smart cities

Review

Augmented Reality in Precision Farming: Concepts and Applications

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Abstract: The amount of arable land is limited, yet the demand for agricultural food products is increasing. This issue has led to the notion of precision farming, where smart city-based technologies (e.g., Internet of Things, digital twins, artificial intelligence) are employed in combination to cater for increased production with fewer resources. Widely used in manufacturing, augmented reality has demonstrated impactful solutions for information communication, remote monitoring and increased interaction. Yet, the technology has only recently begun to find a footing alongside precision farming solutions, despite the many benefits possible to farmers through augmenting the physical world with digital objects. Therefore, this article reflects on literature discussing current applied solutions within agriculture, where augmented realty has demonstrated a significant impact for monitoring and production. The findings discuss that augmented reality must be coupled with other technologies (e.g., simultaneous localization and mapping algorithms, global positioning systems, and sensors), specifically 9 are identified across 2 application domains (livestock and crop farming) to be beneficial. Attention is also provided on how augmented reality should be employed within agriculture, where related-work examples are drawn from in order to discuss suitable hardware approaches and constraints (e.g., mobility).

Keywords: augmented reality; agriculture; precision farming; smart cities

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1. Introduction

Augmented Reality (AR) applications have become prevalent within smart industry manufacturing [1] and wider popular culture sectors over the last decade [2]. This is largely due to the cumulative accessibility of game engine-based Software Development Kits (SDK) (e.g., Vuforia [3], Aryzon [4], Zappar [5]) and the affordability of hardware devices for content display. Several libraries (e.g., AR.js [6]) now also cater for web-based development, providing centrally hosted AR deployment without the end-users required to install software on their own devices. AR is now firmly established within many smart city application domains, with smart production line engineering [7], preventative maintenance [8] and education-based applications in particular benefitting from the lower barrier of entry for AR development.

Within agriculture-based research, digital visualisation technologies are contributing to the betterment of both precision livestock [9] and crop farming by increasing efficiency and reducing supervisory costs [10]. It is within this domain that AR finds an essential use in an agricultural setting. The reason AR is developing a particular role, more so than other related optical technologies such as Virtual Reality (VR), is that the physical world is enhanced by the use of 3D assets or projected data insights, meaning the user's interaction with the corporal environment is not inhibited but rather upgraded through an extension of the reality. For example, as Huuskonen et al. demonstrate, AR has the ability to provide a way-finding process to guide farmers during traditionally laborious soil sampling processes [11]. Gains are also achieved by overlaying visualisations of simulated crop growth models [12], and the projection of data into real-world objects for real-time decision support, such as insect or disease species identification. In all examples, the virtual assets seamlessly co-exist with the visual perception of the real world [13].

It is clear that AR is displaying potential for the enrichment of both the crop and livestock management processes within a precision farming setting [10]. However, even though many works specify the benefits AR offers within agriculture [11,14–16], it must be emphasised that the advantages of AR for precision farming are reliant on a symbiotic relationship with other core smart city-based technologies, such as machine learning or GPS integration, to provide a cite-specific management service. As evidence, consideration is drawn from the aforementioned approach by Huuskonen et al., where the benefits of AR for use in soil sampling are only made possible by coupling the technology with Internet of Things (IoT) data [11]. This is similarly the case for the crop growth monitoring and real-time decision processes that are outlined in the work by Liu et al. [12].

Both the AR software and hardware constraints have unique requirements when used within an agriculture-based setting compared to the use in other sectors, such as entertainment or manufacturing. The role of the farmer is practical in nature, meaning that AR users will tend to work long hours and in remote locations [17]. Therefore, head-mounted displays or hand-held devices should be lightweight, weather resistant, not restrict movement and capable of providing multiple applications from the same hardware. This is confirmed by Maria et al. [16], who discuss that smart glasses tend to be the appropriate route forwards for deployment within livestock-based precision farming applications. The lightweight and unrestrictive nature of the hardware means that the technology can be used for prolonged periods without impacting movement. Additionally, it is possible to further sub-divide the required functionality challenges of AR between the separate domains of crop and livestock farming processes. For example, the task of catering for large geographic areas, such as pastures within dairy farms where, as Zhao et al. discuss, upwards of 600 cows may be present [13] (although the number depends on the country) and moving in a dispersed fashion over a significant areas, is a different challenge to crop management precision farming applications, where the objects, in this case crops, are static organised or condensed and the AR is often sensor-driven.

