A Perspective on Distributed and Collaborative Augmented Reality

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Abstract

This paper surveys the field of Augmented Reality (AR) with an emphasis on the future of distributed and collaborative AR. A summary of the state-of-the-art in AR and its current challenges is presented. This includes sense augmentation, hardware platforms, registration and tracking, interaction, and health concerns.

Keywords: Collaborative Augmented Reality, Distributed Augmented Reality, Computer Supported Collaborative Work, Sense Augmentation.

1. INTRODUCTION

Augmented Reality (AR) is a human computer interaction technique that allows combining digital virtual elements with the real world environment. AR allows computer generated data to be aligned or registered with the real world environment in real time. Augmentation might give a feeling of removal of real objects from senses with applying virtual data [15].

With AR, the user can interact with the real world environment in a natural way, while using and interacting with the computer generated data to utilize related information [111]. As seen in Figure 1, Milgram's Virtuality Continuum Diagram [97] explains the position of AR in the reality domain. Azuma's definition is commonly accepted for an explanation of augmented reality. Azuma defines AR as a combination real and virtual imagery with registration of the virtual imagery on the real world, accompanied by real time interaction [16].

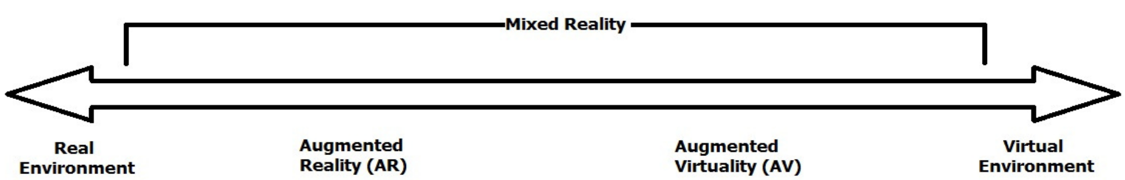

FIGURE 1: Milgram's Virtuality Continuum [97].

Augmented reality is an interdisciplinary field that overlaps a wide array of areas including human computer interaction, computer vision, wearable and distributed computing. AR applications can be applicable for several domains such as engineering, aviation, telecommunication, entertainment, health-care [28], marketing, law enforcement, construction, manufacturing [107], planning, training, maintenance/repair [56, 144], design/art and education. Nikou et al. [109] showed AR solutions for orthopedic surgery. Juan et al. [70]'s experiment of phobia treatment indicates AR can be used for treatment purposes. Olfactory augmentation can be used to treat post-traumatic stress disorder or similar cases on virtual reality therapy treatments [31].

Since the 1960s several symposiums, conferences and workshops have been organized for AR and virtual reality, internationally [6]. However, AR accepted distinct research area after the 1990s.

2. AUGMENTATION OF SENSES

AR can be applied all kind of senses. Vision, hearing, touching, smelling and tasting can be augmented for different purposes. Different augmentation types have their own challenges.

As a UI solution, audio has been used for a long time. Sound makes us aware of the environment. With sound, we assume the existence of the source object and with echo, we can understand the distance of the objects. However, the standalone effect of sound augmentation is not widely explored. As an example; Zimmerman et al. created audio augmentation to provide information based on interest, preferences and motion of museum visitors [4].

Olfactory augmentation is one of the undeveloped augmentation areas. There are no discovered primary odors. Lack of primary odors make it difficult to generate scents. Humans can detect approximately 400k chemical compounds as odor. Based on the research of Buck and Axel [152] and recent genome analysis, humans have approximately 350 scent receptors. Some researchers accept 350 as the prime odor number. Nambu et al. [104] and Hyung-Gi et al. [29] try to decrease the number of required scents based on vision because some scents have similarities, and human's vision-smelling relation may be tricked.

Scents are used for increasing consumers' commercial activities and user psychology. Washburn et al. [145] surveyed the effects of scent on data visualization. In their analysis, they pointed out olfactory augmentation improves data visualization and user understandings. In addition, scent is affecting other senses. Mochizuki et al. created a virtual reality game to understand relation of vision and scent [99]. Scents are pre-produced and augmentation systems are using cartridges to diffuse smells.

Gustatory augmentation is challenging due to the complicated nature of taste sensation. Narumi et al. [106] created gustatory augmentation with combination of visual and olfactory augmentation. Nakamura et al. [102] try to differentiate taste with electricity. If they become successful, sensing of tongue can be increased and we can understand part of complexity of tasting.

