Concept development of a cross-reality ecosystem for urban knowledge transfer spaces

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Figure 1: Early prototyping stage of the urban cross-reality environment. a) Bird's eye view of a section of the virtual model as it would be seen in the current web interface prototype. b) Illustration of mobile AR-overlaid content (the waterside café and the raft are virtual) in the post-industrial environment. c) Collaborative HMD-based interaction with the environment model. The prototype in the image is implemented with the *Tilt Five* augmented reality device (Tilt Five Inc., Fremont, CA, USA).

Abstract

This paper presents the development of a cross-reality (CR) ecosystem designed for an urban knowledge transfer space (KTS) in a post-industrial urban environment. The project is part of a larger initiative aimed at transforming a former industrial river port into a dynamic KTS, facilitating interactions between scientific, commercial, residential, and cultural stakeholders. Our research explores the potential of multimodal mixed reality (XR) technologies to enhance engagement with the content and stakeholders of the KTS. Through a three-phase process, we identified key stakeholders and their target audiences, selected appropriate XR technologies, and developed initial use cases that integrate web applications, mobile augmented reality (AR), and XR head-mounted displays. The preliminary findings indicate that these technologies can effectively cater to diverse user groups, providing different levels of virtuality and interaction. However, challenges remain, particularly in stakeholder engagement and the evolving nature of the KTS initiative. Ongoing work includes the development of a Web-XR-based prototype, which will be iteratively refined to better meet user needs and adapt to future technological advancements. This research contributes to the understanding of how CR technologies can be employed in urban transformation processes, offering insights into the design of flexible and scalable CR ecosystems.

Index Terms: Cross reality, Augmented reality, Knowledge transfer, Smart city, Science communication

1 Introduction

The ongoing evolution and increasing relevance of mixed reality technologies brings along a growing number of applications that require a cross-reality (CR) approach. CR, in this context, refers to systems that include user interfaces using different mixed reality modalities with different degrees of virtuality along the reality-virtuality continuum [9]. We use the term *extended reality* (XR) as a blanket term for mixed reality and virtual reality (VR) environments. While recent CR platforms or transitional interfaces [7] often address specific tasks in confined, or at least defined, environments, this article investigates the CR-based exploration of and engagement with a large-scale environment itself, with a scarcely defined profile of user and stakeholder groups.

The project reported in this article is being undertaken in the context of a multidisciplinary initiative aiming to investigate and facilitate the transition of a post-industrial urban area into a *knowledge transfer space* (KTS). The term KTS describes an urban and digital ecosystem that facilitates the exchange and development of knowledge. This particular initiative has an industry focus on biomedical engineering. This is investigated while balancing the needs of scientific, commercial residential, and cultural stakeholders in and around said ecosystem. In our example, this space is a former industrial river port that has not been in use for some decades.

Within this context, we aimed to devise a concept for a CR ecosystem that would allow local and remote users to participate in the urban transformation process and to engage with the KTS stakeholders' content. The overarching research question in this project can be phrased as: *How can multimodal CR technologies facilitate local and remote users' engagement with content that promotes and aids the development of a successful urban KTS?* This article presents the first project stage of investigating this question: Identifying potentially relevant stakeholders and users, as well as content and interaction venues for such a CR ecosystem. Derived from this, we present an initial Web-XR-based conceptual architecture for the proposed application.

2 Related work

A multitude of approaches to using digital representations and mixed reality interfaces in urban contexts can be found in scientific

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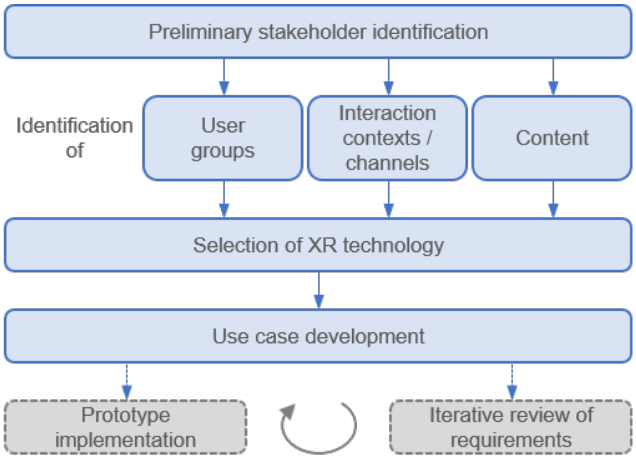

