From off-site to on-site: A Flexible Framework for XR Prototyping in Sports Spectating

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***Abstract*—Developing and researching Extended Reality (XR) prototypes for sports spectating is challenging as on-site testing opportunities are limited and often cannot be used for development and debugging. In addition, conducting user studies and evaluating prototypes within such a large unconstrained live event environment can be problematic. These limitations created a need for a flexible XR prototype development framework that can be used off-site for testing and debugging as well as for user studies, while still providing the option to being directly applied on-site during a sports event.**

We developed a framework for a flexible XR prototyping process with different levels of fidelity. The framework integrated our experiences with the challenges of working remotely to create solutions for an on-site problem. We use our proposed framework to demonstrate how to develop different XR prototypes, such as a miniature lab prototype, a hybrid use-case using indirect AR, an off-site VR prototype and the actual on-site AR prototype.The proposed framework allows us to tackle our overall goal of using Augmented Reality (AR) to provide situated visualizations to on-site sports spectators. Our approach can be applied in AR and XR projects where access to the targeted environment is limited.

***Index Terms*—augmented reality, mixed reality, framework, flexible**

I. Introduction

Most applied Augmented Reality (AR) research prototyping work requires mimicking the targeted environment and context, mostly in an office space or a computer laboratory. This includes the challenge where researchers are not able to frequently evaluate their prototypes in the place of interest where the application is to be used. In our use case, we are developing an AR solution for on-site sports spectating in a stadium [1]. This work is motivated by a decline in live sports spectators observed [2] while technical advancement of sports broadcasting is improving [3]. The main idea of the research was to augment situated visualizations [4] in a stadium environment viewed through the spectators' mobile devices and in the future, AR head-mounted displays (HMD).

The issue of not being able to frequently enough access the stadium venue, due to security and other logistical issues, quickly became a hurdle in our research. Despite teaming up with local sports (rugby) teams to join training sessions, access was still limited depending on the training schedule and the researchers' availability. Therefore, we decided for a more flexible and versatile approach to allow for continuous research and development even when no access to the stadium is possible. We developed four classes of prototypes: (1) a mini-stadium lab prototype, (2) a mobile indirect AR prototype, (3) an off-site VR prototype, and (4) an on-site stadium AR prototype. Depending on the situation we can switch between all four prototypes. Each of these prototypes described in this paper have a specific use-case but share a common basis—our flexible framework.

While there are previous work that investigated and discussed some of the prototypes we mentioned above [5], [6], there is insufficient research done on the integration of various prototypes for a single research project (from lab prototypes to field (on-site) prototypes). While some commercially developed frameworks exist which help with the development of cross-platform and cross-system-target prototyping (as e.g. provided by Microsoft, Facebook, Google, Unity, and Unreal), including PC emulators, there is next to no framework support for addressing the on-site and off-site research need in an integrated way. The lack of a prototyping framework in XR research motivated us to propose and context-specifically develop such a framework for flexible XR prototyping based on our sports spectating implementation, which is our main contribution. Here, each prototype serves a specific purpose while making the whole process streamlined for better organization. Here, we also provide implementation details for our use case towards parts of the framework.

II. Background

Wensveen [7] classified four roles of prototypes: as an experimental component, as means of inquiry, as a research archetype and prototyping as a vehicle for inquiry. This classification did not include prototypes that were developed as a tool to facilitate the development and research process itself. Meanwhile, there is literature [8] that differentiates research prototypes and design or industrial prototype as research prototypes are meant to test theoretical literature rather than looking more "product-like". We think that our prototypes are somewhere in the middle of both concepts, a "product-like"