Touch is the major interaction method of humans. Unlike gustatory and scent augmentation, haptic augmentation can be simulated. Tactile displays can be categorized as, Braille display for the visually impaired and the haptic device to make the virtual world gets tactile textures and seems more real [72].

Different kind of receptors of skin can be stimulated with electrodes or vibrations. Kajimoto et al. accepted Merkel cell, Meissner corpuscle and Pacinian corpuscle receptors as primary receptor to create similarity with primary color in visual augmentation [72]. The majority of haptic augmentation research is in the medical area. Khademi et al. [76] used haptic AR for rehabilitation process. Kurada et al. used haptic augmentation for surgical navigation [82]. Haptic AR is an effective learning tool for virtual surgery. Seokhee and Harders created multi-point interaction with virtual tumor [67]. Especially in robot assisted surgeries, operator needs to feel for issues. Several researches [115, 33, 103] focused on this problem. It is also used for medical [148, 71, 128, 68] and other training [147] and learning [54, 5, 69, 98, 26, 149, 135] purposes.

Dima et al created haptic AR solution for museums [41]. This way users can interact with artifact that normally they aren't allowed to touch.

Haptic augmentation can be used for other robotic solution and unmanned vehicles. Haptic feedback provides different pressure to remote operator. The feedback depends on the robot faced force [3, 58, 59]. The system decreases the response time of the user. OzBot [45] is designed for search and rescue operations with haptic feedback to operator.

Haptic AR is an effective tool for designing implants and working in sensitive areas [66]. Scharver et al. [133] is able to create implant with haptic feedback from patients.

In the research, different augmented reality solutions started to be used together. Currently gustatory AR mainly depends on other AR solutions. Researches show merging several augmentation increase success rate of application [43].

3. HARDWARE AND DISPLAY SYSTEMS

Combining the virtual and real world is one of the most challenging design factors for successful AR systems. This can be achieved with several hardware systems. Researchers are developing hardware for different kind of augmentation [105, 138, 55]. However, AR researches are mostly focused on sense of sight. Mainly computers, electronic glasses, headgears, mobile devices and projectors are used with visual augmented reality applications. Different hardware platforms has their own advantages and disadvantages. There are studies [61,112,151] that show the effect of the screen size or type on task performance, but they produce mixed results. Selection of hardware depends on application development and purpose. In recent years different tools are released for augmented reality purposes. Google Glass [50], Epson Smart Glass [44] are examples of daily user focused electronic glasses on the market. Also specific application related tools are released. Daqri industrial smart helmet [38] is example for it.

Wearable headsets are usually using LCDs or laser image displays (Retinal Image Display-RID). RID requires a complicated mirror and lens system that is decreasing possibility of reducing the size of the display. That is making LCD displays much preferable. However, reducing the size of RID is still an ongoing research area. Katsuyama et al. able to reduce size of a laser beam combiner no larger than a grain of rice [74]. Furthermore, other display improvements are enhancing AR. Magic leap [90] created AR device based on glasses-free 3D tensor displays [146] for more natural, user friendly environment. Microsoft has announced their holographic display solution [96]. Holographic display can be considered for mixed reality solution. HoloLens contains CPU, GPU and HPU (Holographic Display Unit). In addition, Solutions like NVidia's Near-Eye Light Field Display [84] provide thinner and lighter head-mounted displays. Stereoscopic displays usually are considered for virtual reality solutions. However, there are several solutions for using stereoscopic displays for augmented reality. Different headset designs have a large variety of field of views. Researchers are trying to achieve better field of view with different techniques. Cheng et al. [32] applied free form prisms and lenses and Zheng et al. [34] designed an off-axis optical system with x-y polynomial surface for this purpose. This design achieved a 15 mm exit pupil, a 40°×30° FOV, and 70 mm eye relief.

Smart phones and tablets are multi-purpose mobile devices. They have high and increasing amount of usage. Having several efficient parts like camera, GPS, gyroscope, accelerometer and mobility advantage makes these devices suitable for augmented reality.

Projection approach projects the desired virtual information directly on physical objects to be augmented. Cassinelli at al. [30] created laser based projector that is capable of augment all kind of surfaces while simultaneously scanning projection surface information like shape, texture, reflectivity etc. with another laser beam. That allows feature based registration abilities.

When manipulating visual data captured by the eyes, changing information at eye level with contact lenses are considered. Lingley et al. designed a single-pixel wireless contact lens display [88]. Prototype with LED display worn by rabbits for 20 minutes at a time with no adverse effects. However, increasing pixel amount, focusing close range and health issues are still challenges for this approach [121]. Focusing close range is generally problem for augmented reality solutions. Usually optical object needs to be used between eye and display. Innovega created lenses for this purposes [2]. These lenses allow user to focus augmented reality display. Main purpose of the approach to allow immersive augmented reality solutions.

