A Systematic Review of Rapid Prototyping Tools for Augmented Reality

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***Abstract*—The creation of low fidelity prototypes for Augmented Reality (AR) applications can be more challenging compared to the others technologies. Due to the unique characteristics of AR applications (combine the real and virtual world) developers and designers can face a lack of tools that helps in the conception of low fidelity prototypes, reducing the possibility for testing new ideas and iterations. Based on an analysis of 39 different resources from research and industry, we discuss a set of artifacts (tools, frameworks, and software) for rapid prototyping for AR. We found 30 artifacts for high and low fidelity prototypes and provide a list of tools that can facilitate the design of AR applications for HMD and smartphone devices in the early stages of design, discussing their benefits and limitations. Paper prototyping and Wizard of Oz techniques were the most cited artifacts.**

***Index Terms*—augmented reality, prototypes, low fidelity, systematic literature review**

I. Introduction

Augmented Reality (AR) has become one of the trend technologies today, being adopted in several types of applications [49]. This popularity encourages development teams to invest in this technology. To ensure the quality of these applications, developers and designers need to apply a series of processes in the initial development phase to minimize the risk of designing the wrong product [10]. An example of a practice that minimizes this type of risk is the use of prototypes.

Prototypes are used for developing and testing ideas [27]. In software projects, prototypes can be used to evaluate the interface, proposed content, and the interactions of an application through the perspective of designers, customers, and users [52]. In addition, prototypes can be divided between low and high fidelity, representing, respectively, how close to the final product they look. Low fidelity prototypes can provide a cheap and simple method to gather information about a product in the early stages of design, but can be quite limited for achieving new insights. On the other hand, high fidelity prototypes can be harder to produce but can present new types of insights by being more close to the final product [43]. In more traditional technologies, there is a list of artifacts (frameworks, software, and tools) available that assist in the design of these prototypes.

A. Augmented Reality and traditional applications

Augmented Reality differentiates from traditional applications (screen-based systems) by combining the real world with virtual objects through a digital overlay. However, being able to see the world in that way creates implications for designers and developers. While traditional virtual applications rely on screen-based elements, AR designers must take the environment into account [21].

According to Lauber et al. [25], when developing AR applications, two characteristics must be consider in the early stages of design: content stabilization and coexistence of virtual and real content. These two characteristics concern only AR applications.

Krevelen et al. [49] also presents some of the requirements for an AR system to work and display virtual objects into real environments:

- Tracking sensors;
- User movement tracking;
- Modelling 3D objects techniques;
- Inertial.

The user movement tracking must have higher accuracy to set the right perspective to users and handle the objects occlusion. Modeling techniques are required to create 3D objects that will blend with the environment [49]. Even the interaction, that utilizes gestures and voice commands, is different compared to other virtual environments applications [45].

All these requirements differentiate AR from other systems, showing new challenges, especially in the early design stages. Due to these requirements, there is a lack of tools to quickly iterate and create new ideas utilizing low fidelity prototype methods. Other virtual environments and screen-based interfaces offer many tools to create design concepts and prototypes. Figma[1], Sketch[2], and Photoshop[3] are examples of tools that are easy to learn and also offer all the fidelity spectrum expected for these interfaces.

Nibeling et al. [32], in their position paper, discussed the authoring tools for AR/VR that facilitate the creation of rapid prototypes classifying them in five classes focused on 3D content, interactions, scenes, and mobile screens. However, the study is a position paper and presents only the authors opinions about the problems of authoring tools for rapid AR prototyping. The study also not systematically review the authoring tools.

Therefore, the purpose of this study is to systematically review the state-of-the-art in the AR rapid prototyping area, finding the tools, trends and opportunities regarding this topic.

B. Study organization

This paper is organized as follows. The next section contextualize Augmented Reality and Prototypes. In the Review Methodology section, we detail the research questions and the protocol that was followed during the systematic review. In Results we present an analysis of the results found during this study in order to answer the research questions. Finally, in Conclusion, we present our conclusions and final considerations.

II. Background

This sections presents an overview of the main themes of this study. Next, we contextualize Augmented Reality in order to provide an overview about the area. Finally, we detail the concept of Prototypes.

