ROADMAPPING EXTENDED REALITY

Fundamentals and Applications

Edited by
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Foreword

It is my honor to present this book about extended reality (XR) technologies and application areas. Extended reality is part of the Information and Communication Technology domain and includes virtual reality and mixed reality, the latter including augmented reality and augmented virtuality, as defined in the reality–virtuality continuum of Milgram and colleagues in 1994. In spite of its numerous already existing applications, XR has incredible societal potential; therefore, Europe must invest much more than it currently does. To this aim, bundling a vision about what the future of XR should be seemed a prerequisite.

The EuroXR Association was founded in 2010 as a continuation of the work in the European Union funded FP6 Network of Excellence INTUITION (2004–2008). It is an umbrella organization gathering not only individuals, but also national chapters and associations, large companies, small-to-medium enterprises (SMEs), as well as research institutions, universities, and laboratories. In November 2020, the EuroXR Association launched the XR Open Forum. This initiative aims to organize regular meetings with EuroXR members, but is also widely open to external experts, to brainstorm on the new actions that our association could lead on, with the aim to increase the awareness of Europe in the Extended Reality domain. This book presents the EuroXR Delphi consensus study results and a wide variety of XR technology reviews and XR application areas—the first outcome of the XR Open Forum initiative of the EuroXR Association.

Therefore, as the new president of EuroXR, it is a great pleasure to first congratulate the editorial team of this book, namely, Pr. Mariano Alcaniz Raya (Director LabLENI, Universitat Politècnica de València, Spain), Dr. Marco Sacco (Past president of EuroXR, Head of CNR-STIIMA subsidiary in Lecco, Italy), and Dr. Jolanda G. Tromp (Consultant to EuroXR Association for the Delphi consensus study; Director Center for Visualization and Simulation, Duy Tan University, Vietnam; Visiting Assistant Professor, State University of New York in Oswego, NY, USA;

visiting researcher, 3D DIANA research lab, University of Malaga, Spain). More widely, I want to express my genuine gratitude to the renowned scientists and experts who contributed chapters to this great project that the association has decided to undertake. This book allowed EuroXR members and many external collaborators to work together to achieve something bigger, and we are happy to underline once again the importance of collaboration in such a scientific and advanced technology field. I also thank Beatrice Palacco (EuroXR Communication Manager), Yves Geunes, X3D webdeveloper, and John Bottoms, 3D Internet consultant, who helped the editorial team so much and contributed to the Delphi consensus study, and I thank all the EuroXR association member volunteers and respondents who generously contributed their time and knowledge to the Delphi consensus study and this book.

This book is based on an internal report to the European Commissioners charged with future technology investment portfolio, and aims to deliver a synthetic but strong overview of the state-of-the-art in XR as of today. Over the past 11 years, the EuroXR Association has developed many friendly relationships with international XR experts, specifically to serve within the international expert committees of our annual conferences. Therefore, it was quite natural for the EuroXR Association to collect the latest views of international XR experts and share its vision with anyone working in the XR area. We really hope that everywhere in the world, our vision of XR will be useful for scientists to expand research questions and address new challenges, for providers and new companies to set new goals and envisage next steps, and for end-user analysts to be able to specify more complex needs and/or target many more people.

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Research Director at CNRS; Co-Head of VENISE team (Virtual & Augmented Environments for Simulation & Experiments – http://www.limsi.fr/venise/), University of Paris-Saclay, France

Preface

Recently, according to the Gartner Hype Cycle, extended reality (XR) technologies have graduated from being described as mature technologies and are now entering the plateau of productivity. Several leading tech giants are announcing that they will focus their future on the upcoming "metaverse." While the "metaverse" is too new to define, there is a clear consensus about XR's (VR/AR/MR) importance. This book offers a comprehensive overview of the technological aspects of XR and discusses the main challenges and future directions in the field. It is divided into two parts. The first part, "XR Technologies," covers the main technological aspects of XR. The chapters in this section review and discuss relevant fundamental concepts of XR, the actual state-of-the-art, and future challenges. The second part, "XR Applications," focuses on a wide range of applications, including a future roadmap. All in all, this book, which is geared towards a wide multidisciplinary audience of academic and industry stakeholders as well as government agencies and non-profit organizations, offers a snapshot of the state-of-the-art of XR and addresses the necessary requirements for its application.