For audio augmentation, we are using auditory displays to create sound. Curran surveyed audio haptic, tangible audio displays in his book [37]. In his book, he points out tangible user interfaces and auditory displays needs to improve. Pebblebox [116] and Reim Toolbox [37] are example of audio haptic tools for audio augmentation.

SmartTools [72] are used for haptic augmented reality. Tools like pen or surgeon equipment are integrated with sensors and feedback devices. Ando et al. [9] created finger mounted module that using vibrations called SmartFinger. Whenever user try to interact with visual data or object, feedback devices will give force, like electricity or pressure, to user. Kajimoto et al. [72] created tactile display to stimulate receptors. Teslatouch [17] gives haptic feedback on touch screen with electrostatic friction between screen and users finger. ImmersiveTouch [89] is a high-resolution and high-pixel-density stereoscopic display with a head and hand tracking, and haptic feedback systems. Recently haptic augmented reality devices started to be on market. Touch based augmented reality device named Gloveone [49] has been announced. It gives user the feeling effect with vibrations. Projection augmentation model is also used for haptic AR systems. Visual image can be projected on a real object that has haptic feedback abilities. User can interact with visual objects with the help of real objects [21]. Bertham et al. [22] created tactile helmet for haptic AR. The helmet, that mimics animal whiskers to gather information, can get environmental data. Wozniak et al. [62] created a haptic glove that gives feedback related to color information. The glove is primarily designed for color blind people to see environment with haptic sense. RippleTouch [150] is providing full body haptic AR system with low frequency acoustic wave propagation properties of the human body.

Olfactory augmentation can be created with specific scent generator. Several patents and researches are developed by researchers. Krull designed a scent generator that is activated by heat. [81] Scent distributing systems or scent generators require specific multimedia devices. Scent delivery can be created two different way. It can be provided with direct inhaling with scent mask or tubes. Manne developed wearable scent delivery platform for direct inhaling. [92,93] Scent also can be distributed to the user's nose by diffusion. Research of Manne [94] and Santandrea [130] are example designed tools for diffusion technique. Diffusion based electronic cartridge systems are becoming commercially available. Scentee [132] and oPhone [119] are electronic diffusion based mobile phone extension gadgets. Yanagida et al. used an air cannon to plant air in localized area. [13]. Using one scent resource to create augmentation may create unnatural breezing effect. Nakaizumi et al. used multiple air cannon to decrease unnatural effect of odors [101].

4. REGISTRATION AND TRACKING

Registration is the one of the main component of the AR. Integrating virtual information in real data requires proper registration. Registration is the process of real detection with distinct features. The features can be provided from different type of sensors like camera or GPS. In most AR applications, user's movement, position and environmental changes needs detection to be tracked with previously configured reference data. Position information allows AR to retrieve and display location or item based information. Proper augmentation requires user situation (user location, distance to physical object etc.) and user actions (user movement, head movement, eye movement etc.). There are several methods for registering augmented data on the real world. Hardware based or software based tracking techniques can be used. GPS, gyroscope information can be used for outdoor location based solution. Ultrasonic, magnetic, optical, radio frequency and inertial technologies can be used to achieve very accurate positional data [129, 57]. As mentioned before, LIDAR solutions can gather position and orientation information as well as physical object features. Using ultrasonic waves for distance calculation is a popular, simple method. Distance is found by measuring the travel time of the sound. Alusi at al. were able to create low cost high precision ultrasonic based tracking device [7]. With stereo vision systems, Gordon at al. [51] is able to calculate 3D position and user's viewpoint's orientation while tracking user's fingertip or a pen.

RF technology has increasing popularity for tracking and localization. RFID tags are used in assets, inventories, industries, groceries, logistic facilities, hospitals etc. RF technology for tracking can be categorized mainly in two methods. In the first method, environmental RF module acts as an anchor hold its position information. Environmental RF module contains position coordinates. When the user contacts with environmental module, user's location is calculated [127]. Other method is known as fingerprint based method. Unique identifiers and their signal strength is known as fingerprints. User's position is calculated by mapping the fingerprints locations. Fingerprint based method is a research area and needs to be improved.

