minutes is possible. Moreover, as the HINTS-lab accommodates various hardware resources, it allows users to access a variety of software in combination with different hardware sets while, for example, benchmarking the prototypes and/or ensuring delivering the same functionality regardless of the used hardware.

3 HINTS Laboratory Example Activities

Although the HINTS-lab is relatively newly developed, some initial examples of its use are highlighted below, along with some important lessons learned.

3.1 Eye Tracking PhD Course

In the HINTS-lab, a PhD course is run for students and staff interested in eye-tracking technology, analysis, and interaction. Eye tracking can identify a specific point in both space and time that is being looked at by an observer. The information can be used in real-time gaze-controlled applications. Recent eye-tracking innovations include alternative input modalities to provide an enhanced, more immersive user experience. In particular, gaze control has increasingly been used as an input modality in video games and XR applications. The PhD course introduces eye-tracking technology, analysis, and interaction. The theory covers key eye-tracking technology concepts, analysis, and case studies highlighting recent research. The course participants are introduced to human visual attention, eye movements, and eye-tracking technologies. The course includes a practical workshop in which eye-tracking technology and software are used to generate standard eye-tracking visualization techniques, such as gaze plots, heat maps, clusters, and areas of interest (AOIs). The PhD course is worth 3hp and has two individual assignments: (1) an Eye Tracking Workshop, 1.5 ECTS and (2) an Eye Tracking Project, 1.5 ECTS (both with a pass and fail grade). The project should be connected to a potentially relevant research topic and use eye-tracking technology and an experimental study to record participant eye movements for additional analysis. Lecturer staff have also taken the PhD course, involving additional members to be part of the research community. A positive outcome has led to one additional lecturing staff joining the PhD programme. The course has, so far, focused mainly on eye tracking for traditional interfaces like different-sized screens. Still, as the HINTS-lab has the eye-tracking VR module as part of the iMotions platform, we will continue to explore eye-tracking in immersive environments.

3.2 360 Degree Video for Healthcare Education

A case study of 360-degree video-based VR education for older adults' healthcare has been conducted in the lab. A health technology company in Malmö, Sweden, develops the VR application. This VR application aims to help care workers who care for older adults. The application uses the affordable Pico Neo 3 headset. By wearing the VR headset, caregivers experience everyday situations from the point of view of the people they care for, helping them better understand their challenges. In total, 12 participants were recruited in this specific case study in the laboratory in 2024. They are all nursing students from our university. The instructions were introduced in written and oral form when the participants arrived. The participants then signed the consent forms. Participants received a paper-based scenario description of older adult healthcare to read when it started. After reading it, the VR-based education program testing started. A pre-survey was conducted, which included age, gender, XR experience, and Simulator Sickness Questionnaire (SSQ) before the HMD was administered to the participants. The VR-based education includes five 360-degree videos with various simulation scenarios. Each scenario had two parts: the situation and the recommended way to handle it. After viewing the videos, more questionnaires were completed. Those include the User Experience Questionnaire (UEQ), System Usability Scale (SUS), SSQ, and several open questions. The open questions address the topics, including other educational methods, their preferred learning methods, their perspectives on VR-based videos in group training, and any additional feedback regarding the VR application. The study showed the positive results of VR-based education in nursing students, who felt motivated and found the technology helpful in understanding care situations. It believes that VR can serve as a valuable complement to traditional educational programs [5].

3.3 Student Thesis Projects

With the increase of XR applications, it is important to provide compelling user experiences (UX), for example, regarding interaction between virtual hands and digital objects to achieve realistic collisions. Tegelind [11] explored different methods (with and without collision) in MR using the HoloLens 2 and evaluated the UX and several task performance metrics. The UX was evaluated using the System Usability Scale (SUS), and the metrics gathered included the number of grabs and the time required to complete the task of knocking down balls from pillars in the scene. Experiments have been performed in [4] to test the impact of foveated rendering using the Meta Quest 2 headset by Tobii on a first-person shooter (FPS) game. The students developed a simple FPS game for their thesis to study if the foveated rendering impacted the user quality in fast-changing VR environments. The user study consisted of 23 participants who reported no noticeable degradation of quality (blurriness or eyestrain); see also their published conference paper [3]. Another master thesis project in computer science conducted in the HINTS-lab investigated different menu systems, interaction methods, and how users' sitting or standing postures affect their experience and motion sickness in VR applications [1]. An experiment was conducted with 20 participants. The results indicated that traditional top-down panel menus combined with motion controls offer the best user experience. Additionally, a sitting posture led to milder motion sickness symptoms than standing. A conference paper has also been published based on this thesis [2].

3.4 Ethical Vetting and Protocols

When working with human participants, it is crucial to consider ethical issues before conducting any experiments or user studies with people. In Sweden, the Ethical Review Act (2003:460) states that research should protect individuals and respect human dignity. The risks must always be balanced against the need for new knowledge gain. In research, all participants must be protected if there is any risk, be it physical, mental, or personal data privacy [10]. Hence, before running any studies requiring ethical vetting, the researchers in the laboratory conduct a self-assessment based on experience and, if needed, submit an ethics application to be evaluated by the Swedish Ethical Review Authority. If the research does not require ethical vetting, we follow general protocols and research ethics principles to mitigate potential issues and impact on humans. A good practice working with this process is that new researchers and PhD students can learn about experiment design and ethical guidelines from more experienced staff. We can also learn from previous ethics applications to improve future ones. Being active in this work is essential since new guidelines can occur. Over the last few years, the process and questions asked have changed in the questionnaires to fill in, including, for example, more questions about potential biometric data.