The three main aspects that were holding XR technologies back from mainstream adoption—price, cables, size—have been overcome. However, there are many aspects of XR technologies currently being explored and developed that still need urgent research in terms of security, privacy, health and safety, long-term effects, addiction risks, and age-related developmental concerns; therefore, our aim is to inform all readers of these open issues and challenges. The main benefit of technology roadmapping is to summarize information to inform and direct technology investment decisions. There are currently a great number of interdisciplinary researchers and developers working in the XR R&D field focused on identifying critical technologies and technology gaps and identifying ways to leverage R&D investments.

The intended audience of this book includes XR enthusiasts, researchers, developers, students, and practitioners at large institutes and companies, SMEs, etc. To serve this audience in the best way possible, the book has been divided into two sections. The first section, "XR Technologies," provides a scientific overview of the technologies and discusses technical state-of-the-art aspects of XR. This section starts with a chapter that describes a Delphi consensus study amongst XR experts to gauge their opinion on the future of XR. Then, subsequent chapters address the following topics: digital narratives, haptic interfaces, audio interfaces, visual interfaces, software platforms, human perception engineering, XR & AI, XR open standards, and human factors. In the second section, "XR Applications," a practical overview is given of the various application areas that have been found promising for innovation with XR solutions, and informs readers of the potential return on investment. Subsequent chapters in this section cover the following topics: neurorehabilitation, retail and marketing, industrial training and maintenance, human resources skill training, and surgery. A brief summary of each chapter of the book follows.

- Chapter 1 describes the Delphi consensus study financed by the EuroXR Association into the state-of-the-art of XR R&D, which gathered information from more than 400 international XR practitioners as input for a dedicated panel of 7 invited XR experts for the Delphi consensus seeking process, who formulated 42 consolidated forecasting statements after 2 consensus rounds, regarding future directions, challenges and a roadmap for XR, created based on their responses.
- Chapter 2 sets forth that it is of utmost importance to address the central role of narrative as one of the main factors contributing to the expressive and representational potential of XR technologies in many domains of application.
- Chapter 3 sets forth that haptic technologies are still under-exploited in XR applications, which makes it all the more important to understand the obstacles that remain to be overcome in terms of technology and applications.
- Chapter 4 sets forth that immersive audio is a very active research area with many potential applications in XR and that there is huge potential in this field, which is underrepresented in the area of XR, and should therefore be included in any future research roadmap on the topic.
- Chapter 5 discusses the main approaches visual interfaces are following these days to attain the goals fixed by the different brands in the XR field, along with a short overview of future technologies with the potential to become the state-of-the-art in the next few years.

- Chapter 6 sets forth that the evolution of spatial computing is driving the adoption of a new 3D software ecosystem known as the metaverse, a new paradigm that will require a whole new set of software platforms.
- Chapter 7 proposes the foundations of a new field known as perception engineering to unify and guide XR research in human perception, focusing on the current state and potential shortcomings of human perception and XR research, and setting goals for the field to aspire to concerning best practices, inclusivity, and open-source modular technology.
- Chapter 8 highlights the challenge of merging Extended Reality and Artificial Intelligence to build a synergic collaboration between technologies to support and preserve a humancentric vision.
- Chapter 9 sets forth that the convergence of XR technologies creates a computing paradigm shift by facilitating a new 3D interactive multi-user experience accessible anywhere via the internet. This future 3D internet will have certain requirements: it needs an XR enabling internet backbone, based on interoperability, open standards, created together in open source academic-industry cross-disciplinary collaboration, including urgent regulation to mitigate the inherent risks to privacy and security of XR technologies. The challenges and roadmap for the near and mid-term XR Backbone developments are discussed.
- Chapter 10 presents an overview of human factors/ergonomics (HF/E) issues associated with XR regarding user experience models defined in early virtual reality (VR) research, including several recommendations for future research.
- Chapter 11 presents the state-of-the-art concerning the use of XR technologies in the rehabilitation of neurological disorders, concluding that they are a promising tool to address the challenges presented by motor/physical rehabilitation and cognitive training programs. However, several improvements for future developments related to devices and human factors are also addressed.
- Chapter 12 explores the use of XR technologies as a very promising tool to examine various customer behavioral patterns in dynamic, complex, and realistic situations that will enhance our knowledge of new models of buyer-product