High accuracy registration is desired for all kinds of augmentation. Although, the accuracy needs of AR applications changes depending of the usage, applications of advertising, entertainment etc. might not need high accuracy. However, manufacturing, health-care need high accuracy registration. Outdoor AR systems use inertial systems and GPS for tracking purposes. These sensors have high error rate therefore precision and accuracy are generally bad. For indoor applications GPS is not applicable. Usually sensor supported computer vision solutions are used for indoor registration purposes. However, when high frequency motion or rapid camera movement occurs, image processing techniques are failing.

Other than hardware based tracking and techniques, several software based tracking solutions are designed. Software based solutions have increasing popularity, because of decreasing requirement to bulky hardware. Software based solutions mostly use computer vision techniques. Image processing solutions for tracking can be categorized as marker based, feature based and mapping-model based.

Markers are pre-designed artificial landmarks planted on the environment for getting data with specific techniques. Mostly marker based tracking techniques use a barcode, QR code, or tag image as a marker. Also specific texture, image or image pattern can be used as a marker. Augmented reality software can determine the marker and give results based on that. Easily detectable feature points and higher response time makes marker based solutions effective. Research of Santos at al. [131] shows that marker based solution can be used with changing data and higher data types. ARToolkit [83, 12] is the most popular marker based library. Markers with asymmetric patterns are designed to be an easily detectable by augmented reality trackers seamlessly. Several AR applications are developed for research purposes with marker based tracking [134, 117, 118]. There are various projects ongoing porting ARToolkit to different platforms. osgART is a C++ based cross platform library which is supporting marker tracing and AR rendering with integration of OpenSceneGraph graphic library and ARToolkit library or ARToolkit fork ARToolkitPlus. AndAR [8] is a Java library for developing Android based AR applications. ARToolkit has been forked for different project. NyARToolkit [110] supports multiple programming languages (C++, C#, Java, ActionScript, Unity) and it can work on different operating systems. NyARToolkit has several branch projects. FLARToolkit [47], is based on NyARToolkit, has been aimed to flash based AR application development with ActionScript. FLARManager [46], which is also support FLARToolkit, also is lightweight AR library for flash based applications. SLARToolkit [136] is also NyARToolkit based library for Silverlight and Windows phone development. ARTag [11] is another open source tool for fiducial marker based augmented reality. ARTag was released several years later than ARToolkit. ARTag has better image processing and digital symbol processing capabilities. Also, ARTag has better performance under illumination changes [153]. ARMES [10] is a commercialized SDK that uses unique circular markers. Layar [85] is a commercial SDK that uses geotagging and predesigned markers. Geotagging allows GPS based location registration for outdoor purposes.

On the other side, in most cases markerless solutions are more desirable. A markerless solution does not need to change the environment for tracking purposes. Feature based solutions allow natural integration of augmented data or virtual objects on real environments. Most of the current natural feature tracking methods use the robust points as feature for matching. Various algorithms are used for defining, detecting and matching. For AR purposes, Qualcomm released commercial feature based AR library called Vuforia [125]. Vuforia has both markers based and feature based AR solutions. Also FastCV [124], an image processing library that optimized for mobile application released for faster image processing AR solutions. ARToolkitNFT [108] is feature tracking library which is expanding ARToolkit's capabilities with natural feature tracking. BazAR [123] is a computer vision library that detects and registers known planar objects in images with feature points detection and matching with a key-point based method.

Mapping-model based solutions are recently becoming popular among researchers and SDK developers. Several researchers improved 3D environmental mapping and simultaneous localization and mapping (SLAM) techniques for registration purposes. In previous techniques, camera pose has a relation with feature generated target. Also target is usually planar. However, SLAM provides pose estimation in unknown environment and 3D reconstruction of problem while moving in 6 degree of freedom. Klein has proposed a parallel tracking and mapping (PTAM) solution [79]. PTAM is monocular SLAM system that use dense map of lower quality features which is useful for tracking in static and limited small scenes. Parallel Tracking and Multiple Mapping (PTAMM) extents PTAM to allow usage of multiple independent cameras to create multiple maps. This allows to link different workspace maps which in different AR applications to each other. In PTAMM, re-localizer allows cameras to automatically switch between maps by comparing the descriptors similarities between the key frames. This allows PTAMM to support working on large environment. Open Tracking Library (OpenTL) [120] use pre-produced models, such as texture, appearance, movement etc. to match environment features. It is not designed for augmented reality purposes but user friendly API and multi-threading support makes OpenTL considerable. RGB-D sensor based techniques have lowered the error rate of tracking and registration of image processing. Registration, mapping techniques are continuously improving related to hardware improvement. Several ongoing researches are on both hand-held and head wear devices. Different types of devices have different advantages and disadvantages [79].

