A Systematic Review of the Convergence of Augmented Reality, Intelligent Virtual Agents, and the Internet of Things

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1 Introduction

In a seminal article on *augmented reality* (AR) [7], Ron Azuma defines AR as a variation of virtual reality (VR), which completely immerses a user inside a synthetic environment. Azuma says "In contrast, AR allows the user to *see the real world*, with virtual objects *superimposed upon or composited with the real world*" [7] (emphasis added). Typically, a user wears a tracked stereoscopic head-mounted display (HMD) or holds a smartphone, showing the real world through optical or video means, with superimposed graphics that provide the appearance of virtual content that is related to and registered with the real world. While AR has been around since the 1960s [72], it is experiencing a renaissance of development and consumer interest. With exciting products from Microsoft (HoloLens), Metavision (Meta 2), and others; Apple's AR Developer's Kit (ARKit); and well-funded startups like Magic Leap [54], the future is looking even brighter, expecting that AR technologies will be absorbed into our daily lives and have a strong influence on our society in the foreseeable future.

At the same time, we are seeing the continued evolution of *intelligent virtual agents* (IVAs) in the home through products such as Apple's Home Pod, Amazon's Echo, and Google Home. Gartner predicted that the IVA market will reach $2.1 billion by 2020 [58]. The products use sophisticated microphones and signal

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processing to capture human speech in one or more rooms of one's house and via artificial intelligence algorithms and Internet-based services play music, answer basic questions, and check on sports scores, weather, and more. Products like the Gatebox [27], a Japanese take on Amazon's Echo with a holographic display, even provide an embodied representation of the IVA for users to interact with. Various research prototypes in the field of IVA used projectors and TV screens to study natural interaction with embodied virtual agents in the past. While research on IVAs started as an independent trend from AR, we are now seeing that over the last years, more and more technologies and techniques from AR are used for IVA research and commercial developments and vice versa.

The abilities of these products further extend to home automation and more general interactions with the increasingly present *Internet of things* (IoT) [1], i.e., a network of sensors and actuators within or attached to real-world objects. The term was coined by Kevin Ashton [5], who at MIT's AutoID lab in the early 2000s was laying the groundwork for what would become IoT. Cisco's IoT Group predicts there will be over 500 billion connected devices by 2030 [79]. Amazon and other companies networked their IVA devices to IoT and related smart home appliances and found an important application field for IVAs, resulting in a novel research thrust and mutually beneficial overlap between these fields. Many of the research topics pursued in the IoT field, such as privacy [56, 73], the relationship between edge and cloud processing [15], and network traffic optimization [2], will need to be re-evaluated when IoT is deployed in the context of AR and IVA. Furthermore, some IoT applications, such as smart healthcare [3, 77], can benefit from the addition of AR and IVA techniques.

Research in the three fields AR, IVA, and IoT has led to a large body of literature, and active research communities that traditionally received limited input from each other, advancing knowledge and developing novel technologies and systems within each field individually (see Fig. 1). However, over the last decades, we have seen an increasing integration of knowledge, technologies, and methods from

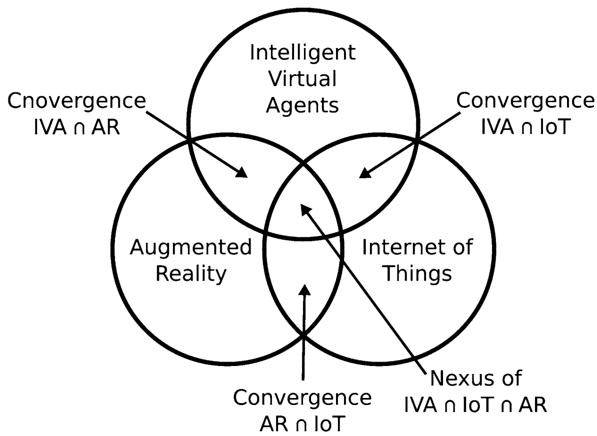

Fig. 1 Venn diagram illustrating the convergence of augmented reality, intelligent virtual agents, and the Internet of things

the three fields that act as frameworks to catalyze new research and development. The National Science Foundation (NSF) acknowledged the importance of such a convergence of research fields as one of the *10 Big Ideas for Future NSF Investments* [30]. According to NSF, "convergence research" is closely related to *transdisciplinary* research, which is generally viewed as the pinnacle of evolutionary integration across disciplines. However, convergence research represents more than transdisciplinary, interdisciplinary, and multidisciplinary research in that the fields not only overlap and integrate but come together to establish a new field with new directions for research that can attract and draw from deep integration of researchers from different disciplines, leveraging their collective strengths, with the hope of solving new or vexing research challenges and opportunities.

In this chapter, we present a review of 187 publications scattered throughout scientific conferences and workshops in diverse research communities over the last decades at the intersections of each two of the three fields AR, IVA, and IoT. We identified impactful research papers and directions for research in these fields, and we discuss a vision for the nexus of all three technologies. We highlight key themes and identify possible future research topics and trends. Overall, providing a review that introduces a substantial and useful perspective, focusing on the era of convergence research in these areas is the main goal. We hope that this paper can benefit new researchers and students involved in academia by providing a summary of the current advances and trends in these research areas and help them identify their research interests. We also hope that it will be helpful for senior researchers to see a big picture of AR, IVA, and IoT research trends, particularly with respect to a future vision of AR that may have a positive influence on humans and our society.

The remainder of this paper is structured as follows. We first describe our review methodology in Sect. 2. Then, we present a high-level description of our considered review topics in Sect. 3, which is followed by a meta-review of publications on AR, IVA, and IoT in Sect. 4. We then present a review of existing convergent research on AR and IVA, IVA and IoT, and AR and IoT in Sects. 5, 6, and 7, respectively, and we discuss trends that were observed from our reviews. In Sect. 8, we discuss a novel vision for future research that we see at the nexus of IVA, IoT, and AR. We conclude the paper in Sect. 9.