A. Augmented Reality

Augmented Reality (AR) is a technology that supplements the real world with virtual elements in order to coexist, transforming the environment around us with new information [30]. AR allows us to interact in a different way with the environment, extracting new experiences and visualizations of the world. Such technology has been growing rapidly and today, most of the mobile devices can use some form of AR interaction.

According to Azuma [7], for a system to be considered as AR, it needs to follow three characteristics:

- Combines real and virtual;
- Allows interactivity in real time;
- Set objects in a 3D environment;

AR is also not limited by the sense of sight. This type of technology will potentially apply to all senses, including hearing, touch, and smell [49].

[1]https://figma.com
[2]https://sketch.com
[3]https://adobe.com

B. Prototypes

Prototypes are the representation of an idea or hypothesis of a design built before a product's final artifact exists [10]. Prototypes can be used to evaluate the quality of content, aesthetics, and the interaction of an application from the perspective of designers, customers, and users [27]. Typically, a development team conduct tests with prototypes in order to watch users perform typical tasks of the product to be designed. Through these tests, the team collects a series of information such as errors and comments from the participants. Thus, developers and designers can identify usability problems in the early stages of development, even before any substantial effort has been invested [10].

Fig. 1. Low fidelity AR paper prototype example.

The most usual classification of prototypes considers their fidelity to the final product. Specifically, low fidelity prototypes provides a cheap, flexible, and simple method of gathering information about the product to be built in the early stages of development. One of the main low fidelity prototyping techniques is the use of paper prototypes [10]. Paper prototypes allow designers to demonstrate the behavior of an interface in the early stages of project development, as well as being able to test ideas conceived with real users quickly [43]. This type of prototype can bring results that can dramatically improve the quality of the product [27]. Rettig [42] describes the advantages of low fidelity prototypes using paper, in addition to demonstrating a systematic approach to testing with users:

- Fast prototyping;
- Usability tests with real users in the early stages of design;
- Easy and quickly to iterate on new ideas.

According to Lim et al. [27], low and high fidelity prototypes can capture the same usability problems even though they have different degrees of development. To Rettig [42], high fidelity prototypes can take a considerable time to be built. In addition, in high fidelity prototypes, designers are more likely to receive criticisms unrelated to the purpose of the test (such as improving the usability of the product). This happens because the prototypes are very similar to a final product and end up calling attention to other aspects that are not relevant to the initial stage of development [27].

Fig. 1 shows an example of a low fidelity AR prototype, made with paper and a pencil, trying to replicate a virtual text label on a tomato. With this prototype, designers can quickly iterate on how the virtual information will be displayed to the users without any development effort. Fig. 2 shows the final AR application design, applying the concepts learned on the low fidelity prototype.

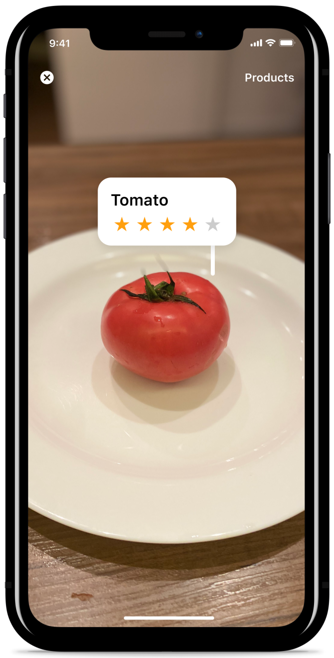

Fig. 2. Final AR example application.

III. Review Methodology

This section provides an overview of our search method, goals and research questions (RQs).

A. Overview (Systematic Literature Review)

To perform this research, we utilized the systematic literature review (SLR) guidelines proposed by Kitchenham and Charters [24]. This type of review is suited for acquiring theoretical background about certain topic, which then enables other research activities to be conducted. We also found that relying on academic literature alone might be quite limiting [50]. Therefore, we utilized the multivocal literature review (MLR) guidelines for including grey literature (non-published, nor peer-reviewed sources of information) proposed by Garousi [18] to combine both the state-of-the-art and -practice in the AR low fidelity prototyping area. Our literature review process is shown in Fig. 3 and detailed in the next subsections.