Figure 2: Overview of the methodological process.

literature. In the context of urban planning by local government and public services, the German Federal Institute for Research on Building, Urban Affairs, and Spatial Planning has identified applications for *digital twins* in real estate planning, mobility, energy supply, tourism, and climate sustainability management [2]. Augmented reality (AR) has been used in urban planning for onsite augmentations of the environment [3, 5] as well as for bird-eye views of digital urban models that enable the overlaid visualisation of complex data [8]. Similarly, Nguyen et al. propose a VR based system for the planning of and interaction with virtual city models [10].

While most of the cited approaches target expert user groups, Hunter et al. argue that XR technologies can be used to engage citizens and facilitate participatory urban development [6]. One suggested route to achieving this lies in AR visualisation of planned or proposed environmental changes or the visualisation of haptically created citizen designs [11]. Van Leeuwen et al. argue that the presentation of planned changes in urban environments are more vividly remembered and more easily understood if experienced through immersive media by lay audiences (e.g., residents of the affected areas) [13].

However, the concept of an urban KTS transformation extends beyond the urban area's structural transformation. It includes the presentation of and interaction with content of scientific and commercial stakeholders within the KTS ecosystem. Prior work shows that XR interfaces may be beneficial in this context. XR applications have been demonstrated to be useful both in scientific visualisation for expert audiences (e.g., [4]) and in science communication to a broader audience, e.g., in science museums [1, 12]. Finally, commercial uses of XR for B2B customer experience management have been reported across multiple industries. Wieland et al. [14] provide a comprehensive review of these applications and report potential use cases such as product visualisation, remote product support, or event-based customer engagement.

3 Methods

With respect to the user-centred design process, this project focuses on the early stages of understanding who the users will be, in which contexts, and with which intentions they may interact with the digital components of an urban CR KTS. Our intention was to derive initial user needs that may facilitate the design of a first experimental prototype. To achieve this, the process was structured into three primary phases: (1) stakeholder analysis, including the identification of potential user groups, interaction contexts / channels, and content types, (2) selection of suitable XR technologies, and (3) design of an initial system concept and architecture (Fig. 2).

Stakeholder identification and analysis The first step involved identifying key stakeholders during the CR KTS's initial development phase. This process was conducted in an internal workshop. Stakeholders were identified based on their relevance to the project, with a focus on their anticipated needs and expectations. We designed a qualitative questionnaire to gather insights into the stakeholders' roles within the wider KTS initiative's context, their understanding of the CR KTS concept, and their preferred target audiences, communication channels (i.e., interaction contexts), and potential content. The questionnaires were distributed to 12 early-stage stakeholders, including:

- Five local research institutions (all of which are involved in some capacity in the wider KTS initiative),
- Three local small and medium businesses (SMB) from the medical technology industry,
- Two local knowledge transfer agencies,
- The local government's *smart city* branch,
- The KTS initiative's management office.

Data analysis was qualitative, summarising responses from the questionnaires and categorising key points. The data was collated into three lists: potential user groups, interaction contexts / channels, and content categories. Each entry was assessed by three authors, who assigned priority points (0-3) based on the criteria (each author was assigned a separate criterion): alignment with the overall strategic direction of the KTS initiative, compatibility with other target groups and channels, and the foreseen technical complexity. For the last criterion, user groups were assessed as to how difficult they were foreseen to be reached. The combined (added) scoring was intended as a preliminary relevance score for the initial use case and concept development.

Selection of technologies The next phase involved the selection of suitable interactive technologies for addressing the preliminary stakeholder needs. This was achieved by cross-referencing a list of eight conventional and immersive technologies with the previously identified user groups, interaction contexts / channels, and stakeholder content. The technologies included: web application, mobile application, desktop application, head-mounted display (HMD) AR, mobile AR, projective AR, HMD VR, Cave VR.

The prioritisation process involved evaluating the feasibility of each technology to (1) reach and engage the respective user groups, (2) within the given use contexts / channels, and (3) with the identified content. The technologies were cross-referenced with each of these lists. Three authors independently scored each combination with -1, 0 or 1 point, where -1 indicated significant foreseen challenges, 0 indicated no particular advantages or disadvantages, and 1 indicated a good match. The scores from the three authors were added and were then multiplied by the priority scores of the corresponding list entries' relevance scores. The resulting technology scores enabled the identification of the most suitable technologies for the CR KTS's initial concept phase.