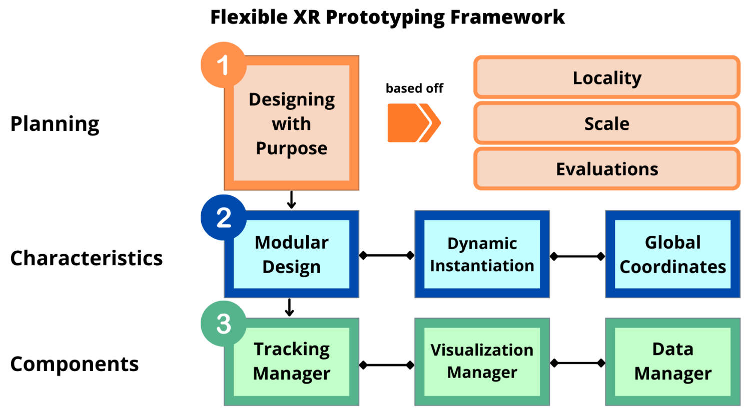

Fig. 1. Flexible XR Prototyping framework: This framework guides researchers to have proper planning alongside the required characteristics and components for a flexible XR prototyping development process.

prototype yet used as an experimental component. One could also call this a minimally viable research product.

There are low fidelity and high fidelity prototypes [9]. Standard examples for low-fidelity prototypes are sketches and wire-frames which require users' imagination to fill in the fidelity gaps. Sometimes this can be augmented by Wizard of Oz technique [10] where the facilitator manipulates the system while a subject is interacting with it. High-fidelity prototypes are closer to fully functional products which can actually be interacted with. There are also mixed fidelity prototypes which are closer to a high fidelity prototype but still have some manual elements in it [11]. Among all these classes of prototypes, it is found that although the low-fidelity prototype is the easiest to produce, it has the lowest score when it comes to understanding the concept of the prototype [11].

Indirect AR [5] is one of the approaches we used for our prototypes that provided many benefits. While simply playing a video on-site [11] might be a similar to an indirect AR approach, it doesn't provide the freedom for users to look around. Apart from just simulating an AR experience, indirect AR could be also used in situations where crowd might be a factor that affects user experience. An example is this museum use case [12] where a combination of traditional AR and indirect AR allows users to see the environment without the occlusion of other visitors.

III. Flexible XR Prototyping Framework

The main purpose of having flexible XR prototyping is to overcome hurdles with respect to accessibility to the on-site environment. Even research for rather accessible locations (such as a park), is often done in a different location, e.g financial and time reasons. The Flexible XR Prototyping framework (Fig. 1) is built on the implementation of our AR sports spectating use case—users are visiting a stadium environment and receive visually overlaid situated information on the sports event happening, in our main scenario case a game of rugby. However, we aim to be generalizable to other AR application scenarios by introducing different characteristics, prototypes and components for a seamless development and evaluation experience. In this section we will discuss the framework starting from the considerations, the characteristics and the components needed while in the next section we explain in more detail the implementation and the distinct differences between the various prototypes.

A. Designing with Purpose

"What prototypes do we need?" is not a simple straightforward question one could answer as most prototypes are born out of necessity at a later stage. The flexible XR prototyping framework prepares researchers for creating new prototypes without producing too many complications and disruptions at later stages of the development. However, it is good practice to brainstorm what do we potentially need throughout the development process so that early design choices could be made with better judgement and knowledge. Based on our research and development experience with AR and XR prototyping in general and with the AR Sports Spectating project in particular, we focus on the following aspects:

1) Locality: Locality refers to the position or site of a prototype, such as *"Does the prototype need to work in a specific place?"* It is probably one of the most determining factors in deciding whether ones' research incorporates a particular kind of prototype. Researchers need to question themselves if they actually need an off-site prototype. This is definitely necessary for large-scale environment AR research [4], [13] such as AR for city navigation, where the subject of interest is not something on a tabletop like labelling of an object [14], [15]. Justification for this could be ease of development, evaluation, off-site demonstration, etc.

In our case, we always have had challenges accessing the stadium due to security and logistics issues, which became increasingly harder to access due to the COVID-19 pandemic mid-way through. Therefore, we developed a mobile indirect AR and a VR indirect AR prototype, which we will just call it as our VR prototype. As the names imply, the mobile indirect AR uses a mobile phone as the hardware while the VR version uses an VR HMD. These are suitable for remotely experiencing large-environment AR where users could be immersed in their environment while having control of their view points and viewing angles. However, we also used a scaled-down prototype to experience a large-environment prototype which we discuss in the next section.