B. Goal and research questions

The goal of this study is to systematically review the state-of-the-art in the AR rapid prototyping area, finding the tools, trends and opportunities regarding this topic. We raise the following research questions based on the mentioned goal:

- **RQ1:** Which artifacts (tools, frameworks and software) can be used to facilitate the creation of low fidelity prototypes for augmented reality?
- **RQ2:** What are the most used artifact for low fidelity prototyping on AR?
- **RQ3:** What are the common challenges faced when prototyping in low fidelity for AR applications?

C. Search strategy

For the search process, we took the following steps in order to: identify the databases and define the search terms.

1) Identify the databases: According to Neuhaus et al. [33], Google Scholar includes all the majors publication databases in computer science. Therefore, we used Google Scholar for searching scientific papers and the Google search engine for grey literature sources.

2) Identify the search terms: We developed our search string iteratively to ensure that the most relevant sources would be found, following the guidelines established by Garousi [18]. Therefore, our first search string was: *"(augmented reality) AND (rapid) AND prototyping"*. After some rounds of searches in the selected databases, we found some papers that use the word *"low fidelity"* for as a synonym for rapid. Therefore, we added the word on the search string. Finally, we determined our final search string to be: *"(augmented reality) AND (low fidelity OR rapid) AND prototyping"*.

D. Inclusion and exclusion criteria

We defined inclusion and exclusion criteria to ensure that all relevant sources are included. This phase establishes the requirements that papers and resources must accomplish in order to be included or excluded in the study. The following inclusion and exclusion criteria are presented below:

- **Inclusion criteria:**
  - Resources/studies that present an artifact (tool, framework or software) for AR low fidelity prototyping;
  - Resources/studies that explain the usage process of those artifacts.
- **Exclusion criteria**
  - Resources/studies whose main objective is not related to prototypes for AR;
  - Resources/studies that do not present some type of artifact for prototyping to AR;
  - Resources/studies that do not specify, in the abstract, an artifact for AR low fidelity prototyping;
  - Duplicated resources/studies.

Finally, we conducted a forward and backward snowballing[4], following the guidelines proposed by Wohlin [53],

[4]Snowballing is the process that use the reference or the citation list of a paper to identify additional papers.