Initial use case development Based on the scoring process, three technologies were selected for the initial version of the CR KTS (see *Results*). In a final step, several use cases were developed that aligned with the high-priority user groups, interaction contexts, and content. This was undertaken in an internal design workshop. The use cases were tailored to the selected technologies, ensuring that the CR KTS would effectively meet the needs of the identified stakeholders while remaining flexible for future adaptations and extensions.

4 Results

Stakeholder identification and analysis The preliminary stakeholder analysis yielded 12 early-stage stakeholders as reported in the *Methods* section. The questionnaire response rate was relatively low with four questionnaires returned, one of which was augmented by an unstructured interview at the respondent's request. The four respondents included one representative each of the stakeholder groups *research institution*, *knowledge transfer agency*, *local government*, and the KTS initiative's management office. The questionnaires yielded 16 potential user groups, 18 potential interaction channels, and 27 potential content categories. While identical responses were unified, there remained partial overlaps between responses, making the 61 data points that were rated, not mutually exclusive. Tab. 1 reports the top five responses in each category by preliminary relevance rating, with partially redundant answers merged. The table entries are ordered alphabetically.

Selection of technologies Based on the preliminary relevance ratings and foreseen technology compatibility, Tab. 2 presents the resulting scores for each of the eight technologies. As a result, we selected a combined solution of web application (low immersion) and mobile AR (medium immersion). We decided to add a third level of virtuality in the form of mixed reality HMDs (high immersion). This had two reasons: Firstly, to address the highly ranked interaction / presentation context of exhibition / conference venues. Secondly, to include a highly immersive technology to future proof the overall concept for content that requires a higher degree of virtuality. The envisioned concept views these technologies as interfaces that provide access to the KTS stakeholders' content with different degrees of virtuality in different use contexts.

Use case development We defined two initial *use cases* for the initial CR KTS ecosystem. Each use cases is defined by one or more target user groups, an early-stage content description, and a subset of the selected XR technologies.

The first use case focuses on making the real estate status quo and existing development plans accessible to interested parties. Relevant audiences include interested citizens, real estate developers, and SMBs and startups that have or consider opening local facilities. This use case will be implemented across the three selected XR technologies. Example illustrations are shown in Fig. 1.

The second use case will be the display and interactive presentation of R&D facilities available in the urban KTS, specifically laboratories and prototyping facilities of local research institutions and SMBs. The intended target audiences for this include local and remote researchers, prospective startup founders, and industry-specific SMBs. These will be presented in the form of virtual popout presentations in the overall representation of the urban KTS. In web-based and high-immersion (HMD-based) KTS representations, the facilities can either be selected by browsing through the spatial representation or by searching for specific R&D facilities / capabilities. In the mobile AR context, the visualisations will be accessed via QR codes outside the relevant buildings.

The third use case will be a mobile AR-based illustration of the urban space's historical context and uses in combination with a vision of its future use and appearance. This is intended to facilitate wider citizen engagement and identification. QR codes will be distributed around characteristic locations in the area, from which visitors can explore a mobile AR illustration of how their surroundings would have appeared historically and how they might appear after the completed transformation. The extent and depth of these mobile AR animations is yet undefined and part of ongoing research. This application is currently primarily intended for the mobile AR interface because the target audience is expected to mainly interact with the content on site.

5 Ongoing work

We are currently implementing a working prototype based on a Web-XR architecture, designed to cater to the three identified use cases. This prototype integrates the selected XR technologies — web applications, mobile AR, and mixed reality HMDs — providing a versatile and immersive experience across different levels of virtuality. The development focus is on ensuring the prototype effectively addresses the needs identified during the stakeholder analysis while remaining adaptable for future expansions. Initial testing and iterative refinements will follow, aiming to refine the prototype's functionality and user interaction based on feedback from potential users and stakeholders.

The prototypes require wide device compatibility, accessibility, and low data usage to ensure flexible CR capabilities. We selected a web-based content delivery architecture to address these requirements. Automated level of detail (LOD) generation enables 3D content creators to focus on designing assets, while low-end, low bandwidth devices stay included as possible end user devices. Also, focus on static content helps keep server costs minimal and web page loading times fast. For possible future multi-user interaction, user position and content synchronization is needed.