2 Methodology

For our literature review, we were faced with the challenge that papers published at the intersections of AR, IVA, and IoT could be published in a wide range of research communities with their own journals, conferences, and workshops. We could further not rely on an established terminology that would describe the convergence research and could guide our literature search. We decided on the following two-tailed literature search strategy to locate relevant publications:

1. We conducted a computerized search for publications in the online digital libraries of the *Association for Computing Machinery (ACM)*, *Institute of Electrical and Electronics Engineers (IEEE)*, *Eurographics*, *Elsevier*, and *Google Scholar* databases. Searches were conducted using a 132-item list of relevant terms, such as "augmented reality," "mixed reality," the "Internet of things," "smart home," etc. with each requiring combinations of two of these terms to identify publications in the intersections of the respective fields. The terms in each area were searched in the title, abstract, and keyword fields of the above libraries if available.
2. We searched the reference lists of located relevant publications for further relevant literature.

The abstract and body of each located publication was examined, and each was selected for further analysis if and only if it matched all of the following criteria:

1. The publication was peer reviewed and published at a scientific journal, conference, and workshop or as a book chapter. Technical reports, posters, and demos were not considered since they are usually shorter and/or not normally reviewed as rigorously.
2. The publication was at least four pages long. Shorter publications were excluded to limit the search to mature research and avoid position papers and work in progress.
3. The publication was released in the new millennium, i.e., in the year 2000 or later, to limit the scope of the literature review to a tractable period.
4. We consider certain related topics as outside of the scope of this literature review:
   (a) We excluded publications on intelligent agent software algorithms that had neither a 2D/3D virtual representation nor a voice-based natural user interface.
   (b) We excluded agents with physical manifestations as robotic humans.
   (c) We excluded VR and "augmented virtuality" display environments [57].
   (d) We excluded wearable devices like smart fabrics, wrist, belt, or foot-worn devices, if they were not connected to the Internet.

From now on we use the mathematical intersection operator, e.g., AR ∩ IVA, to indicate the set of publications that include both AR and IVA concepts and satisfied the above criteria, i.e., publications at the intersection of the respective fields.

The above procedures resulted in a sample of 187 publications in total between the years 2000 and 2018 for the fields AR ∩ IVA (65 publications), IVA ∩ IoT (43 publications), and AR ∩ IoT (79 publications). Of course, we do not make any claims that this list of publications covers the entirety of research in the identified converging fields, but we hope that the analysis and review of the located publications can provide an excellent snapshot of the work listed at these premier tools for disseminating academic research.

The second part of the review process focused on the following points:

1. We divided the total number of publications among the first four authors and classified all publications based on their research contributions using the research topics described below.
2. We collected the citation counts for all publications on August 19, 2018. Due to the different sources of the publications, we decided to collect citation counts from *Google Citation Index*, which covered the largest portion of the publications compared to *Scopus* and other databases. If we could not find a citation count for a specific publication on any of the databases, we set it to zero for the analysis.
3. We divided the publications among the first four authors based on their expertise and performed in-depth reviews of the most highly cited publications in the converging fields. If publications were released recently (in 2017 or later), we did not entirely rely on the citation counts as a measure of impact but included a quick first review of the publications before performing an in-depth review. We considered analyzing further metrics of the impact of these publications, but honors and awards such as *Best Paper* or *Honorable Mention Awards* proved intractable for our diverse set of publications.

During the review process, we focused on identifying and reviewing those publications that had a high impact on the convergence of the fields, novel trends, and directions that stemmed from those publications, as well as challenges that were encountered.

3 Review Topics

During the literature search process, we identified groups of publications related to different research topics that guided our analysis process. We refined our list of topics based on related literature surveys, including [22, 41, 59]. We refined or removed topics from that list based on the number of related publications in our literature search. In the end, we decided to group all publications into seven research topics, ranging from core technology areas needed to deliver an AR, IVA, or IoT application to emerging research fields. Publications may belong to one or more of these topic categories.

The research topic categories are:

1. *System*: research on systems covering at least in part two of the three areas AR, IVA, and IoT
2. *Application*: research on systems in application domains such as manufacturing, healthcare, and defense, among others
3. *Evaluation*: research focusing on human-subject studies evaluating systems or techniques
4. *Review/Survey*: literature reviews including at least in part two of the considered convergence areas
5. *Multimodal*: research into combined modalities such as speech and gesture interfaces

6. *Collaboration*: research on interactive collaborative systems for multiple users
7. *Interaction*: research on user interfaces or interaction techniques

We further aimed to understand the input and output modalities of these systems at the intersections of AR, IVA, and IoT in more detail. We hence decided to classify all publications based on two general concepts related to the information transfer between the real/physical world and the virtual/computer-controlled content during interactions:

- *Input*: The "virtual" is aware of something "real."
- *Output*: The "virtual" is influencing something "real."

We considered the input and output dimensions for different human sensory and related modalities: light, sound, touch, motion, temperature, fluid, smell, and airflow. Most of the publications addressed light or sound output (e.g., visual or auditory displays in AR), some considered light or motion input (e.g., camera-based user tracking in AR) and sound input (e.g., voice-controlled agents), and some considered physical output (e.g., exerting influence over smart homes with IoT). For each paper we also looked at the types of displays used for the AR content and the IVAs. The displays considered are *HMDs*, *mobile* devices (e.g., cell phones, tablets), *screens* (flat screens, TVs), and *other* less often occurring types of displays that we grouped together such as projection-based AR and CAVE environments. We used the tag *N/A* for publications where a display type was not indicated as part of their work, and we also categorized publications that developed setups that are migratable to multiple different displays as *cross-display*.