2) Scale: The scale here refers to the scale of the environment the XR prototype is to be used in. By using printed image targets, we recreated a smaller scale of the actual stadium environment with the same visualizations in which we call *miniature lab AR*. This can be imagined as having the stadium in AR right on the surface of a table, where one can walk around it, seeing the visualizations from a birds-eye view. Often times it is easier to get an overall picture of how visualizations are performing when seen from a third-person point of view (POV). For instance, targeting the question whether there are any occlusions between visualizations that might not be noticeable from the first-person POV. Having the miniature-scaled AR prototype aids in evaluation of visualizations as well, since the user is free to maneuver to different spots in the AR environment relatively unconstrained, and can even access some of the spots that might not be easily accessible from a first-person FOV.

This miniature lab AR prototype also benefits off-site demonstration, since it is now portable due to the smaller scale. There were many occasions where the miniature lab AR was used in demonstrations for interested parties, lab demonstrations and conferences. We just brought along a foldable canvas pitch image target and a mobile device with our prototype installed. It also aided with the understanding of what AR is all about to the general public without needing to demonstrate it on-site in the stadium.

3) Evaluation: Evaluation could be from the researchers' perspective and from the user study perspective. As mentioned in locality, if a prototype is designed to work at a specific location, how do researchers demonstrate it remotely, for example in a board meeting or at a conference? Researchers might also face issues running on-site user studies if there are confounding variables such as noise, distractions and uncontrollable events. These confounding variables are of course important in a final usability testing environment, but could weaken the integrity if the evaluation is only focused on a specific area. In our user studies, we used the mobile indirect AR prototype to standardize the visualizations as we wanted to prevent ambiguity from random events.

For some AR research the locality might involve some element of risk such as the use of AR in vehicles. A more controlled environment or a simulation might be an appropriate alternative. All of these mentioned issues could be resolved or reduce with an indirect AR prototype. For the sports spectating use case, preliminary user studies could not be conducted at an actual game. This was not only due to confounding variables but also to the availability and monitoring of the devices during a game as the application is yet to be published. Also, it is hard to monitor participants in a crowded stadium especially when alcohol is served on-site as well.

B. Characteristics

We will now consider some of the characteristics these different prototype classes should have in order to ease the development process.

1) Modular Design: A modular design allows for scalability while streamlining the development process when multiple prototypes are present. Researchers would need to think the development of prototypes in the form of modules, in our case the tracking, visualization and data manager which we will describe in the components subsection. All prototype developments probably start with some sort of a base module (minimal recreation of the environment) before adding on other modules.

The idea with these modules is that they each will share the same code-base or prefabs, as they called in game engines. Therefore, if a change is made to the visualization module of the indirect AR prototype for example, the changes in the script should appear in all prototypes, regardless of in which prototype the changes were made. The benefit of this approach is that changes will be available across all prototypes, saving the developer time to implement it one by one, and with this decreasing the chances for error and inconsistency. However, it also carries a risk in which a modification made for prototype A might indirectly affect prototype B without the developer noticing. Hence, more frequent testing of other prototypes is required, but when done correctly, it promotes good coding practices, easier debugging and should also save more time in the long run with more efficient code.

2) Dynamic Instantiation: Dealing with multiple prototypes often means developing in multiple scenes, even though it is in one project. The manual way of doing it is to individually create and place every object and visualization in the scene, as we are currently doing with our sports spectating use case. This process is rather time consuming and would result it some error if the objects in the scenes are not synchronised. Therefore, it would be very beneficial to the development process if the majority of the dynamic content in the AR experience could be automatically instantiated by script. In this way, developers would need to test out the visualizations in the editor, then instantiate the visualizations as prefabs via scripts. It is slightly more work in the beginning but would greatly benefit the development process if there are multiple prototypes where visualizations or game objects are shared.