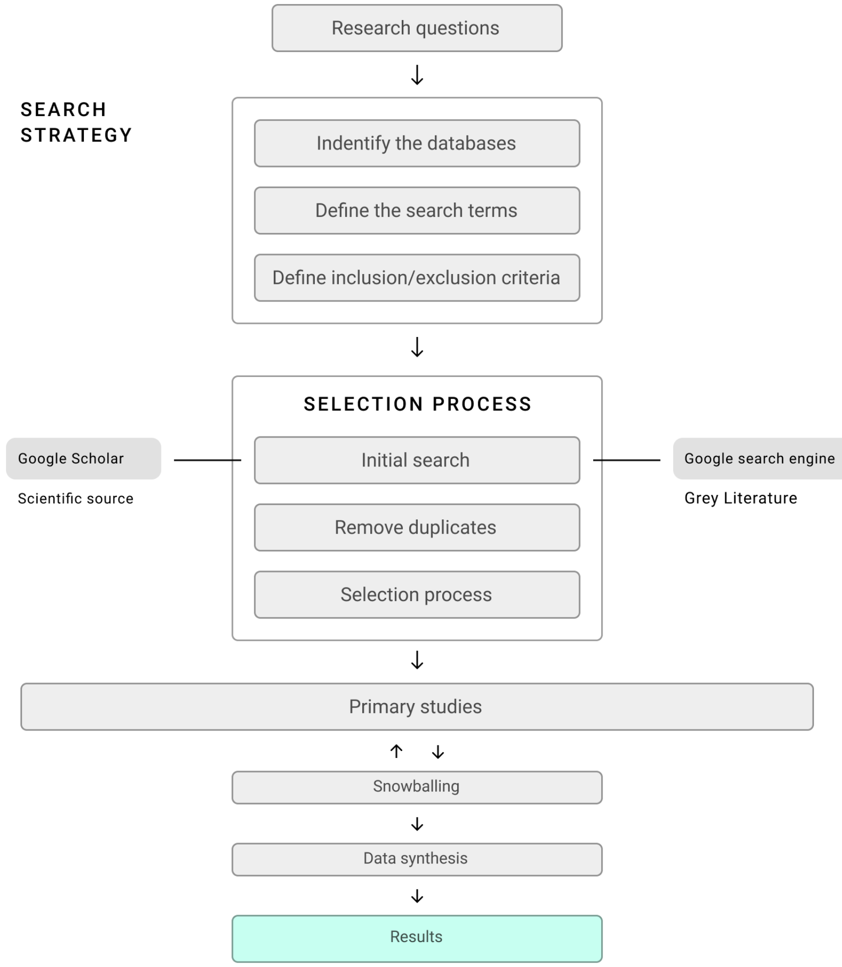

Fig. 3. An overview of our literature review process [11].

on the set of papers already in the pool, to ensure that all the relevant technical papers are included.

E. Final pool of sources

Our initial pool started with 758 sources. After an inclusion and exclusion criteria filter applied on the abstracts, just 39 sources left: 21 from peer-reviewed sources and 18 from the grey literature (e.g., internet articles and white papers).

IV. Results

Results of the study are presented in this section, according to the research questions.

A. RQ1: Which artifacts (tools, frameworks and software) can be used to facilitate the creation of low fidelity prototypes for augmented reality?

To respond this questions, we analyze the artifacts that better address the replication of an AR application proposed by Azuma et al. [7]: combines real and virtual worlds, allow interactivity in real time and the possibility to set objects in a 3D environment.

The results revealed that there are at least 30 artifacts that help in the design of rapid prototypes for augmented reality applications. Fig. 4 shows the artifacts by the skill required and level of fidelity. For the distribution of artifacts shown in this image, we considered the skill set required to a non-technical user to create an AR prototype. For instance, we see the Video artifact way below Unity. This happens because recording a video is a more easy and accessible way to prototype an AR application than use a developer IDE like Unity, for a non-technical person.

During the full reading of the studies, it was clear that most of them used more than one artifact for the creation of the prototypes. Therefore, the same tool or software appears in several researched sources. The artifacts from each source were classified according to the level of fidelity of the proto-

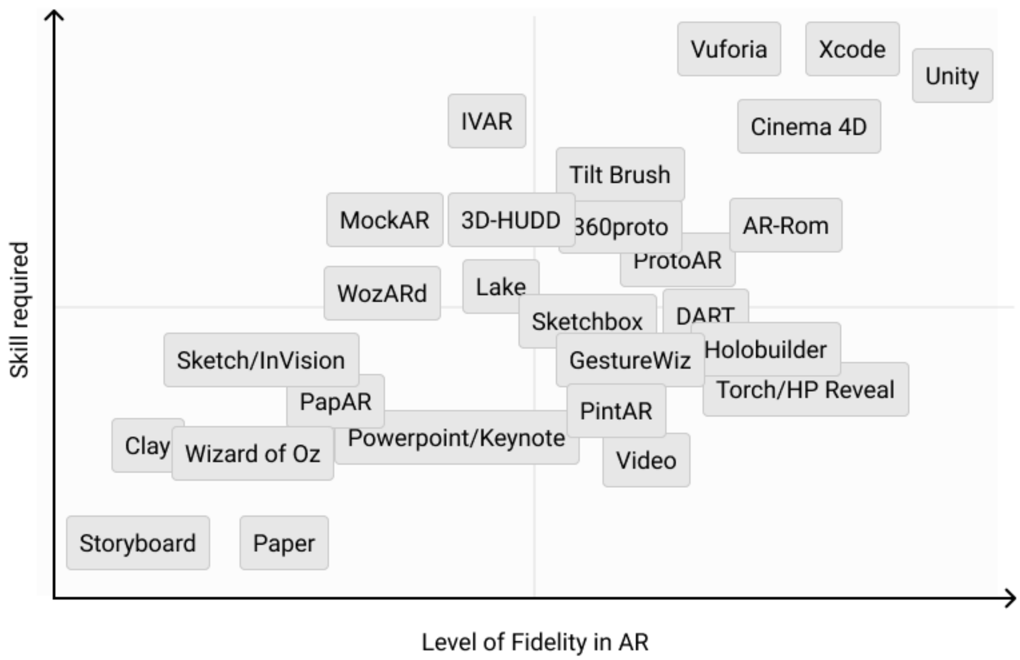

Fig. 4. All the artifacts founded distributed by level of fidelity (*x*) and skill required (*y*). The *y* axis values are based on the skill set of an end-user and non-technical person. The *x* values are based on the artifact level of interactivity and concept presentation.

type they presented. For example, in the study by Nebeling et al. [31], the artifacts presented can be used to create prototypes from low to high fidelity.