4 Meta-Review of Publications

In this section, we describe a high-level meta-review analysis of the number of publications and citations for each convergence field and research category. As stated above, we considered a total of seven research topics that we want to discuss in this chapter. First, we evaluated the number of publications for each convergence field over time (see Fig. 2). Then, we evaluated them for each research category and their percentage over the total number of classifications (see Fig. 3). Publications could cover multiple topics; thus, this classification count is larger than the number of publications—338 classifications among 187 publications.

As shown in Fig. 2, research in the field of AR ∩ IVA goes further back compared to the other two fields, which is understandable considering that IoT is a comparatively more recent area of research. Also, in line with the technological advances in the field of IoT in the past few years (e.g., Amazon's Alexa, Microsoft's Cortana, and the Google Assistant), we observe a significant increase in the number of publications in both of the fields converging with IoT. Interestingly, the drop in the number of publications in 2009 and 2010 coincides with a rise in publications in the fields of AR ∩ IoT and IVA ∩ IoT.

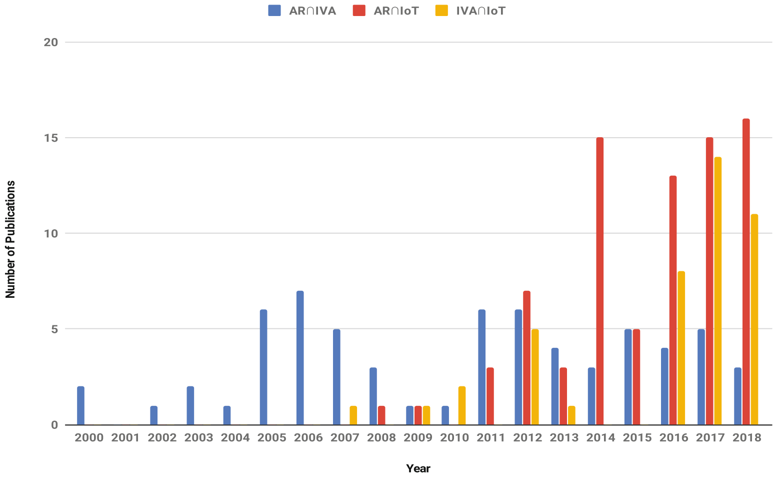

Fig. 2 Number of publications in the convergence fields from the year 2000

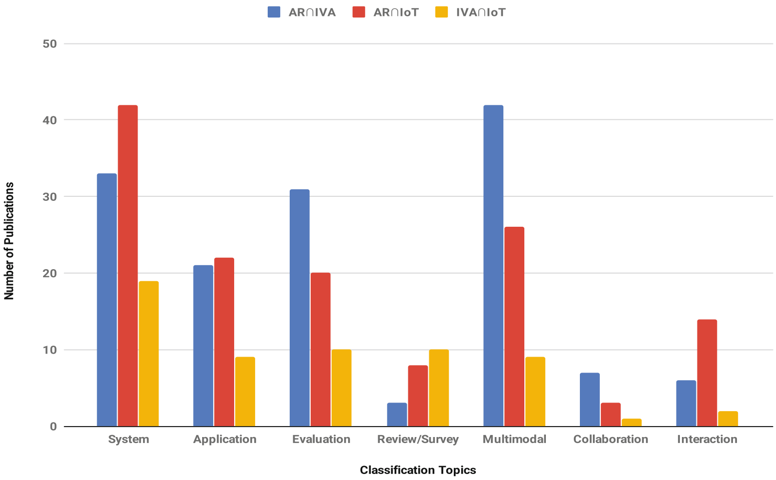

Fig. 3 Number of publications in each convergence field grouped according to classification topics

Looking at the distribution of classification topics for each field in Fig. 3, excluding review and survey papers, we observe a lower number of publications in the remaining topics for the field of IVA ∩ IoT, which is partly due to our exclusion criteria #4 in Sect. 2 and the novelty of this topic. Also, with research in the field of AR and IVA being more developed than IoT, we observe fewer system papers in AR ∩ IVA compared to AR ∩ IoT and more research involving user studies.

Interestingly, even though the research in the fields of AR and IVA goes back further than IoT, we see a similar number of application papers in AR ∩ IVA compared to AR ∩ IoT, which in part may be due to the sudden growth in using

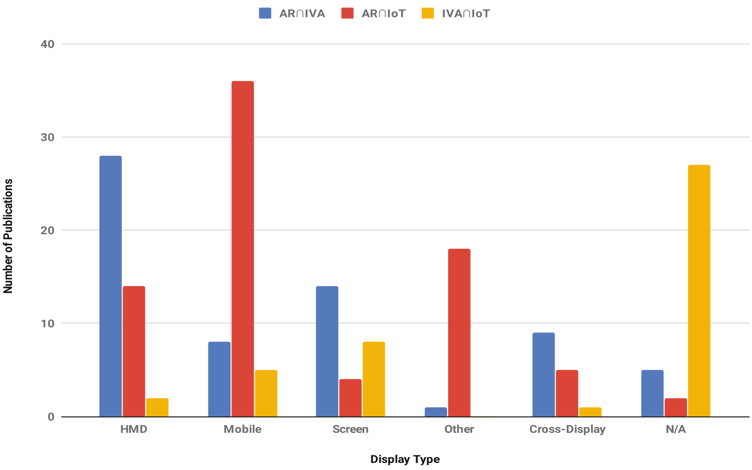

Fig. 4 Number of publications in each convergence field grouped by display type

IoT devices in one form or another by the general public unlike AR ∩ IVA, due to high price or technical difficulties of developing and interacting with holograms.