4 Future Developments

Below, we discuss areas for future developments in the HINTS-lab.

Immersive Analytics: The HINTS-lab aims to present advanced solutions for immersive analytics (IA) tasks. As immersive interfaces bring up more potential for interactive methods for humans to explore complex data and address data-driven tasks than conventional 2D display interfaces, the HINTS-lab can contribute to investigating the capabilities of immersive interfaces for various data visualization and analytical tasks. Additionally, collaborative intelligence between multiple users in complex data-driven tasks is a central scenario of future IA applications. Therefore, the HINTS-lab may contribute to proposing novel methods for collaborative IA applications. As AI has also been applied to a lot of data analytical tasks, with the capabilities of computing data and generating data-driven content, the HINTS-lab may explore hybrid intelligence between multiple users and AI agents in addressing IA tasks, in which AI agents are regarded as novel digital assistant for analytical tasks. Following these research directions, the HINTS-lab may support leveraging immersive spaces to enable humans to explore data better and gain insights efficiently.

Educational Applications: VR can transform the learning experience by providing immersive, interactive environments where learners can engage with environments in ways that traditional methods may not allow. As one of the largest laboratories in the university, the HINTS-lab provides a platform for immersive learning. It aims to develop and apply VR educational applications continuously. These applications will apply the advantages of VR, such as enhanced engagement, immersion, personalization, collaboration, and high access to different target learners. The applications could be used by students and university staff, including researchers, teachers, and administrators. One example we are exploring involves collaborating with the student office to design, develop, and test a 360-degree video-based VR educational program. This program aims to help staff gain a deeper understanding of various scenarios faced by students with disabilities.

Distributed and Meso-scale Scenarios – The HINTS-lab-in-a-Box: IRs are expected to become highly distributed systems comprising many users at different locations. However, testing such scenarios in traditional and single-location labs is challenging. These labs are restricted by their physical boundaries and access for specific user groups only. The scalability of future IR systems, however, might be formulated along independent architectural design dimensions such as a) the number of users, b) the nature and depth of immersion (such as pure consumption vs. interaction), c) the distance between users as well as of the distribution of computation along the device, edge, and cloud continuum. These requirements might individually but also mutually impact the capacity of IRs. Thus, they increase the design complexity of IRs. Theoretical methods might give principle insights. However, they can quickly fail when modeling relations with many constraints is required. Hence, a lab concept is needed that scales beyond a small scenario, i.e., which can address requirements on *meso-scale* (or "in-between" scales) that are not limited by the physical restrictions of traditional labs and which involve larger user groups. Hence, a suggested future development of the HINTS-lab is its miniaturization as a portable *HINTS-lab-in-a-box*. Such a box can be duplicated and shipped to various locations for experimentation. Hence, the lab-in-a-box concept permits investigating distances between users and introduces distance between computing elements. It also opens up the possibility of reaching out to user groups not typically available in static laboratory environments, such as hospitals or public security facilities, or users, such as police. A HINTS-lab-in-a-box lab may comprise novel networking technologies such as private 5G systems, reference applications, and reference assessment techniques (incl. assessment hardware). Finally, its ability to be portable permits the scaling of IR testing meso-scale environments, i.e., to scales not yet available in a single lab.

Need or Testing for Multi-user Scenario: The HINTS-lab-in-a-box aims to give users a real-time interaction experience that requires a high-performance network supported by advanced network technologies. Zero or ultra-low latency is crucial for multi-user networks to ensure real-time responsiveness. Additionally, high bandwidth is essential for smoothly transmitting high-resolution images and videos. Compared to single-user networks, synchronization between users is the most different characteristic, ensuring users can interact in a shared virtual environment in real time to deliver an immersive experience. Furthermore, security and privacy are critical requirements to protect data transmission and safeguard users' virtual identities and personal information from unauthorized access or disclosure. The system should be evaluated under varied network conditions (e.g., low bandwidth, high latency) and across different use-case scenarios (e.g., multi-user meetings, collaborative environments). Stress testing is necessary to simulate many concurrent users online to test the system's maximum load capacity. Finally, it requires participants' feedback on the interaction with the system, which is used to optimize system design and functions.

VR Pass-through and Spatial Computing Scenarios: In addition, the HINTS-lab can support the exploration and evaluation of immersive multimedia across the XR spectrum, which includes VR, AR, and MR. For example, it can explore applications such as a path-through VR system that visualizes the tracking zone to ensure the virtual world can be safely activated. Additionally, this system could make the virtual world transparent, allowing the real world to appear and enabling MR to bridge the gap between different realities. Future development in the HINTS-lab could focus on advancing spatial computing applications, particularly in enhancing the integration of XR with physical reality to create more seamless and intuitive interactions. It also opens the door for interactions within the XR landscape through hand gestures, eye tracking, and even facial expressions using spatial computing headsets such as the Apple Vision Pro. This enables the creation of experiences that were previously impossible.

5 Conclusions

Our paper has presented a new infrastructure investment, the HINTS-lab at BTH, as a space to work with novel research, education, and collaboration with society. This paper presented some of the hardware and software solutions available for working with novel human-centered IRs. Example research studies are given with highlights of master theses and a PhD course run in the HINTS-lab. We also describe some positive lessons learned that might be useful for others working with these technologies, in particular, how we work with ethical vetting and ethical and privacy guidelines. Finally, we have discussed areas for future developments in the HINTS-lab to share opportunities and challenges for the future.

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