Next, we present the studies that stand out the most, concerning the design of AR prototypes along the fidelity spectrum. Nebeling et al [31] present a tool that combines low and high fidelity techniques, using paper and clay as the main artifact for creating the digital elements of the application, the first for the UI wireframes and user flows and the second for 3D objects. From this, ProtoAR, a tool developed by the researchers, scans the objects made in clay and transforms them into 3D virtual objects, using an overlay method to show them on screen. Other studies also use some type of Paper prototype method like Storyboards and Sticky Notes [25] [23] [8] [39]. Lauber et al. [25] proposed a paper prototyping technique for AR applications called PapAR where designers, by drawing on two layers of paper instead of one, can represent the dynamic behavior of this type of system. The first layer represents the real-world scenario and the second the device field of view. This technique represents how methods that are familiar to us, like Paper, need to adapt to work properly due to the unique characteristics of AR applications. Fig. 5 an example of the two-layer AR prototype. The device field of view is created by cardboard with notes attached to it, representing the virtual dynamic buttons.

Many studies [2] [12] [48] [13] [26] [15] addressed the possibility of interactions in both a physical and digital environment, using a technique called Wizard of Oz[5]. The application called WozARd [2], for example, provide a set of tools that help the test leader to control the participant test. Chen et al. [12], provide a method for testing mobile applications remotely, where the test leader manipulates the application that is being tested through a video call.

In the study by Alce et al. [3], a technique for using virtual reality (VR) for prototyping AR applications is described. According to the authors, the sense of ”being in the environment” is important for creating usability tests, something that VR provides. They also allow the users to produce 3D content in a easy way. Other studies corroborate the idea of using a virtual environment for creating prototypes in AR [51] [4] [36] [37]. Regarding this aspect, the two artifacts that stand out the most are the Tilt Brush [6], Storyboard VR [7] and Sketchbox[8]. However, even though these tools can facilitate the creation of prototypes, they end up not being very easy to share with others due to the type of equipment required and the individual focus experience they provide [37].

According to Park [34], the use of markers tracked by the AR applications camera can also facilitate the creation of AR prototypes. The markings helps to registered 3D objects in the scene. Other artifacts help in reading these markings, such as

[5]Wizard of Oz is a technique that allows users to use a digital application controlled by a human, giving the illusion that the processes are being conducted by a real computer [2].

[6]https://www.tiltbrush.com/

[7]https://www.artefactgroup.com/case-studies/storyboard-vr/

[8]https://https://www.sketchbox3d.com/

HP Reveal [9] [29].

According to the study by de Sá et al. [44], the use of videos can help in the rapid design of prototypes by providing a rapid way to simulate an AR application camera. After a post production process in a video editor application, this artifact can effectively reproduce the combination of real and virtual world. According to the authors, the use of videos as artifacts provides relatively high fidelity for the prototypes, however, lacks in terms of interactivity. Other studies seek to use the video with presentation platforms, such as Keynote[10] and PowerPoint[11] [40] [6].

Table I shows the found artifacts. A series of other artifacts also appear in the results:

- AR-Room, a component, and a scenario-based prototyping framework [34];
- MockAR, an application for designing interfaces of AR handheld applications [22];
- GestureWiz, a prototyping tool that allows gesture definitions [45];
- IVAR, a framework that uses a virtual environment for prototyping wearable AR applications [3];
- PintAR, a tablet application that utilizes a pen for drawing simple sketches and visualize them in an AR application [19];
- Lake, a mobile application tool that uses Wizard of Oz to simulate AR interactions [16];
- Holobuilder, a tool similar to PowerPoint for creating AR applications for factories and industries. [46];
- 3D-HUDD, an application for the conception of a HUD (head-up display) in 3D environments [9];
- Cinema 4D, a robust tool for the creation of 3D objects that can be used in AR [5];
- 360proto, a group of digital tools that can capture paper mockups and preview them in a Google Cardboard, set interactions events through a live editor and an app for test the prototypes [30];
- Vuforia, a software development kit (SDK) for AR [14];
- HP Reveal and Torch [20], mobile applications that allow users to create and manipulate AR prototypes by adding 3D objects and defined interactions;

Sketch and InVision [20], tools that allow users to create 2D interfaces and define regions of interactions, also appear in the results. Their main objective was to create 2D screen-based elements for AR applications. However, these tools don't have any interaction focused on AR, working mainly for traditional interfaces.