Looking at the type of displays used in each field in Fig. 4, we observe that the majority of publications in the field AR ∩ IVA used some type of HMD, either video see-through or optical see-through, compared to using mobile devices such as cell phones and tablets. The opposite pattern is observed with AR ∩ IoT. We see more publications in AR ∩ IVA that built frameworks and/or applications that were migratable to different display hardware, which can be explained by the age of this research field. Many publications especially the ones involving IoT did not necessarily mention or use a display device mostly because their research was focused on techniques, algorithm, and theoretical frameworks. We also observe more publications focusing on new interfaces and interaction techniques in AR ∩ IoT which is understandable as virtual assistants and information overlay through mobile devices has shown to be a popular topic in this field.

We also computed the average yearly citation counts (ACC) for each field of research which is shown in Fig. 5. The sudden increase in ACC for both AR ∩ IoT and IVA ∩ IoT is indicative of the fast-paced improvements and high impacts in both fields considering the high ACCs in 2016 and 2017.

5 The Convergence of AR and IVA

Although extensively researched in VR, intelligent agents have been introduced to AR for the first time at the beginning of the new millennium. This convergence field brings together the field of AR, in which *virtual* content is overlaid or mixed with

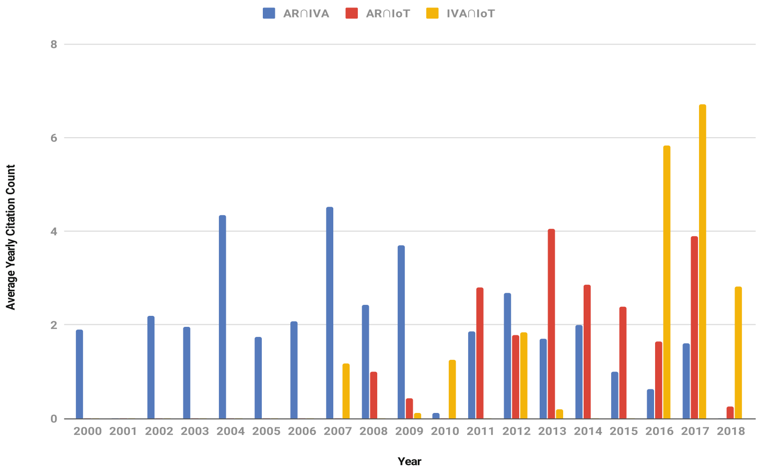

Fig. 5 Average yearly citation count per convergence field

the *physical* world, and the field of IVA, which is concerned with *virtual* agents and how these can interact with *physical* users and objects.

5.1 Meta-Review

At the intersection of AR and IVA, we found 65 publications with 143 classifications in total. Figure 2 shows the number of publications by year, and Fig. 3 shows them by classification. As shown in Fig. 3, the majority of the publications in this field included aspects of system development (33), evaluation (31), and employed agents and/or setups that supported several input/output modalities (42) with fewer papers focusing on applications (21), collaboration (7), interaction (6), and survey papers (3).

Looking at the types of displays used per year in Fig. 6, we noticed an inclination towards HMDs (28). The second most used display type were flat screens (14), e.g., computer display, TV, etc., followed by publications supporting several hardware platforms (9); mobile devices (8), e.g., cell phones and tablets; and a CAVE environment (1). Five papers did not focus on aspects that would require specific displays.

We also looked at the input/output modalities used in the publications in this field. As shown in Fig. 7, light followed by sound were employed as the main modalities of the works published. We observe a similar number of input and output publications for light since many of the devices used in this field included depth sensors and cameras as input and overlaid virtual content as output. We also see a higher number of publications using the sound modality as output due to many virtual characters being able to speak to users but not having speech recognition

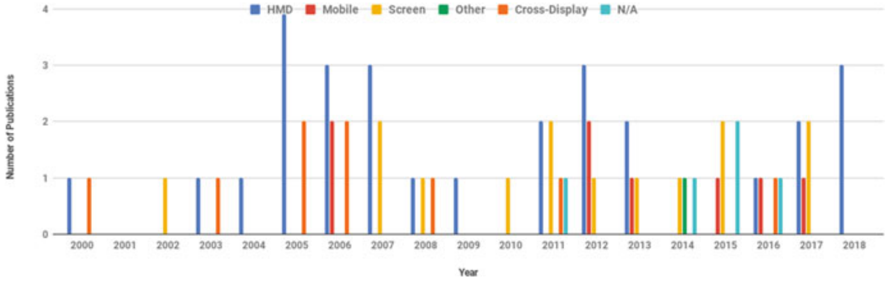

Fig. 6 Variety of displays used over time in the field of AR and IVA

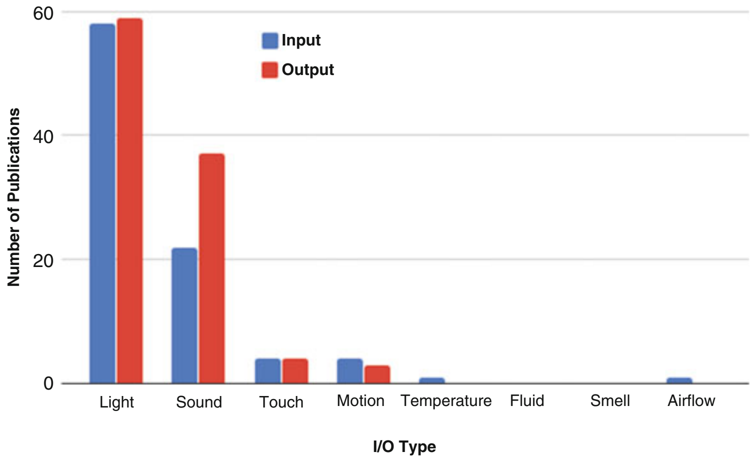

Fig. 7 Publications in the field of AR and IVA grouped based on the modalities used

capabilities. A few publications adopted sensors to bring about touch and motion capabilities and only one paper experimented with airflow.