and buyer-seller relationships. It also sets forth that it is necessary to provide a standard framework that will allow the creation of controlled laboratory situations to study the factors that affect the acceptability of new products and retail spaces and the influence that the different elements that surround consumers have on their decisions.
- Chapter 13 describes recent research results that present XR as a promising solution for assembly, training, and maintenance tasks in Industry 4.0. However, before XR becomes widely used, the industry must overcome several challenges like 2D and 3D data standardization challenges, authoring tools, and new interfaces among others.
- Chapter 14 emphasizes that XR is a very important tool for assessing training skills of the 21st century that companies need to address the strategies they use to develop their human resources in terms of knowledge and leadership. In this chapter, the latest developments in XR technology and organizational sciences are examined. It introduces the concept of XR-based behavioral biomarkers (XRBB) which can be obtained for the evaluation of skills using a neuroscientific organizational paradigm based on implicit brain processes measured through psychophysiological signals and behavior of subjects exposed to complex social conditions replication using XR interfaces.
- Chapter 15 shows the current state of XR technologies in surgery, highlighting their strengths and weaknesses, showing examples of implementations, and outlining the future work that should lead to overcoming current weaknesses and result in giving surgeons efficient and effective tools for their work.

Lastly, contact information gathered from this book's many contributors is presented to facilitate direct discussions between readers and leading research and industry professionals interested in XR technologies.

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Future Directions for XR 2021-2030: International Delphi Consensus Study

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Abstract

XR has been put forward as one of the "Essential Eight" key enabling technologies of the 21st century. Together, they are expected to drive the digital transformation that has started only recently in many areas of business, daily life, and leisure. Importantly, XR has the potential to play a major role in supporting the achievement of several if not all 17 Sustainable Development Goals set forth by the UN. The path towards realizing the full potential of XR technologies needs to be clarified in order to make informed decisions about research and development agendas, investment, funding, and regulations. In order to provide insights into the best approach to further develop XR towards its full potential, the EuroXR Association initiated a study using the well-established Delphi consensus method, drawing on the expertise of independent senior XR experts to formulate future directions for XR R&D. The results are presented in terms of a roadmap for the future of XR, identifying the prerequisites to clear the path for this, and clarifying the roles and responsibilities for the XR research community, the XR business community, and the government and regulation bodies. The main findings of our XR roadmap are summarized into a number of specific areas for the stakeholders to act upon, in order to push the cutting edge of XR and be part of the early-adopters who have this key enabling technology at their disposal throughout industry, education and society.

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1.1 Introduction

Leaders, governments, companies, educational institutions, researchers, and members of the general public aim to understand and anticipate the opportunities offered by new technologies. Of particular interest are emerging technologies that are expected to have a transformational or high impact potential. Currently the synergy of a number of technology developments is converging with such transformational potential, referred to as the "Essential Eight" Key Enabling Technologies (KETs) that are transforming the way we organize work, education, communication, socialization, information access, and our identity (see Figure 1.1):

1. **Augmented Reality (AR):** location-based, multi-sensory, window between real and virtual;
2. **Virtual Reality (VR):** real-time interactive 3D Computer Graphics (CG), collaborative design spaces, simulation, testing, and optimization spaces;
3. **Artificial Intelligence (AI):** big data analytics, machine learning (ML), micro and macro process analysis, and optimization;
4. **5G Cloud Computing:** decentralization, mobile computing;
5. **Blockchain:** cybersecurity, privacy, and trust;
6. **5G Internet of Things (5G IoT):** high-speed connectivity between IT and Operational Technology (OT), smart cyber-physical twins;
7. **Drones:** autonomous and semi-autonomous robots and virtual agents
8. **3D Printing:** additive manufacturing.