5. INTERACTION

Augmented reality is usually used as an output method. Input methods for virtual reality are naturally applicable for augmented reality. Augmented reality can also use equipment that is used for registration and tracking purposes like gyroscope, GPS for an interaction inputs. Also, separate input equipment can be used. Input devises can be different for distinct setups. Billinghurst et al. [23] demonstrated that, when it comes to selection and searching, spatial head tracked displays offer a better option as compared to screen stabilized approaches. Thomas [141] also looked at using head motion for selection.

Haptic feedback provides interaction tools and creates immersive and interactive application environment for the user. Body tracking devices like ControlVR [36], Manus [95] are effective tools for augmented reality. Also combination of different AR senses can give input information. Haptic AR devices are good example for it. Li et al. [87] used haptic real object to provide interaction with virtual object. Their research has created a synchronization problem between real and virtual objects as a new challenge.

Olfactory augmented reality usually is accepted as supportive augmentation. Scent augmentation can increase interaction and success rate of other augmentations. However, odors have therapeutic effect and scent can increase focus and interaction quality of user. Abid et al. created a smell generator for web objects [1]. System generates smell whenever user places the mouse on text, image etc. Research of Tsai et al. show olfactory feedback may increase coding and writing quality [143].

6. HEALTH CONCERNS AND HUMAN ASPECTS OF AUGMENTED REALITY

There is limited research of the effect of the AR on human health. Increasing improvement on visual AR systems allowed head mounted display devices to be applied widely in AR applications. Head mounted displays facilitate direct perception of the augmented reality. However, wearing head mounted displays may cause headaches, dizziness, nausea and eye problems.

Olfactory augmentation can be beneficial for user health. As mentioned Abid et al. [1] by vacuuming current air, filtering then generating air can;

- freshens the air,
- gives aroma therapy effect,
- alleviates allergies and asthma,
- removes dust and pollen,
- emits negative ions that help increase the humidity in a room, when using pure water.

7. DISTRIBUTED AUGMENTED REALITY

Augmented reality is a complex field that combines an extensive range of algorithms (computer vision, registration, localization etc.) and several devices and sensors (cameras, displays, tracking equipments etc.). Because of the complexity, developing and managing the functionality of AR frameworks is becoming harder. AR contains different components. Separating AR components and managing them separately increases re-usability of AR libraries and allows extendibility. In parallel, to growth of AR researches, several distributed solutions are emerged.

Dwarf (Distributed Wearable Augmented Reality Framework) [27] is a decentralized component model based framework. It is using common object request broker architecture (CORBA) to provide communication with different languages. Dwarf uses concept of independent services. Services work on their needs and abilities between each other. Every network node contains a service manager that controls its local services. Service managers can cooperate each other to connect remote services. DWARF aims rapid prototyping of AR applications. Independent services allow decentralized development with Dwarf.

Studierstube [140] is mainly developed for multi user, groupware AR and VR applications. It is built on device management and tracker framework OpenTracker. Studierstube has named each of its components as application objects. Each application object inherits from an application type. Application objects can be instantiable from different application types in same time. These applications can communicate between each other. In Studierstube architecture, service manager manages overall system.

Every framework has their distinct advantages. Dwarf and Studierstube are both component based and expendable. Bauer et al. [18] wanted to use both systems advantages by integrating these two system together. Extending their component for communicating both of the system allow developers to use both of the systems advantages.

MORGAN [113] is proprietary component based framework. It is CORBA based like Dwarf. However, it is also using different proxy pattern for other protocols. MORGAN is designed for making AR application development with multiple user easier. In this architecture, components subscribe to input devices that they are interested in. The system creates publisher subscriber architecture between components. MORGAN frame work has its own rendering engine for support multi user solution in distributed system. Component management is provided with a specific component called broker.

Tinmith evo-5 [122] is a modular architecture that aims to solve complex development problems like data distribution, rendering, interaction, tracker abstractions, modular extensions. It is written in C++. Modules can be application specific or generic. The communication between modules is provided with client server style architecture. The system is asynchronous and uses data flow methodology. If there are no data changes, there won't be any action.