In this article, the investigation put forward highlights the different challenges concerning the development of AR applications for precision farming. Whilst AR is often present in works related to this article, for example by Neethirajan et al. [9], existing discussions of the technology typically fall under a wider survey of precision farming-based technologies, of which AR is proposed as a communication medium. Therefore, this article stands apart from existing literature, as few works within the precision farming research domain place the main emphasis of the investigation on AR hardware frameworks. As such, the following three research questions (RQ) are identified. RQ1: *How is AR currently deployed within an agricultural setting*? RQ2: *What technologies is AR coupled with to provide a service for farmers*? and RQ3: *What hardware frameworks are used to deploy AR technologies in an agricultural setting*?

To address the research questions, a snowballing approach was adopted as a review protocol for considering applied AR solutions within the agricultural domain, focusing on articles from November 2016 to November 2021. The five year range is selected due to the advancing pace of AR technologies and SDK solutions within this time frame; for example Microsoft released the HoloLens in 2016, which can be recognized as a landmark in AR tech (as discussed in [18] by Szajna et al.) sparking an interest in wider developments in this area. For the review process, digital libraries involved in the search included Scopus, IEEE Xplore, MDPI, with Google Scholar employed for checking any missed articles from the repositories.

Findings and recommendations can be used to support those aiming to develop AR applications within a precision farming setting. The remainder of the paper is organised as follows. Section 2 provides a background discussion on the software and hardware requirements for AR deployment in a precision farming setting. Section 3 discusses AR deployment models and Section 4 discusses the findings. The paper is concluded in Section 5.

2. Augmented Reality in Agriculture

In this section, the focus is on AR applications currently deployed for agricultural use and documented in research articles. Only specific use cases are included, as many papers mention AR as a keyword within the investigation, or part of a wider discussion on emerging technologies (such as Digital Twins for agriculture [19]) to support precision farming, but do not cover specific applications of the AR technologies for a direct use. For example, Klerkx et al. discuss AR as part of an introduction to the different forms of potential digitalisation within agriculture to produce novel spatial dimension effects, but no specific applications of the technology are discussed [20]. As is the case in [21], where AR is reflected on in a high-level context as a potential solution for merging graphical depictions with real-world objects for assisted decision support. Similarly, Verdouw et al. outline how the technology could be part of an elevated user interface innovation for digital twin settings [19], but in this case the focus is on wider digital twin technologies rather than applied examples.

Also, Lin et al., discuss how AR could be integrated into a learning framework to support the digital learning process of students in the agricultural technology domain [22], however education falls outside the scope of this research.

Finally, consideration is also not given to agricultural articles that are unrelated to actual deployment within an agricultural setting but may have an association with farming as a keyword; for example, within the food supply chain as in [23]. Therefore, in this section, only specific use-cases of the technology are considered. After the snowballing approach was completed, it was evident that all articles found could be classed into two application domains, either (i) crop applications or (ii) livestock; both with unique technological challenges. The section also reflects on technologies that are coupled with AR for the benefit of precision farming, concerning papers published from 2016 onwards, with the search string as follows for selecting the papers for review.