3) Global Coordinates: As AR research usually involves the definition and use of many different coordinate systems, it is advisable that all coordinates are referring to one global coordinate system, which is visible and measurable in the real world. We used one of the corners of the playing field as our point of origin in the stadium, therefore in all of our prototypes, the position vector (0,0,0) would point to the same spot. This greatly assists in scenarios where there is object tracking data as an input source, in our case, player tracking data and event-based data. With this approach, all appropriate visualizations appear at the same position for all prototypes, reducing the trouble to individually translate incoming vectors to suit each prototypes' coordinate spaces.

C. Components

The components of the framework are some of the important modules that we mentioned in the characteristics. Almost every AR application would have these three important aspects, being some sort of tracking data, visualizations and incoming data source. In the AR sports spectating use case, we have three main modular components which are the tracking, visualization and data manager, where in our implementation each of them is a prefab game object in Unity consisting of scripts shared among all prototypes.

1) Tracking Manager: The tracking manager manages most of the tracking and localization done in the application. Hence, this manager only exist in our stadium AR and lab AR prototypes. In our case, the tracking manager consists of two sub-components, one being the *image target manager* which deals with the multiple image targets we have scattered throughout the stadium environment and a *manual target registration* which stores the details of various seat positioning and manual controls for initializing the stadium in the stadium AR application.

2) Data Manager: During a game, we obtain data from various sources, from the sports statistics provider to data from other mobile devices for crowd-based interactions and engagement. The data manager is the module that handles these incoming data and sends them to the right destination to be visualized or processed. It takes in data controllers that processes raw data coming in from the sports statistic provider which usually are XML queries so the coordinates and details are correctly translated if needed.

3) Visualization Manager: The visualization manager is the largest module, as it contains many scripts related to visualizations—from the actual stadium model itself to the text augmented onto a spectator stand. The visualization manager takes in output from the data manager and feeds it to the different visualization scripts attached to show the correct visualization at the right timing. The visualization manager also contains some game objects such as colliders as used in the indirect AR and XR prototypes. Currently, everything is still manually added to the manager when a new visualization is created but we look into automating it in the future as part of the dynamic instantiation characteristic.

IV. Implementation

Our implementation does not cover all of the characteristics of the framework yet as it is rather work in progress. It was built with a modular design and we did use global coordinates, however, dynamic instantiation which is something we derived after development is planned for future work. We describe the different prototypes we developed and the challenges we faced. For our project, we developed a total of four, mainly mixed fidelity prototypes, each with its own use-cases (Fig. 2). All of the prototypes described below are created in the Unity

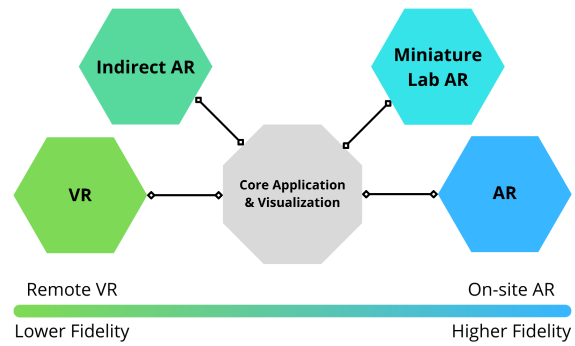

Fig. 2. Overview of our sports spectator XR prototypes, all originating from a core application where main components are synchronised between each prototypes.

game engine and are all contained in the same project within different scenes. Prototypes that utilize AR tracking were done using Vuforia for image target tracking and extended tracking. The basis of all prototypes was the same: a stadium environment with visualizations attached to it. However, the differences are in the implementation, use case, scale and environment the prototypes are being used.

A. Miniature lab AR

The miniature lab AR is a small-scale version of the final product, designed with the purpose to be used in the lab or in situations where portability is needed (Fig. 3). Utilizing a big A0 sized printed field with advertisement logos as an image target, it allows for a bird-eyes' view of the stadium model, while still allowing the various visualizations to be shown. Due to the smaller scale, this prototype is the only prototype that gives the user the ability to have a "God-mode" where they can walk around the stadium and view visualizations from different perspectives, including moving through the structure and viewing visualizations from inside the stadium.