Ten publications in this field had a citation count of four citations per year or higher. The average citation count in this field was 1.9 citations per year ($SD = 1.8$). The papers below were selected based on the citation count and qualitative criteria for years 2017 and 2018, for which the citation counts are not yet well established.

5.2 *Impactful Papers and Trends*

Barakonyi et al. [10] presented the first general framework for IVAs called *AR Puppet,* which has been developed specifically for AR applications. They discussed agent-specific aspects of AR such as that IVAs should react to the physical environment, avoid collisions with physical obstacles, and should be able to influence objects in the real world. In later work, the authors introduced numerous AR applications in this field [8, 9, 11]. For instance, they presented an AR tabletop game called MonkeyBridge [11] in which small embodied IVAs dynamically recognized changes and events in both the virtual and physical world and adapted their movement behavior to these changes. Similar responses to dynamically changing physical environments in AR for IVAs were realized by Chekhlov et al. [18] in their high-impact *Ninja on a Plane* game, with SLAM-based sensing of the physical world. Blum et al. [14] presented an interactive location-aware AR game based on mobile AR devices and IVAs, which uses real locations and includes virtual characters with basic physical behaviors. They showed in a user study that the sense of embodiment has a positive impact on player experience.

Multiple publications were focused on IVAs in AR that exhibit more sophisticated reasoning, proactive behavior, and some awareness of the non-verbal behaviors of a real human [44, 45, 52, 67]. Others examined the effects of awareness and influence of IVAs in AR settings using cameras, microphones, and custom devices to develop automated awareness of environmental effects such as sounds, movements (felt and observed), light, air flow, and IVA interactions with other humans [21, 39, 40, 48, 50, 70]. The results indicate that, like VR, congruent and plausible behaviors matter—virtual humans and objects should be responsive to real-world events. However, in practice, it is much more difficult in AR, because unlike the case with VR, where the system controls everything, AR systems are typically unaware of dynamic real people and events. As recognized by Helen Papagiannis, "the second wave of Augmented Reality (AR) is driven by a contextual understanding and interaction with your surroundings" [60].

Much high-impact research on IVAs in AR was driven by application fields demanding more useful and engaging IVA technology. For instance, Hantono et al. [31] reviewed the literature between 2005 and 2015 concerning IVAs in AR with respect to possible uses in *education*. They observed that most AR realizations at that time were not personalized to the user or the environment, limiting the learning experience. Wagner et al. [75] presented one of the first IVAs in (hand-held) AR for educational purposes. A wide range of prototypes of IVAs in AR were developed for application contexts [4, 17, 30, 42, 61].

In a highly cited paper, Dow et al. [23] described an interactive drama using autonomous characters presented on an AR HMD, artificial intelligence-based story management, and natural language processing to immerse the player in a dramatic story in AR. They showed with a qualitative study that AR interfaces make the experience with IVAs more immediate and can lead to a higher level of perceived presence in a dramatic story than desktop interfaces. Interestingly, their results also showed that this AR-enhanced immediacy of the experience does not necessarily lead to higher engagement with IVAs since players do not perceive there to be a safe zone for them to experiment and make mistakes.

Holz et al. [36] presented a multidimensional classification method to understand differences in the realization of IVA prototypes in mixed reality called the *MiRA (Mixed Reality Agents) Cube*, which divides agents based on their corporeal presence (virtual to physical), their interactive capacity (virtual to physical), and their agency (weak to strong).

While most embodied IVAs in AR are presented on projection screens or HMDs, Krum et al. [46] presented a mixed reality projection framework called *REFLCT* for IVAs and virtual content in general that couples a near-axis head-mounted projector with retroreflective props and surfaces to provide personalized, perspective-correct imagery that is uniquely composited for each user directly into and onto a surrounding environment. They demonstrated it with a virtual character that made eye contact with each person in a group of visitors.

Lee et al. [51] evaluated an optical see-through HMD as a means to present IVAs in AR. They performed a user study and showed that the limited field of view of current-state AR HMDs changes users' locomotion behavior and proxemics in the presence of an embodied IVA. They further found that subtle vibrotactile feedback of the IVA's footsteps transmitted through the floor while walking can significantly benefit a user's sense of copresence.

Overall, with a few exceptions, the highest impact in the convergence field of IVA and AR so far was made by publications focusing on system prototypes driven by application needs. Researchers have made continuous low-key progress on IVAs in AR since the early 2000s, but research on the nature and underlying peculiarities of IVAs in AR is still in its infancy compared to related efforts for IVAs in VR.

6 The Convergence of IVA and IoT

While the concept of IoT goes back to the early 2000s, it took until around 2014 with the release of Amazon Echo, and the integration of IoT devices into the agent's affordances, for research in this convergence field to take off. This convergence field brings together the field of IVA, which is concerned with *virtual* agents and how these can interact with *physical* objects and users, and the field of IoT, which strives to network *physical* devices, including sensors, appliances, and displays, to improve interaction and control by *virtualizing* the components.

6.1 Meta-Review

At the intersection of IVA and IoT, we found 43 publications with 60 classifications in total. Figure 2 shows the publications by year, and Fig. 3 shows them by classification. Fifteen publications in this field had a citation count of four citations per year or higher. The average citation count in this field was elevated to 4.29 citations per year with a large variance ($SD = 6.32$) due to a few highly cited papers in this field.