("Abstract":Augmented reality) AND (("Abstract":farm) OR ("Abstract":agri*) OR ("Abstract":crops) OR ("Abstract":livestock) OR ("Abstract":cultivation) OR ("Abstract":plantation) OR ("Abstract":cattle)).*

2.1. AR in for Crop and Livestock Management

The basis of the precision farming concept within crop management, is the achievement of a higher production using fewer resources through technological enhancements, by supporting management spatially and temporally through industry 4.0 technologies [21,24]. This may include working with existing equipment, such as human-driven machines, but adding remote sensing or data collection methods that provide a data-driven insight, unlocking an optimisation of resources; or a layer of automation [9]. More advanced smart city technological solutions, such as drones, and digital twin technologies further enhance solutions, providing autonomous services using intelligent data insights; with a comprehensive range, including yield mapping, parallel running of machinery and automated soil sampling, provided by Klepacki et al. [25]. However, there are additional added values aside from increased agricultural output, namely better operational economics, reliability and general insight into the systematic operation of the farm as a whole. Notably, as demonstrated in this article, AR has the flexibility to be deployed comfortably within each precision farming setting. By coupling with existing equipment, in parallel with the diverse industry 4.0 applications, and integrated into new autonomous machine solutions, AR is able to synergise virtual objects with the existing physical real world. This makes the technology particularly suited to practical crop farming, as discussed in the following examples.

Huuskonen et al., present the use of AR for the supervision of two autonomous agricultural machines [15] for sowing, spraying or harvesting. In this setting, AR provides the farmer with situational awareness, relaying operational information, such as the directional movement and fault status. There are, of course, other solutions which can provide this information to the farmer (e.g., data dashboards, mobile applications), however the use of AR means that the users' focus on the real physical world can be sustained when viewing the data. In this specific example, in order for AR to fulfil a data visualisation function, integration is required with other services; namely a platform capable of autonomously controlling machines when in the field. This is also the case in the aforementioned research presented by Lui et al. [12], where AR provides a visual outlet for the integration of other industry 4.0 digital solutions such as sensors, network infrastructure, GPRS, Wi-Fi, compass, crop information, a decision layer for crop image detection and database matching technological services [12,26].

Within crop farming, AR's adaptability suits a wide spread distribution model. Relevant and on time information is a powerful tool for farmers, even more so when the data is provided as an integration with the real-world. This is demonstrated by Salve et al., who discuss an AR-based application for crop disease detection to support farmers in India. Smart phones, which have become a highly accessible technology (provide network access when working in remote locations), mean that widespread deployment is possible. AR can be positioned successfully, where more immersive-heavy solutions such as VR may not prevail.

Regarding livestock management, precision farming principles are based on the production and management of animals, driven through sensors and data services; as demonstrated by Pandey et al., who work with ear-tag sensors and machine intelligence for the remote behavioural trail analysis of pigs [27]. In other words, precision livestock farming concerns the implementation of technologies to enable real-time monitoring for a per-animal approach. Demand and consumption of animal products are projected to increase in the coming years [28]. At the same time, the number of farms is decreasing and the farmer population is older on average. For example in the United States, the average farmer age is 57 [29] while in Europe, 7 out of 10 farmers are 55 years or older [30]. This results in less manpower to manage larger numbers of animals, making individual management and subject identification a difficult task. Implementation of technological tools, such as radio frequency identification devices (RFID) and livestock monitoring systems (LMS), offer solutions for this per animal identification and management concept [13,16]. However, the provided implementation is limited without a visual or interactive outlet for the information. Yet, similarly to the crop management applications, AR opens up the possibilities for a real-time data-driven display of individual animals in the farmers view, both in dynamic scenarios (i.e., grazing cows) and more static scenarios (i.e., lactating cows) as demonstrated by the examples presented as follows.

Maria et al. [16] showcase the advantages of using AR through smart glasses to retrieve information (feeding, milking, breeding, health etc.) per subject in real-time. Farmers are able to scan QR codes attached to subjects in the field to access files containing information on that particular animal. A significant added value of using AR technologies within this setting is that it allows farmers to access information without interfering with the tasks they perform. The technology provides a window to the remote sensor data on a per animal approach level. Additionally, retrieval of information (that is otherwise time consuming) is conducted systematically and in real-time, providing the farmer support for efficient decision making.

A further example is presented by Zhao et al., who developed a mobile application to locate (track) and manage large numbers of cattle in extensive areas [13]. The application combines GPS measurements and computer vision algorithms to deliver information of cow locations in the field. As a result, the application offers the possibility to track any registered animal via its unique identifier and guide the farmer to its position in the field through augmented features (arrows). The farmer is then able to select an animal (again, demonstrating the per-animal level requirements) in the real world within the smartphone's camera range and visualize data through superimposed text coupled with 3D models relevant to management.