B. RQ2: What are the most used artifact for low fidelity prototyping on AR?

The results show that the most used low fidelity artifact in the concept of AR prototypes is the usage of paper [25] [31] [12] [40] [21] [22] [38]. Paper is still commonly used for prototyping, even technologies such as AR that offer novel types of interactions. Paper also offers great flexibility when combining other features like post-its and other types of sticky notes, especially when trying to reproduce a low fidelity HUD (heads-up display) [38]. From these artifacts, it is possible to check the size of labels and fonts to be used in the final product, in addition to other usability problems involving the user interface. Fig. 6 shows the low fidelity techniques to address the Azuma et al. [7] requirements for an AR application.

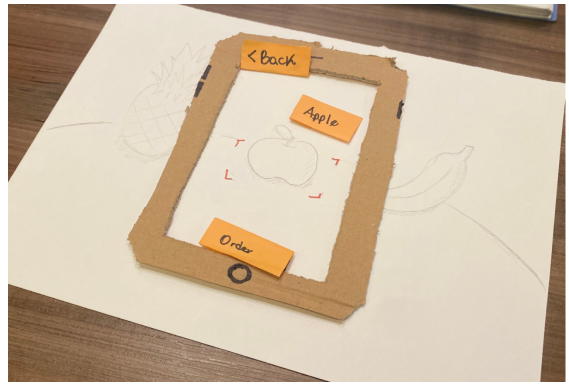

Fig. 5. Two-layer paper AR prototype. The cardboard layer represents the mobile device field of view. The paper layer represents the real world.

Another artifact that stands out within the low fidelity spectrum is the Storyboard. Berry [40] proposes the use of storyboards to obtain a macro view of how the user will interact with the environment. From drawings on paper in the form of a visual story, the storyboard technique allows developers to visualize how the product will be used from the user's perspective in different environments. Another point discussed is the concept of these storyboards that, for AR prototypes, should always be built with an external view (third-person) in mind, showing all the environment elements the user have, and never based solely on the smartphone screen or HMD (head-mounted display) [8].

C. RQ3: What are the common challenges being faced?

According to McIntyre et al. [28], the main problems faced concerning augmented reality prototyping area:

- There are no simple, flexible programming environments for AR;
- 3D content is expensive and time-consuming to create;
- Dealing with multiple, unrelated tracking technologies is extremely difficult;
- Sensing and reasoning technologies are expensive (in time and money) to create and deploy;
- There is no separation of concerns between system components;
- Managing relationships between the physical and virtual worlds is difficult;
- Having to actually work (develop) in the physical world can be prohibitively difficult;
- Working in real-time is difficult.

[9]https://www8.hp.com/us/en/printers/reveal.html
[10]https://www.apple.com/keynote/
[11]https://office.live.com/start/powerpoint. aspx