VARU [63] is designed for VR, AR or ubiquitous computing development. VARU uses XML based configuration descriptors. In VARU, components can use these reusable XML configurations for different development projects. Users can interact each other like co-located in same space without depending on their reality (AR, VR, and ubiquitous). VARU framework contains two main part: VARU server, and VARU client. The server synchronizes objects in space. Objects are described using: Class, Individual and Extension. A Class is an abstract group of objects with an assigned purpose. The Individual is an instance of Class. An Extension is a representation of an Individual in the interaction space. Each application store objects in the database with an individual's and extensions tables. VARU uses different libraries for different requirements. OpenSceneGraph is main rendering library for VARU. For managing an AR application, osgART, ARToolkit or OpenSceneGraph can be used. For smart device connection, it uses CAIM middleware, UPnP protocol and VRPN for the interaction peripherals.

ARCS (Augmented Reality Component System) [40] is designed for rapid prototyping of distributed AR applications. It is written in C++ with multi-platform support (Unix, Linux, Windows). It can provide centralized or decentralized distributed architecture. ARCS is using component orient programming. ARCS components can be configured and composed with other components. ARCS works with finite state machines. Applications is described as threads and threads are controlled with finite state machines that states specific configuration. The configuration is called sheet. Sheet contains pre-connection, connection, post-connection and cleanup states. Pre-connection states configure components. Connection states configures links between components and manage data transfer. Post connection invokes application configuration. Cleanup state restores component states. When states change, global configuration of the components also change and global configuration reconfigure the connections. There is also ARCS.js JavaScript library under development with same principles. It is intended to run both browser and node.js environment.

AMIRE [52] uses a component oriented architecture and consists of the minimal set of components required for a demonstrator, a reusable augmented/ mixed reality software collection and a visual authoring tool for building AR applications.

8. COLLABORATIVE AUGMENTED REALITY

Desktop computer supported collaborative work (CSCW) applications might separate users from each other and from their tools [64]. This is an important disadvantage for collaborative environment. Also classic CSCW applications provide hard to use solutions to three dimensional problems. AR enables us to enhance the physical environment with a computer generated virtual environment. That allows us a more natural communication and removing desktop type CSCW limitations [25]. Collaborative AR allows physical interaction and virtual interaction simultaneously that allows developer to use virtuality and reality as different parameters. This provides application development capabilities without depending time or space constraints. The research of StudierStube [24] defines collaborative AR environments features are:

- Virtuality: Objects that don't exist in the real world can be viewed and examined.
- Augmentation: Real objects can be augmented by virtual annotations.
- Cooperation: Multiple users can see each other and cooperate in a natural way.
- Independence: Each user controls his own independent viewpoint.
- Individuality: Displayed data can be different for each viewer.

The features are shown as collaborative augmented reality allow natural communication independence. Also Kiyokawa and Billinghursts research on communication behaviors in collaborative AR [77] shows that users think AR is the most natural way to see information.

Collaborative augmented reality (CAR) is powerful user interface tool that can be applied in all kind of position on time/space matrix. In same time/ same space domain, CAR applications can create identical or user customized augmentation for different user to assist interaction. Tabletop solutions which have surface or equipment tools that provide shared augmentation is the main application area for same time/ same space domain. Table top approach is a traditional collaboration solution. Several applications designed for productivity [42, 53], gaming [60, 39, 139, 114], education [75], design, training [111], maintenance/repair [19, 86] etc. use this approach. Researchers designed several co-located systems that use the same database platform. [134, 127, 126, 137, 78] Also manipulating 3D models that augment in the user view are tested in several experiments. In the same time/ different space domain, Kato et al. [73] and Barakonyi et al. [14] experimented face to face video conferencing tool with CAR. Using avatar is one of the main approach for distributed collaboration. Avatars provide character recognition of different users in different places. Users can communicate and interact with avatars that is representing other users. Archaeological digging is an example one time gather-able sensible data type of work. Benko et al. [20] created mixed space CAR tool for solving the problem. Augmented sensation allows several users to inspect historical area. Also remote users can get information about work environment. Freer [48] is provided collaborative messaging system on augmented reality.

Different time aspect of the collaborative work for AR is not widely evaluated. In same space situation, location registration is enough for AR collaboration. In different environments, overall UI needs to change for new data. Challenges in synchronous AR situation are mostly answering asynchronous AR problems. Thomas et al. [142] provides examples of the different time problems with logistic area.

Mueller-Tomfelde created hybrid sound reproduction in audio augmented reality [100]. This solution can create direct undisturbed inter-individual communication within the team and at the same time a personalized augmented sound environment in collaborative augmented reality [100]. Knoerlein et al. designed visual and haptic AR solution for entertainment purposes [80]. Their ping-pong game is an example of a collaborative visuo-haptic AR solution.

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