To allow for flexible building of the prototypes, the Unity-based package Needle Engine[1] is used. Needle includes these technologies that are not part of the Unity core feature set: automated LOD, static content deployment to the web, and session management for multi-user interaction.

6 Discussion

Developing an initial vision for an CR KTS has surfaced several critical challenges and limitations. A primary issue is the limited engagement from stakeholders, with only four out of twelve contacted stakeholders providing feedback during our initial analysis. This low response rate raises concerns about the comprehensiveness of our findings, as the small sample size may have led to an incomplete understanding of stakeholder needs and preferences, potentially skewing the prioritisation of technologies and use cases. While the response rate limits the results' comprehensiveness, the four respondents represent four of the five stakeholder categories. We, therefore, believe that the data provide a sound preliminary basis for the initial system concept.

The variation in familiarity with XR technologies among stakeholders complicates the design process. While some stakeholders, particularly those from research backgrounds, were well-versed in XR, others demonstrated limited prior experience and exposure to XR use cases. This disparity may have led us to prioritise more conventional use cases, which might have restricted our ability to explore more advanced, innovative CR applications.

Another significant challenge is the evolving nature of the KTS initiative itself. With many aspects of the project still in the early stages, it was difficult to precisely define user groups, interaction contexts, and content needs. This lack of clarity could lead to misalignment between the selected technologies and the eventual use cases, requiring future revisions and adjustments as the project matures. We address this issue in two ways: first, by treating the presented concept as an initial iteration of an evolving ecosystem, with regular reviews of the stakeholder community and requirement assessments throughout the project. Second, by ensuring that the prototypical implementation is flexible and adaptable, allowing for the future integration of additional XR technologies or content.

The preliminary relevance scoring system, while useful, also has its limitations. The criteria used for scoring were subjective and heavily influenced by the existing knowledge and biases of the project team. This subjectivity could result in an overemphasis on

[1] https://needle.tools/

Table 1: Preliminary stakeholder analysis results, including key user groups, interaction contexts / channels, and content categories.

User groups	**Interaction contexts / channels**	**Content categories**
Local citizens	Conferences	Citizen participation
Local government	Public events	Digital events
Real estate developers	Public spaces within the former port area	Local R&D capabilities
SMBs	Trade fairs	Real estate developments
Startup founders	WWW	Urban space use scenarios

Table 2: Suitability scores for the eight investigated interactive technologies. The scores are reported separately for the scoring categories and the total, as well as the total added score.

	Web application	Mobile application	Desktop application	Mobile AR	Projective AR	HMD AR	HMD VR	Cave VR
User groups	139	58	13	84	-39	3	6	-2
Interaction contexts / channels	106	33	22	58	-36	-10	-18	-69
Content	164	133	121	69	-30	37	25	-51
Total	**409**	**224**	**156**	**211**	**-105**	**30**	**13**	**-122**

certain technologies while underestimating others that might be better suited for less familiar use cases or emerging needs.

The reported use scenarios and the ongoing work on the initial prototype may appear to be based on three distinct technologies. However, we envision these technologies as context-dependent interfaces of an overall CR ecosystem. Our preliminary architecture is intended to allow future content creators (local and remote stakeholders) to create a single back-end representation that will then be accessible across various XR technologies and degrees of virtuality.

While the initial phase of the project has provided valuable insights, significant challenges remain. The limited stakeholder engagement, disparity in XR familiarity, and the evolving nature of the KTS initiative all suggest that our current approach may need to be re-evaluated as the project progresses.

7 Conclusion

This paper presents an initial vision for a CR-based KTS in a post-industrial urban environment, namely an out-of-use river port. It reports the challenges of engaging diverse stakeholders with varying levels of familiarity with XR technologies. Our work offers a twofold contribution to the field. First, we propose a method for navigating the complexities of undefined user profiles and needs in the early stages of a complex CR-centred project. By iteratively refining our understanding of stakeholder requirements and maintaining flexibility in our technological approach, we aim to align our project outcomes with evolving user needs. Second, we introduce a large-scale CR scenario designed to serve as a dynamic platform for exploring innovative CR and transitional interface solutions. This scenario not only supports current project objectives but also provides a foundation for future experimentation and development within the CR and transitional interface community.

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