2.2. AR Types and Coupled Technologies

The previously discussed articles demonstrate the flexibility of AR within different farming contexts. While it is clear that AR is employed as means to communicate information visually, it is the integration of AR with other technologies that enables the tailored functionality for precision farming and the visual-based modality [10,31] Therefore, the coupled technologies used in the aforementioned articles are diverse, but core commonalities are present; such as the use of on-line databases, machine learning algorithms and sensor/IoT connectivity (i.e., humidity, temperature and weather sensors). The choice of technologies can be described as dependent on the context and domain in which the application will be used, with both foundational differences and overlaps between the two application areas of crop farming and livestock management.

Whilst each AR application addresses a specific need (often unique to its deployment context) resulting in aspects that might be most notable for one domain but not be relevant for the other, AR technologies do share common requirements. For example, the use of QR codes to facilitate management tasks in environments where a low region of movement in space is expected; for example for indoor dairy farming or greenhouse management [16]. However, when dealing with a more dynamic scenario, for instance livestock dispersed over a wide area or large-field crop management, synergies between the AR deployment may include the combination of GPS and computer vision algorithms, as demonstrated by [13].

Yet a notable consideration is apparent in all deployment scenarios, and that is that location is key. Whether it is a local coordinate system enabled by cameras or a geographic coordinate system using GPS sensors [15], or a hybrid approach [13], applications are only able to properly convey information through AR with an appropriate level of location awareness and suitable coupling technologies to enable the process.

The type of coupled technology provides insights into the nature of the application for precision farming. In that regard, it is possible to classify the applications into specific AR types. Edwards-Stewart et al., for example, categorize AR applications based on their functional characteristics and propose two main categories, (A) triggered and (B) view-based AR applications [32]. For this article, focus is on triggered AR applications, which as the name suggests, are AR approaches that need to be triggered by a stimuli to deliver the augmentation of reality. In contrast, view-based applications can augment content without the need of a reference in the view.

Triggered applications can be of four types: (1) marker-based, (2) marker-less (location-based), (3) dynamic augmentation and (4) complex augmentation. Marker-based involves the use of a QR code pattern to initiate the AR projection. Marker-less does not require a QR code, and in some instance the user would be required to tap on screen to create the projection on their desired location. The latter two types (dynamic and complex augmentation) highlight specific types of AR marker-less applications. Figure 1 displays an overview of the reviewed works in Section 2.1 divided by AR type, based on the four classifications in [32], to provide an example of the triggered applications currently deployed within an agriculture setting.

Coupled technologies are facilitators for AR. For example, without GPS to facilitate location tracking [15], it would not be possible to create a marker-less AR approach. Similarly, without the combination of more than one coupled technology, higher location accuracy might be unattainable impacting the success of [10,12,14,16,26]. As further evidence, without the combination of different technologies higher location accuracy would not be possible to achieve, which in turn would result in applications not being able to fulfil the demands of a precision farming application. Similarly, machine learning and computer vision algorithms (together with databases to cross-reference data) enable marker-based

AR applications to perform their functionalities, as in [31]. Both AR types present advantages and challenges that might skew/narrow their application to specific scenarios within precision farming.