Extended Reality (XR) technology solutions consist of various combinations of the KETs, using VR, AR, Mixed Reality, and 360° interactive 3D

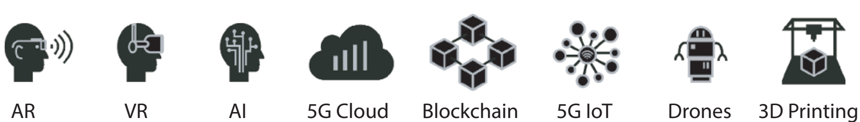

Figure 1.1 The essential eight key enabling technologies. Illustration by: Maxelante Bussemaker.

scanned real world spaces and objects, to provide an interface to interact with remote machines or view 3D computer generated visualizations and simulations, and display augmentations and big data results dynamically, facilitating and facilitated by the other current KETs. XR provides the online 3D communication and interaction space, similar to how AI provides the underlying intelligence for the behaviors of cyber-physical IoT systems, 3D CG spaces, and VR/AR user interactions. XR facilitates the embodiment of the interactions, the space in which the activities are situated, providing a spatial context to the information. While AI has recently been prioritized by many governments and companies, XR has not been prioritized as much yet.

The innovations that the current KETs are predicted to enable are expected to greatly change our local and global societies because they will allow us to optimize the time needed to get things done, and the way we do it, and in the process creating a multi-billion industry. The increased interest can already be witnessed by the plethora of research publications, business reports, and forecasts about the anticipated opportunities of the KETs that have been produced recently and are rapidly increasing in volume [1–23]. The early adopters of novel solutions using XR in combination with AI and IoT will be able to optimize their product or service design via big data analysis using Machine Learning (ML) and this will enable them to gain a rapid advantage [5, 24–27].

These days, advancements in eye and hand-tracking capabilities are built into XR headsets and allow for psychophysiological measurements of the user while interacting with the XR experience. This information is used to analyze customer engagement, and what is more, it can be tested and quantified, thus allowing calculations to measure Return-On-Investment (ROI) to be based on actual time and motion studies with quantitative data [15]. There is clearly a huge potential advantage in being able to save users and institutions time and money, accelerate development processes, measure user engagement to personalize their experience, facilitate communication and collaboration better than a videoconference, and enable a rapid iteration of new business models with increasingly more optimized processes and profitable ROI.

To better understand where funding for future XR applications research and development will be best allocated to facilitate the cutting-edge advantages, the EuroXR Association conducted a consensus survey among global XR experts using the Delphi consensus seeking method. This chapter summarizes the results.

1.2 XR and the Delphi Study Forecast

The Delphi method is an interactive multi-stage forecasting procedure where specific experts identify technical developments and trends in an iterative process to achieve clarification and consensus [28–32]. The method was developed by the RAND Corporation to generate scenarios for long-range strategic planning in the 1950–1960s and became a widely accepted approach to facilitate the development of reliable group opinions using expert panels [33, 34]. It was developed to structure time-consuming group opinion seeking processes, among a set of experts by getting them to participate in a panel, and seek consensus on future developments for complex problems, using participative inquiry that has its roots in humanistic psychology [35]. The Delphi forecast consists of statements formulated by the group of domain experts regarding the topic that is being studied.

A core benefit of the Delphi method is the opportunity to provide domain experts an anonymous place to express different opinions and reach consensus within a structured asynchronous and synchronous text-based information exchange setting. The domain experts express and share views in the group, directly or mediated by the Delphi organizers, depending on the online consensus tool interface and design of the study [36–38]. Since the start of the COVID-19 pandemic, the frequency of use and popularity of using consensus tools via the internet such as online Delphi have risen considerably. The full description of the Delphi study reported here can be found in [39].