This prototype contains all of the components mentioned in the framework, since it does have tracking, albeit on a different scale. It was originally developed for designing situated infographics. Since even in the stadium we cannot simply move around quickly to the opposite stands to test our visualizations, this prototype serves as an ecologically valid alternative by allowing evaluation of visualizations from various perspective to, e.g. prevent occlusions. All these can be done right in the lab without the need to visit the venue with an easier interaction method compared to manipulating a CAD model on the computer. On certain occasions, the miniature lab prototype was also used for user studies in a controlled lab environment, in which we investigated spatial understanding in situated infographics compared to traditional on-screen infographics.

The main disadvantage of this prototype is the single person experience. It is hard to demonstrate to a crowd as depending on where the person was situated in the environment, the perspective would be very different from the one in the lab

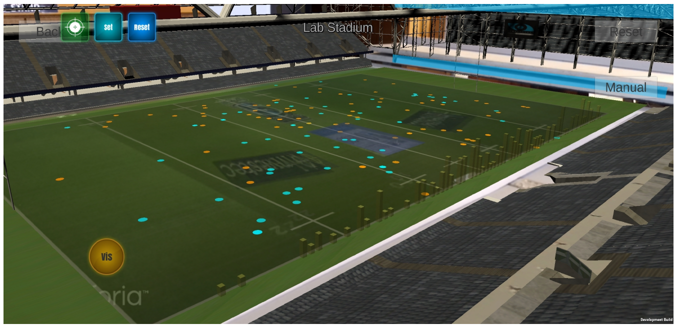

Fig. 3. Miniature lab AR prototype developed to ease evaluating visualizations from a third-person perspective

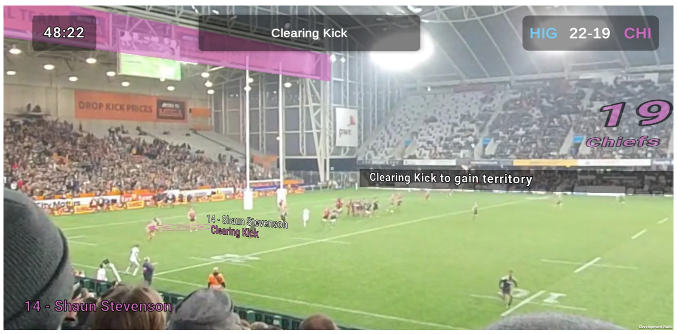

Fig. 4. Indirect AR Prototype mimicking what spectators will see at the stadium through their devices.

AR situation. In addition to that, occasional tracking errors cause misalignment of the stadium. It is more suitable for small groups where they can move around the printed poster as well. Apart from that, since visualizations appear smaller in the lab AR prototype due to the scale, it might give a false impression of the visualization size and orientation when compared to the actual use-case in the stadium. Often there will be visualizations looking just right on the lab prototype but was too large in the actual stadium scale environment.

B. Mobile Indirect AR

The mobile indirect AR prototype [5] is the main prototype used for out-of-stadium demonstration and lab studies (Fig. 4). We started off using 360 panoramic photos (instead of videos) captured in the stadium via a Ricoh Theta S to simulate the spectators' viewpoint as the Theta S only takes low resolution video. Upon upgrading to a Insta360 One X, we replaced still images with 360-videos. This gives the users freedom to look around the virtual environment in which the situated visualizations are placed. Depending on the scenario, different types of 360 videos have been used, such as an empty playing field or an actual game. This prototype proved to be very useful in the development and testing of visualizations as it is independent of the tracking challenges faced during an on-site testing environment or with the miniature lab AR prototype, meaning it does not have the tracking manager from the framework.