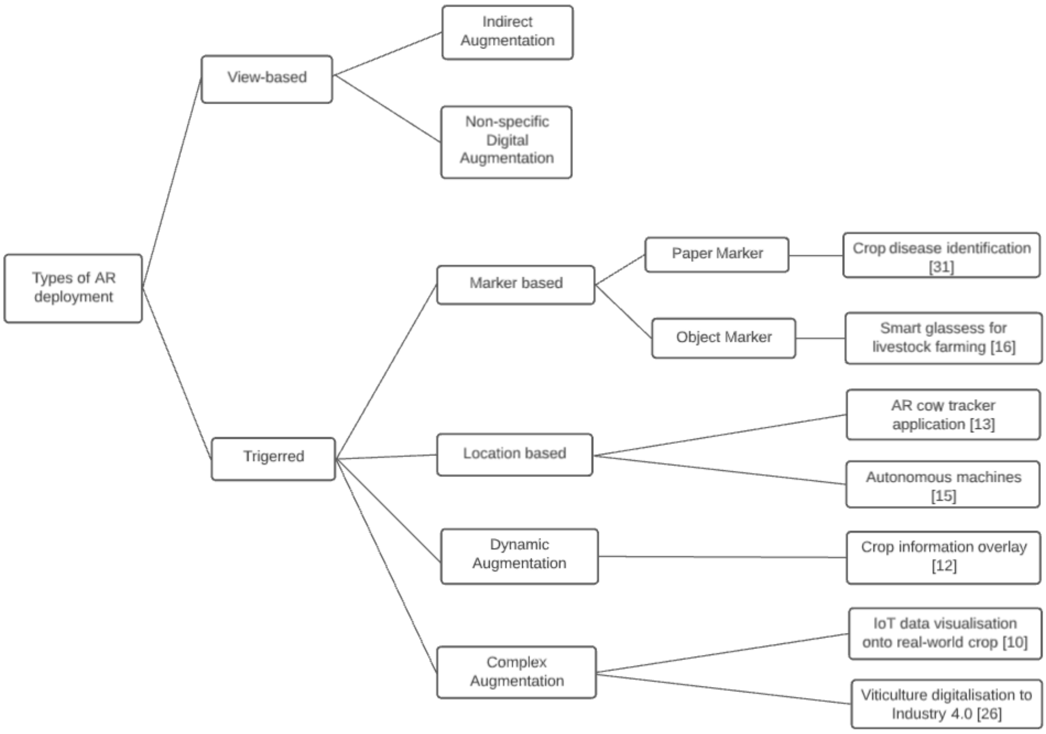

Figure 1. Types of AR deployment within crop and livestock management, adapted from the model in [32].

For marker-less applications, position is often not the only factor involved in the correct overlay of data. For example, the multirobot system developed by Huuskonen et al., requires information on the orientation of the AR headset used by the driver to correctly overlay objects in the real world [11,15]. The accuracy of the internal headset orientation sensor was, however, not sufficient for this application; therefore, an extra sensor is introduced into the framework.

3. Deployment Models

In the examples discussed in Section 2 the core themes are apparent. Namely, flexibility, scalable deployment and real-time. These core themes need to be considered within the scope of the fundamental challenges for AR deployment, as defined in [33], including, (i) interaction, (ii) technological limitations and (iii) realism. In this section, the focus is, therefore, on existing hardware deployment models for AR within precision farming settings; as well as potential AR deployment models for use in precision farming based on existing AR technologies yet to be used within farming.

3.1. Existing Hardware Frameworks

Three main traditional AR interaction models (Monitor-based AR, Optical see-through, Video see-through), have been well documented for over 20 years, for example in [34–36]. Figure 2 displays an adapted version of each inspired by the aforementioned articles [34–36]. Of the three models, optical and video see-through can be considered the most dominant at present within the AR precision farming applications discussed in Section 2.1, largely due to the use of AR on smart phones. Video see-through, for example, would be the equivalent of using a mobile phone for the AR view but directly looking at the screen. Whereas, optical see-through would be a projection in front of the user's eyes combining video captured in real-time and coupled with the AR input. For example the OGD hardware used in [15] is poised around the head-mounted display optical see-through approach.