The preparation for the Delphi consensus process starts with an open survey to collect topics regarding the theme of the Delphi from the wider forum of experts. These themes provide the basis for the initial forecast statements. The Delphi consensus seeking process itself uses a group of specifically selected participants, a panel of domain experts. The panel of experts is asked to assess and rewrite the statements until they can fully agree with the contents. Typically, for Delphi studies, depending on budget and time available, the consensus seeking rounds are repeated until a minimum of 70% consensus has been achieved for each statement by the panel.

The preparation survey that aims at collecting the starting points for the Delphi statements was distributed via the EuroXR Association (www.euroxr-association.org), the VRISI network (www.vrisi.de), and other international XR professional groups, and many members of these lists forwarded the invitation to their mailing lists, such as the German and the French VR/AR/XR Association. Respondents were invited to nominate themselves for the Delphi XR Expert panel. Eighty-two respondents submitted a response to the online survey; however, of those 82, 40 had to be discarded because they were very incomplete, leaving 42 complete records for our analysis. On average, it took respondents 1 hour to reply to the survey. There were 24 academics in the sample, 18 employed in business, and four of these respondents stated that they were both involved in academia and business. They are from 15 different countries. In the previous waves, they worked 42 years in XR R&D, and there is some visibility of the previous waves of the VR/AR development over the years, as illustrated in the Gartner Hype Cycle [1] in the clusters of respondents' number of years involved in XR R&D; the current influx of newcomers in the field was found. A similar cluster distribution was found in the age brackets in which the respondents fit, showing the normal distribution in age that one would hope and expect for a field that has been in existence for more than 30 years. Forty-one out of forty-two respondents are members of one or more professional XR membership groups. There were 9 women (21%) and 33 men (79%) in the sample, and they are aged between 25 and 75. The original full set of 82 records (before excluding the abandoned/incomplete responses) showed a similar ratio of female/male respondents of 16 females (22.2%) and 58 males (75%) and 2 respondents who preferred not to share their gender information (2.8%)—the latter showing the growing trend of more openness towards non-binary gender orientation, and gender orientation diversity is also reflected in the XR community and the Delphi sample group.

Twelve participants for the Delphi XR expert panel were selected from the anonymized list of self-nominated respondents for the Delphi panel of the first survey, based on the following selection criteria: >35 years old to ensure significant amount of experience in XR, Senior position in their respective organization (e.g., professor, team leader, etc.), active position in academia or industry, actively working in XR, and gender balance 50/50 was attempted by inviting additional female experts.

This Delphi study consisted of two rounds of consensus seeking. For the first round, 43 Delphi statements were prepared based on an exhaustive content analysis of the initial open survey and a literature review, with an estimated time of 1 hour to respond to complete it. Participants were asked to read each of the statements and decide in what way they agree/disagree with them and correct it, if it did not reflect their opinion. The aim of this Round 1 survey was for each participant of the XR panel to rewrite the statements in such a way that it is fully in line with their opinion. The statements were followed by a four-point scale to indicate their agreement with the statement as follows: Strongly Disagree, Disagree, Agree, Strongly Agree, and an open response box asking them to rewrite the statement in case they could not fully agree with it.

The survey was open for 7 days, and reminder emails were sent out with an extension of the deadline by a few days in order to maximize the number of responses. Seven experts responded in total: 7 male and 0 female respondents, working in multiple, diverse, and different areas of the XR R&D field: Industry 4.0 (43%), 3D interaction (14%), Mitigating cybersickness (14%), Optics (14%), Personalized interaction (14%), Virtual tours (14%), XR for business, (14%), XR for training (14%), and XR UXUI (14%).

The statements were initially grouped into four overarching themes relevant to creating a technology roadmap: the market, the enabling environment, human capital, and the innovation ecosystem, further defined as:

- **XR Market:** statements regarding the position of the XR market and statements are related to building XR development skills and awareness for different Technological Readiness Levels (TRL).
- **XR Enabling Environment:** statements regarding leadership in terms of standards for XR R&D.
- **Human XR Capital:** statements regarding building XR development skills and awareness for different TRL.
- **XR Innovation Ecosystem:** statements relating to the XR development platforms: middleware/real-time 3D engines.