Since most of the demonstrations of the prototype are done out of the stadium, this prototype closest resembles using a mobile phone on-site. Users could see the visualizations as if they were seated in the stadium and can do almost everything that could be done with the actual AR prototype. This also makes it the best prototype for a user study evaluating visualizations on mobile AR since there will be less confounding variable effects regarding the tracking and localization. We conducted one on-site user study with the mobile indirect AR prototype despite being at the stadium. Participants viewed a recorded game while being physically in an empty stadium to get better understanding and immersion with the sports spectating use case. The mobile indirect AR is also more predictable and reliable in terms of data visualization compared to obtaining information from a live game.

One of the drawbacks of the mobile indirect AR is the quality of the 360 video as it is not as high quality as their mobile devices' camera. This is due to the technical difficulties of recording a 360 video in high resolution. Despite the video was being recorded with an Insta One X at 5.7k resolution, the footage is relatively blurry compared to a standard mobile devices' camera as the 5.7k pixels are spread out in a sphere. We are still trying to overcome this issue by using a professional grade 360 camera such as the Insta360 Pro 2 with multiple small cameras recording simultaneously. However, this device costs significantly more than the consumer-grade 360 cameras and would introduce a huge video file which might not be feasible for this prototype.

C. VR Prototype

The VR prototype is a continuation of the mobile indirect AR prototype, used in a VR headset. This prototype aims to recreate the closest experience to using an AR HMD at the stadium. By using the indirect AR prototype in a VR headset, users can turn their head around to look at the stadium surrounding while spectating a pre-recorded 360 video of a game, alongside with situated visualizations. Due to the lack of a reachable touch screen, this prototype forces the testing of alternative interaction methods as would happen when using an AR HMD, where users also cannot interact via touch screens. This prototype also retains the advantage of the mobile indirect AR prototype, which is the elimination of tracking and localization issues when compared to the other prototypes.

This prototype is the one to be used in terms of testing out a "hands-free" interaction experience as participants often complained of arm fatigue when using the mobile indirect AR for a prolonged period of time. This allows us to research on center of screen gaze-based input and also collect better data on where the spectators are looking at during the experience. When using the mobile indirect AR, some participants did not really move the mobile devices much, presumably this concept of AR is still quite new to them. On the contrary, moving ones head to view something is more natural and is easily picked up by participants.

Fig. 5. On-site Stadium AR Prototype where it closely resembles the final product. Players on field are real players.

Although this prototype might seem like the best off-site prototype to be used, it does still comes with its shortcomings. The lower resolution of the 360-video is slightly amplified as in VR, the pixels looks larger than on mobile, making the difference in quality even more noticeable. The other issue involves user studies in which facilitators of the user study would not be able to see fully what is happening in the VR HMD. There are casting options where the screen is replicated on a desktop such as the Oculus Cast, but the field of view still differs from what the actual participant sees in the headset.

D. On-site Stadium AR Prototype

The on-site stadium AR prototype (Fig. 5) closest represents the final product meant to be used in the stadium through a mobile device, although we did also implement a Microsoft Hololens AR HMD version. Among the prototypes, this was least used due to the lesser opportunity we have to conduct tests in the stadium, alongside the tracking challenges it faces. For this prototype, users watch the game through the mobile devices' camera, similar to what they see on screen when taking a video. However, through the AR interface, users gain additional game information in the form of situated visualizations [1], [4].

The challenges of an on-site AR prototype as mentioned was the accessibility to the stadium venue. Other than that, since spectator movement is limited during a game, it is hard to initialize the localization process using image target. Depending on seating, the image target might not be visible or is viewed from a perspective where the camera could not recognise. Therefore, another approach to tracking and localization is needed for the on-site prototype. We looked into different solutions such as Spherical SLAM [1] and line homography [16] to try to localize users in the stadium.

V. Conclusion

We presented our approach to support the development of research prototypes in an AR Spectator scenario, representing large-scale AR situations. With the proposed flexible XR framework it is possible to support a continuous process of on-site and off-site development, testing, and evaluation. We illustrated this with the presentation of our four different prototypes all targeting the final AR Spectator experience. We hope that our work will inspire and influence researchers in the area of AR and XR developments for larger scale environments. Our flexible XR framework is a first step to more effective and efficient research and development cycles.

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