As shown in Fig. 3, the majority of the publications in this field focused on system development (19), followed by evaluation (10), survey (10), application (9),

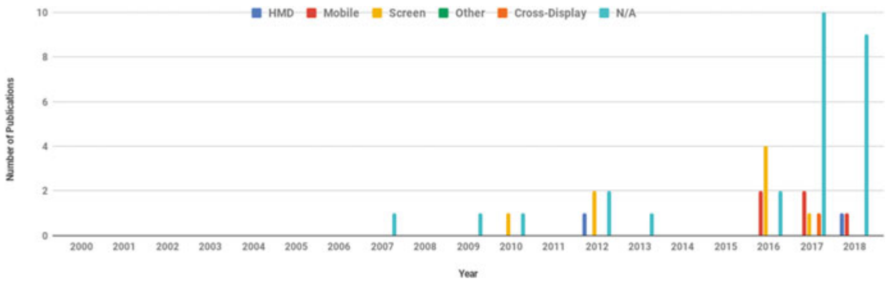

Fig. 8 Variety of displays used over time in the field of IVA and IoT

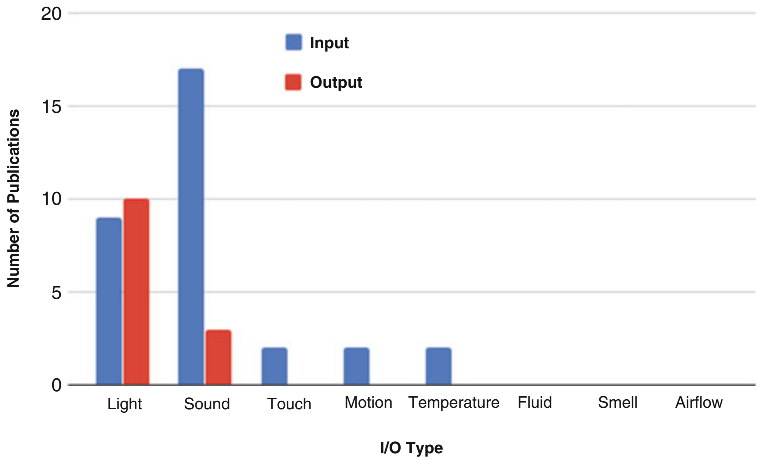

Fig. 9 Publications in the field of IVA and IoT grouped based on the modalities used

and multimodal aspects (9). Considering the novelty of the field, only one publication investigated collaborative opportunities, and two publications introduced new interaction techniques.

As shown in Fig. 8, with publications focusing on voice-based assistants such as Amazon Alexa, algorithms and theoretical frameworks, and survey papers, the majority of them did not include a specific type of display (27), followed by flat screen displays (8), handheld devices (5), HMDs (2), and one paper that focused on several hardware devices.

Looking at the type of input/output modalities employed in the field of IVA ∩ IoT, in Fig. 9 we see a similar pattern as in the field of AR ∩ IVA with regard to the emphasis on using the light and sound modalities, but the difference here is the increase in the number of publications that utilized sound as input through speech recognition which is in line with many smart home virtual assistant systems.

6.2 Impactful Papers and Trends

Soda et al. [71] developed one of the first prototypes of a voice-based IVA system in the scope of a research project, using a device with a microphone array as an interface for smart home devices, similar to the later consumer devices popularized by Amazon, Apple, and Google, among others, for natural interaction with IoT devices.

Multiple highly cited papers focused on comparative evaluations of the different consumer products being released over the last years in the field of IVA and IoT. For instance, López et al. [53] presented a comparison of existing speech-based IVAs like Amazon Alexa and Google Assistant. The authors describe a user study in which the effectiveness of the speech-based user interfaces was evaluated. Reis et al. [66] proposed a model that allows elderly people to more easily interact with IVAs, and they compared Google Assistant, Amazon Alexa, and others to evaluate which of the devices/assistants would incorporate the proposed model most efficiently. Druga et al. [24] conducted a user study that involved children interacting with IVAs including Amazon Alexa among others. The children were surveyed with regard to the agents' trust, intelligence, personality, and engagement. The authors proposed design modifications for IVAs that are capable of interacting with children in the future. Hoffman and Novak [35] provided a general discussion of the experience of consumers when interacting with IVAs and IoT networks.

Knote et al. [42] presented a recent literature review of applications for IVA assistants. The authors identified three application domains (daily life and family, work support, and e-learning) in which future research is particularly promising. Austerjost et al. [6] developed voice-based agent user interfaces for a virtual "lab assistant." The virtual assistant, through IoT devices, could control and modify physical devices and data and react to speech command inquiries.

With the aim to better understand IoT networks in smart home environments, Helal et al. [33] and Lee and Cho et al. [49] presented simulators with 3D autonomous agents that populate a smart home environment, trigger motion detectors, etc. They modeled a typical human behavior and provide a user interface to keep track of the state of the IoT network and smart environment.

Since all new technology, including IVAs and IoT in digital ecosystems like Amazon Alexa, has security concerns and could be used to commit crimes due to natural voice-based interfaces with the IVA and related vulnerabilities or could in general be important as potential sources of digital evidence for crimes committed in the real world [19], Chung and Park et al. [20] developed a proof-of-concept digital forensics tool, called *CIFT*, that supports identification, acquisition, and analysis of the state and actions within such an IVA-IoT ecosystem. To prevent the illegitimate use of one's private data in an IVA-IoT ecosystem, e.g., in commercial systems, Campagna et al. [16] developed open, crowdsourced, privacy-preserving, and programmable virtual assistant architecture, called *Almond*.

Overall, early research on the convergence of IVA and IoT had not received much attention in terms of citations in the research community, potentially because the research communities on IVA and IoT were focusing on other challenges at the time. However, commercial developments and products extended that early research demonstrated the importance for our daily life and thus caused a widespread interest by researchers in this convergence field over the last years.

7 The Convergence of AR and IoT

This convergence field brings together the field of AR, in which *virtual* content is overlaid or mixed with the *physical* world, and the field of IoT, in which *physical* devices are connected and *virtualized* for computer-controlled networked interaction.

7.1 Meta-Review

At the intersection of AR and IoT, we found 79 publications with 135 classifications in total. Figure 2 shows the publications by year, and Fig. 3 shows them by classification. Ten publications in this field had a citation count of four citations per year or higher. The average citation count in this field was 2.19 citations per year ($SD = 3.66$).