Author	Date	Artifact used	Source type	Prototype fidelity
M. Nebeling et al. [31]	2018	ProtoAR, Paper, Clay	Scientific paper	High, low
B. MacIntyre et al. [28]	2004	DART	Scientific paper	High, low
M. de Sá and E. Churchill [13]	2012	Paper, Wizard of Woz, Video	Scientific paper	Low, mixed
M. Nebeling [30]	2019	360proto	Scientific paper	High, low
K. Chen and Haoqi Zhang [12]	2015	Paper, Wizard of Oz	Scientific paper	Low
A. Thompson and L. E. Potter [47]	2018	Smartphone frame	Scientific paper	Low
F. Lauber et al. [25]	2014	PapAR	Scientific paper	Low
G. Alce et al. [2]	2013	WozARd	Scientific paper	Low
G. Keating et al. [23]	2011	Paper, Sticking, Smartphone frame	Scientific paper	Low
M. Lee and M. Billinghurst [26]	2008	Wizard of Woz	Scientific paper	High
M. de Sá et al. [44]	2011	Video	Scientific paper	High
Jong-Seung Park [34]	2011	AR-Room	Scientific paper	High
A. J. Hunsucker [21]	2017	Paper, Wizard of Oz	Scientific paper	Low
M. Speicher and M. Nebeling [45]	2018	GestureWiz	Scientific paper	High
A. Kampa [22]	2016	MockAR	Scientific paper	High, low
G. Alce et al. [3]	2015	IVAR	Scientific paper	High
D. Guasques et al. [19]	2019	PintAR	Scientific paper	High
A. Finke [16]	2019	Lake	Scientific paper	Low
M. Speicher [46]	2015	Holobuilder	Scientific paper	High
N. Broy et al. [9]	2015	3D-HUDD	Scientific paper	High
S. Dow et al. [15]	2005	Wizard of Oz	Scientific paper	Low
G. Sheridan [14]	2018	Unity, Xcode, Vuforia, Video Prototyping	Grey literature	High
D. Hong [5]	2019	Unity, Xcode, Vuforia, Cinema 4D	Grey literature	High
K. Hamilton [20]	2019	Torch, Sketch/InVision	Grey literature	High
P. Dawande [6]	2020	Keynote	Grey literature	Low
P. Mealy [51]	?	Sketchbox, Storyboard VR	Grey literature	High
J. Przybylo [41]	2018	Paper, Sketch/InVision, Video	Grey literature	Low
L. Vasquez [1]	2019	Unity, Paper, Storyboard	Grey literature	Low
K. Green [48]	2012	Wizard of Oz, Paper, Storyboard	Grey literature	Low
A. Berry [40]	2012	Keynote, PowerPoint, Unity	Grey literature	High
Woman Techmakers (Youtube Channel) [39]	2019	Paper, Video	Grey literature	High
Apple (Company) [38]	2018	Keynote	Grey literature	Low
A. Berry [4]	2019	Paper, Video, Storyboard, Storyboard VR	Grey literature	Low
Google (Company) [8]	2018	Paper, Storyboard	Grey literature	Low
PowerPoint Spice (Youtube Channel) [29]	2017	PowerPoint, HP Reveal	Grey literature	High
S. Kamppari-Miller [35]	2019	Paper, Clay, Storyboard	Grey literature	Low
R. Poulson [37]	2018	Tilt Brush	Grey literature	Low
I. Kunjasic [36]	2020	Tilt Brush	Grey literature	Low

TABLE I
SYSTEMATIC REVIEW STUDIES.

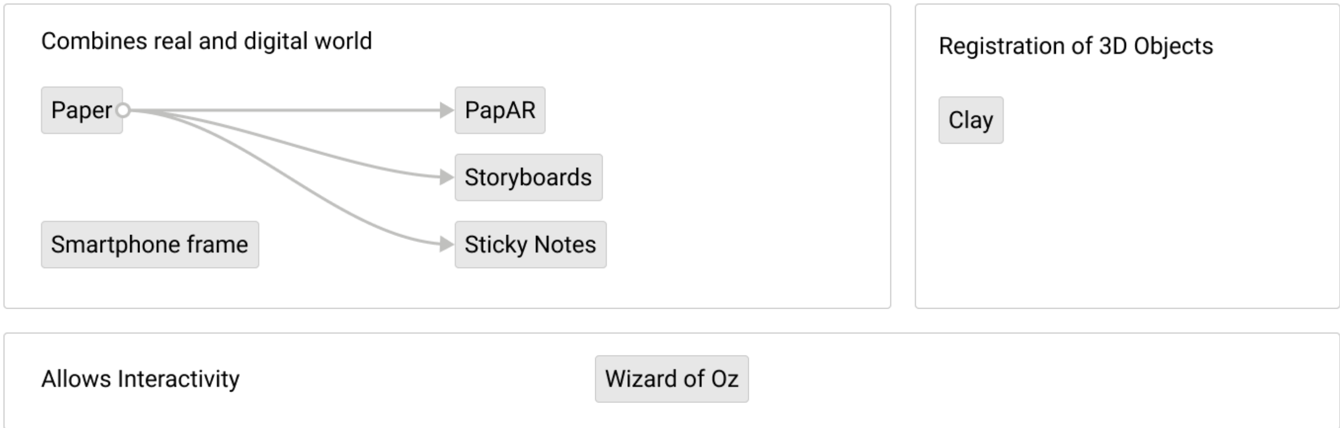

Fig. 6. AR Low fidelity techniques that address the Azuma et al. [7] requirements and do not require any software. The arrows represent the inheritance from the artifacts.