Of the 43 statements of Round 1, 28 statements had full consensus, leaving 15 statements with less than 70% consensus to be improved by the expert panel in Round 2. The statements from this first round of consensus seeking and the comments and rewrites from the panel members are reused for the next round of consensus seeking, after a reconciliation of each statement by the Delphi study designers. The reconciliation consists of removing any overlap introduced by the multiple and diverse rewrites from each of the panel members, coordinated by the Delphi study designers.

Round 2 of this Delphi was the final round. During this round, a final effort to find consensus for the 15 statements that were not fully agreed yet was sought, and additionally all statements were analyzed in terms of their importance and urgency. Round 2 closed with a total of 42 statements accepted, and one statement really had the panel divided (R2 Q12, in XR Enabling Environment). During the final round of the Delphi, the statements were weighted by the panel in terms of importance and urgency. In many statements, the respondents already explicitly expressed urgency or priority or strong agreement in the statement, or it was added at the request of one or more of the panel members. To visualize the collective opinions of importance/urgency on the statements the scores placed in colored columns in the tables below:

- Column A: extremely important/totally agree/extremely urgent
- Column B: very important/strongly agree/very urgent
- Column C: important/agree/urgent

1.2.1 XR Market

These are statements regarding the position of XR in the market, and statements are related to building XR development skills and awareness for different TRLs.

XR market statements	A	B	C
1 XR technologies are a strategic source of competitiveness, and their development must be strongly supported. (R2 Q31)	7		
2 Focus on the potential market share in creating 3D asset libraries specific to Industry 4.0 use-cases, to help speed up XR development, because many industry use-cases are early-adopters of high-precision manufacturing using XR Industry 4.0 solutions, and the Industry 4.0 use-case specific 3D assets are expected to become of interest world-wide. (R2 Q9)	5	1	
3 Urgently support the development of industry specific XR Development Asset stores, with high quality shareware assets that are available for developers under a sustainable non-profit business model, crowd-sourced, no-cost, or low-cost. (R2 Q25)	5	1	
4 It may or may not be too late for newcomers to catch up on the global consumer XR input/output device manufacturing market, because there are many big companies producing consumer XR input/output devices, but stakeholders should explore this direction. (R2 Q14)	3	2	1

5	XR developers and stakeholders can capture the market by prioritizing research into XR Customer eXperience (CX) measurements and psychophysiological user behavior data. (R2 Q11)	**2**	**4**	
6	With several global companies interested in monetizing users' data, more research into General Data Protection Regulation (GDPR) is needed, specifically regarding protection and regulation of XR users' personal and psychophysiological data, and because the GDPR may not cover all legal aspects; additionally, a complete classification of the psychophysiological data should be made, and this will be especially important for BCI solutions. (R2 Q15)	**2**	**3**	**1**
7	XR technologies are essential for the development and success of Industrial Data and Clouds. (Q48)		**7**	
8	Facilitate the market uptake of XR applications for healthcare by establishing more flexible rules for experimentations and by creating a funding instrument dedicated to the certification process. (R2 Q19)		**6**	

Based on these statements, it is clear XR is part of the KETs, has been used in the manufacturing industries for decades, and is now entering many new sectors due to its consumer-grade availability. Consequently, all experts in the Delphi XR panel unanimously and strongly agreed that XR is of strategic importance. It is now important for many areas of industry, business, health, science, and environment, and will be in the future for many more.

With respect to spurring on "supporting" markets and technologies (statements 2, 3, 4), such as input/output devices and 3D assets, the Delphi XR panel experts suggest that newcomers should be prepared to invest heavily to catch up with global developments; otherwise this might be wasted effort, since global XR developments are extremely fast-paced and dynamic in this area. However, there is an opportunity to develop use-case specific tailored solutions for future XR markets.

XR offers serious potentials for multinational companies to intrude on people's privacy and monetization of user data, and could, potentially, cause serious issues with respect to society as a whole (statements 6 and 8). Therefore, the experts feel that regulating the applications of XR is an important task for governments, regulators, and end-users.