Papers in the field of AR ∩ IoT were mostly concerned with system development and theoretical frameworks (42), followed by application topics (22), evaluation (20), interaction (14), and survey papers (8). Twenty-six papers employed multi-modal setups, and three papers developed collaborative designs.

As shown in Fig. 10, many of the publications in this field relied on mobile devices to implement and display their work (36), and fewer used HMDs (14), followed by flat screens (4), cross-displays (5), and projection-based AR (2). A good number of papers focusing on theoretical aspects did not employ a specific display for their work (18), and five papers developed frameworks that could be used on different types of displays.

As shown in Fig. 11 we see a high number of publications with light input/output and fewer with sound input/output which can be seen as human modalities or qualities of an IVA. Touch, motion, and temperature sensors were slightly more used in this field compared to others which also include specific IoT sensors in the environment affecting virtual content.

7.2 Impactful Papers and Trends

Most research at the intersection of AR and IoT considered AR as an interface for IoT devices that avoided limitations of traditional user interfaces in smart home

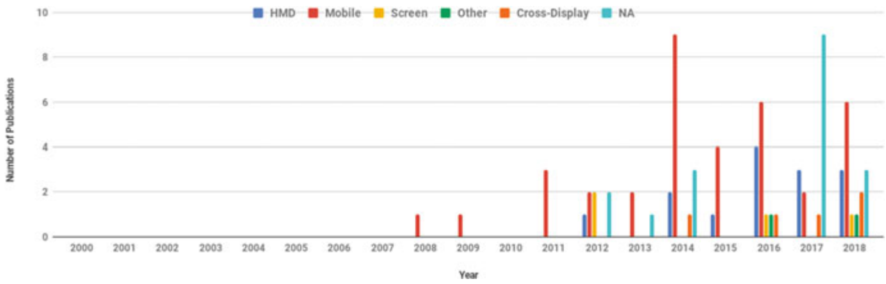

Fig. 10 Variety of displays used over time in the field of AR and IoT

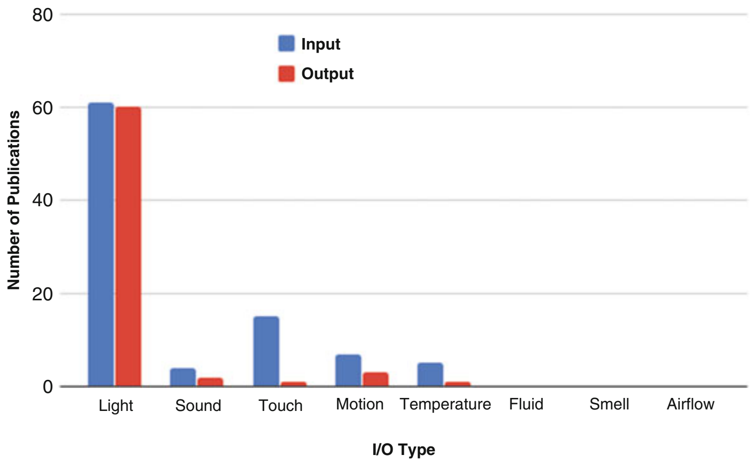

Fig. 11 Publications in the field of AR and IoT grouped based on the modalities used

environments. Gimenez and Pous [29] noted that "AR has recently been touted as one of the ideal interfaces for IoT." For instance, Garcia-Macias et al. [26] presented a mobile AR application to "browse" through the Internet of things. The rationale for using AR was that IoT unlike the traditional Internet constitutes a mix of virtual and physical entities. The authors developed a mobile AR application similar to a magic lens that lets users see smart objects in their environment when the mobile AR device is pointed at them, thus allowing the user to understand the virtual services provided by the IoT devices and interact with them. Wirtz et al. [76] presented a similar approach with the difference that the smart devices in the environment would not be directly connected to the Internet but connect to the mobile AR device on demand when pointing the AR device at the smart device. Another similar system was proposed by Heun et al. [34], called *The Reality Editor*, in which users hold a mobile AR device near a smart device to open an interface that allows users to reprogram the behavior of the smart device and to define relationships between smart devices in order to create new functionalities.

Kasahara et al. [38] further extended the approach with mobile AR as an interface for IoT to a novel class of actuated IoT devices. In their prototype, users could point a mobile AR device at an actuated smart connected appliance, and by touching the screen of the mobile AR device, users could then drag the target in the AR view, which the smart appliance would then match using an actuated motion platform.

Instead of using mobile AR devices, Lik-Hang and Pan [47] recently resumed different ways in which AR glasses and corresponding user interfaces could provide an accessible and intuitive user interface for interaction in a modern smart home environment. To note are in particular gestural and gaze-based interfaces, which allow users to control smart home appliances at a distance, e.g., by flicking a finger towards a light to turn it off without having to walk over to a light switch [43, 78]. Martin and LaViola [55] further introduced a *Transreality Interaction Platform (TrIP)* to "enable service ecosystems which situate virtual objects alongside virtualized physical objects and allow for novel ad-hoc interactions between humans, virtual, and physical objects in a transreality environment."

While smart home environments with AR interfaces were among the highest cited papers, they were not the only application fields for using AR and IoT. For example, Hao and Helo [32] emphasized on the importance of AR and IoT for the manufacturing industry. They investigated the application of AR and wearable technology to visualize information derived from IoT sensor networks in a cloud manufacturing environment.

Also, AR has been used as a test-bed for IoT environments. In particular, Seo et al. [69] designed multiple test-beds to experience and understand smart home environments and IoT networks in VR and AR with respect to context and awareness, before they are realized in an actual smart home environment.

In contrast to the aforementioned research that largely leveraged AR as a tool for interaction with IoT devices, it is interesting to note that researchers so far have not fully leveraged IoT devices as a tool to improve AR experiences.