The study was one of the first papers to explore the development of an authoring tool (DART) for prototyping for AR. The researches points out that, in 2004, there were not many programming environments proposed at creating projects in AR. Nowadays, we have examples like Unity and Xcode, which offer a more robust environment for creating AR projects [1][5]. However, such environments are intended only for programmers, making the process inaccessible to people who have no knowledge of programming. In 2014, Gandy et al. [17] analyze the current state of DART and concluded that the problems raised in the 2004 paper concerned with AR prototyping still relevant. The researches also concluded that there is a lack of authoring tools for non-technical persons regarding AR prototyping.

The study also points out the difficulty of creating projects that involve a 3D environment, due to the complexity of creating such assets. ProtoAR [31], as seen in the sections above, can scan objects made of modeling clay, facilitating the work of creating 3D objects for AR projects.

Regarding the camera, two studies [23] [47] propose the use of a 3D printer to create a prototype smartphone without a screen, making the device's hole simulate the actual visualization of an AR application. According to the studies, simulation of the camera in low fidelity is one of the main problems of prototyping AR applications for smartphones.

Another problem found is about the difficulty of prototyping the interactions of an application in AR, pointed out by four studies [12] [26] [2] [22] [1]. According to the researchers, prototyping interactions in a cohesive way can be quite difficult, especially those involving gestures and audio. Table II shows the prototyping challenges and the rapid prototypes techniques [45].

Prototype challenge	**Artifact address**
3D Objects	Clay, ProtoAR, Vuforia, Unity, Cinema 4D
Gesture	GestureWiz, Wizard of Oz, Sketch
Validated interactions	Wizard of Oz, WozARd, ProtoAR, DART, MockAR, Lake, PowerPoint, Keynote, Sketch
Camera simulation	Smartphone frame (3D printed), Video
Communication of concepts	Paper (Stick Notes), Storyboard, 3D-HUDD, Video, PintAR
Real-time environment	Wizard of Woz, WozARd, Lake, Unity, Xcode

TABLE II
PROTOTYPING CHALLENGES.

V. CONCLUSION

Augmented reality is still a very recent trend in our daily lives, compared to other technologies. However, it has gained a lot of space in the mainstream with different applications such as Pokemon Go [12] and the Google Translate ambient live translations [13]. Therefore, it is important that the quality of these new applications can be maintained, providing the best experience for its users in terms of development.

[12]https://pokemongolive.com/pt$_b r/$
[13]https://translate.google.com

With this in mind, testing and prototyping, right in the early stages of development, becomes essential for the final quality of the product. In this study, we present, through a literature review that uses both academic and industry data, 30 artifacts that facilitate the development of prototypes in AR. We went deeper into understanding of what artifacts (tools, software, and frameworks) are available to facilitate the creation of these prototypes, focusing mainly on low fidelity aspects.

From the results, artifacts that use Paper or Wizard of Oz techniques were the most cited, especially when it comes to low-fidelity prototypes. Another finding was the use of virtual reality (VR) for the creation of prototypes in AR, which enables greater control over the test environment.

The sources studied, both scientific and industry (grey literature), showed us the importance of prototyping in the early stages of development, revealing a lack of research, especially in the context of low fidelity.

VI. Limitations

Our filtering of scientific studies was based only on abstracts and papers that propose some tool, software, or framework for AR prototyping. Therefore, papers that used some artifact to create a prototype in AR and that did not mention the same in their abstract, were left out of the study.

Because we chose to use grey literature to obtain an overview of the industry in relation to the topic, many of the artifacts and studies presented were not independently validated.

VII. Acknowledgment

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