In the research field of AR, various input and output devices have been prototyped, some have been connected to the Internet, and some have been commercially pursued. However, while many of these research prototypes developed in the field of AR could be realized in the form factor of an IoT device, this is hardly done so far. This might be explained by the perceived overhead involved in adhering to IoT protocols and standards and associated fears of added latency and suboptimal performance [68]. It may also be related to recent trends in the field of AR today that most developments are egocentric with respect to a physical device, i.e., sensors and displays are mounted on the user's body or head instead of them being placed throughout the environment, which makes it harder to think of them as Internet-connected *things*.

At the same time, we have to note that the steady integration of IoT capabilities into everyday devices all around us presents an opportunity for the addition of more allocentric pervasive real-world capabilities to AR. In particular, Jo and Kim [37] proposed an IoT extension to support scalable AR environments called *ARIoT*.

We predict that over the next years, further advances in AR user interfaces and technologies towards everyday use cases in a smart home environment will give rise to the standardized integration of IoT devices into AR frameworks and the development of new IoT devices specifically for the purpose of enhancing AR experiences with improved sensing and multimodal sensations, e.g., driven by the gaming industry.

8 The Nexus of IVA, IoT, and AR

While each of these convergent technology thrusts has shown benefits due to the integration of the research fields and can advance on their own, the nexus of the three concepts and technologies could enable further novel solutions and research directions. In particular, we see a vexing vista for the future of virtual agent technologies that becomes possible and tractable at the intersection of the three fields. This idea of a sophisticated futuristic agent could be manifested in the form of an embodied *augmented reality agent (ARA)* with pervasive *awareness*, *appearance*, and *abilities* through IVA intelligence and human-agent communication, IoT networks to sense and influence the real world, and AR display and sensor technology to seamlessly blend the agent with the real world. Such empowered agent technologies would be *transformational*.

Beyond one's physical "surroundings" [60] and the state of oneself and one's home, the contextual *awareness* would be *pervasive* in that it could extend to all matters of one's life that one allows (via privacy controls): one's health, calendar, daily fitness information, and even awareness of one's family members—shared awareness between the ARAs of the family homes. Indeed, the awareness could include ongoing assessments of one's physical and emotional health, which could be shared with a healthcare provider or family members. New privacy mechanisms would then be needed to control which aspects of awareness (and appearance and abilities) are shared.

The *appearance* of one's ARA would be *pervasive* in that it could move around within one's home, e.g., appearing anywhere in 3D if one is wearing an HMD, projected onto physical surroundings via *spatial augmented reality* [12, 62–65] in one's IoT-enabled television, in the display of one's IoT-enabled refrigerator, among others, to best match the current location of the human [8]. The ARA could be transferred to any network and device that one allows, e.g., one ARA could travel on one's mobile devices, one's car, and even one's office computer. One of many questions surrounding ARAs is whether there is value in seeing an embodied agent, even in cases where it is not necessary. For example, if one asks one's agent to check the calendar to see if one is free for a date tonight, and the agent just says "Yes," one might not trust the ARA's response as much as if it *appeared* to carry out some action that corresponds in some way to checking one's calendar. Among other things, we see the importance of new knowledge related to this "seeing is believing" and the importance of visual embodiments in general. More generally we see the need to advance knowledge on different agent representations based on their tasks and contexts and appearances that are adapted to each user [74], static or variable, which can range from single to multiple agent representations, e.g., when the agent is multitasking.

The *abilities* of one's ARA would be *pervasive* in that it could have *physical influence* throughout one's house under a variety of circumstances. For example, today one can purchase light switches and outlets that are compatible with various home automation protocols, e.g., Insteon, Z-Wave, and Zigbee. In the future, manufacturers could include AR features and data such as embedded textual and verbal descriptions, the ability to embed location information, etc. In terms of *social influence* [13], an ARA that is aware of one's dietary circumstances could coach one on what to eat using immediate caloric information from one's body-worn fitness devices, awareness of one's calendar for the day, etc. One's ARA could directly influence the person, e.g., by greeting one cheerfully and appreciatively when one returns home from work—the "Cheers effect" (American sitcom)—or could reach out to family members or friends if, for example, it becomes aware that one is overly tired or depressed. Among other directions, existing voice-controlled agents, home control, and custom technologies could be enhanced by giving ARAs the ability to control IoT devices.

There are two perspectives of ARA *affordances* [28] we propose should be examined: the affordances the ARA offers to the human and the affordances the environment offers to the ARA. For example, with respect to the former, embodied AR agents offer the opportunity to study the "seeing is believing" idea. With respect to the latter, ARA awareness of nonverbal communications by the human would support verbal instructions that are intentionally brief or ambiguous, such as "please turn of *that light*" while pointing to a particular lamp. This is in contrast to today's voice agents where one has to remember and use the precise name corresponding to each device, e.g., "please turn off the Living Room Floor Lamp!"

In summary, by extrapolating from the current developments discussed above, we believe that these affordances become tractable at the intersection of the three research fields AR, IVA, and IoT. As technology and prototypes are developed to address these challenges, we see much potential for an interesting and transformative research domain being established at the nexus of the three fields.

9 Conclusion

In this chapter, we resumed the body of literature at the convergence fields between augmented reality, intelligent virtual agents, and the Internet of things. We performed a literature search at the intersections between each two of these fields, and we analyzed the research topic categories of the publications and their impact as indicated by their citation count. We further highlighted and reviewed the most impactful papers and trends in these convergence fields. Our results show a large increase in publications in these convergence fields over the last years and much potential for future research. We predict that the three fields will grow in importance over the next years and attract interdisciplinary research teams to advance the technology development and improve our understanding of the challenges and goals in these fields. Finally, we presented our vision for the convergence of all three technologies.

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