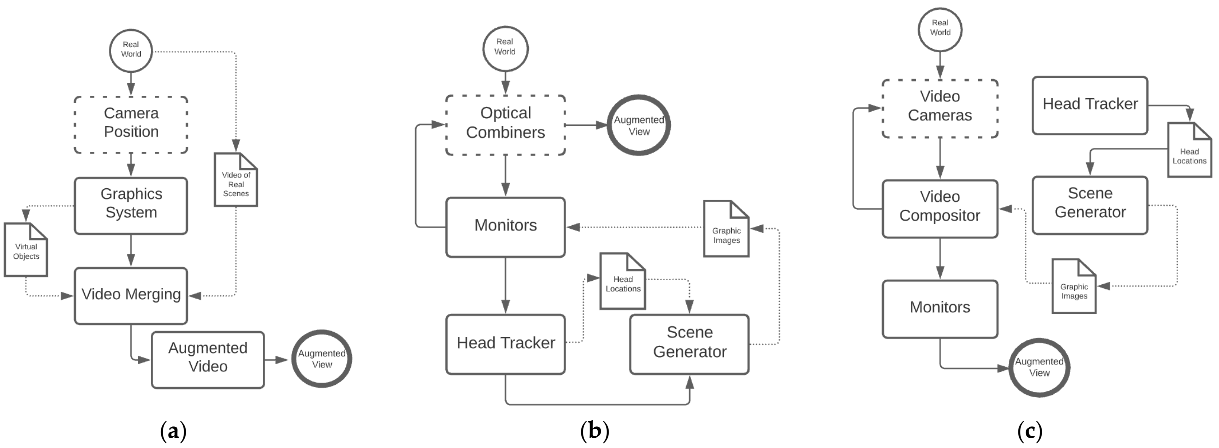

Figure 2. (**a**) Monitor-based AR, (**b**) Optical see-through, (**c**) Video see-through.

Emerging immersive approaches, such as the Aryzon headset [4] extend these models further by adopting a mirror-based approach for the optical merging, as displayed in Figure 3. This takes the output from monoscopic to stereoscopic. Where an affinity with the real world environment is created, meaning the user is able to view as a volumetric output without looking directly at the device monitor, transforming the approach from video see-through to optical (however, given its infancy, at the time of writing this article, the related work search found that this technology is yet to be employed in an agricultural setting).

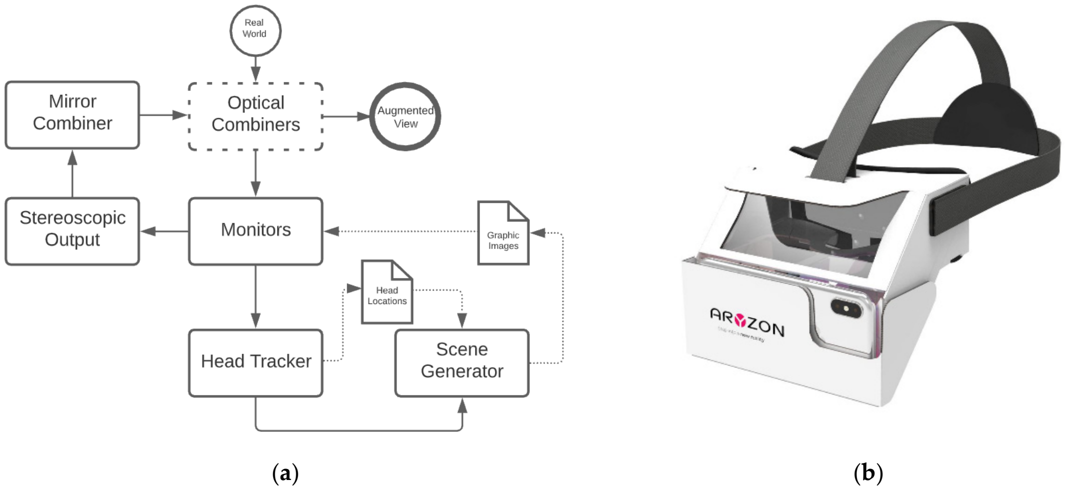

Figure 3. (**a**) Mirror-based AR, (**b**) Aryzon Headset.

Advancing the AR hardware framework further, approaches include coupling the headset with hand-held controllers, for instance with embedded QR code markers on the controller shaft. This provides real-time detection of the users' hand movements. In this instance, the AR hardware framework can be extended to include motion input, as in Figure 4. Humans naturally prefer a multimodal approach for a higher level of interaction [33], rather than being passive observers. The integration of controllers into the mix provides natural extension of the AR interaction processes for a greater level of control.

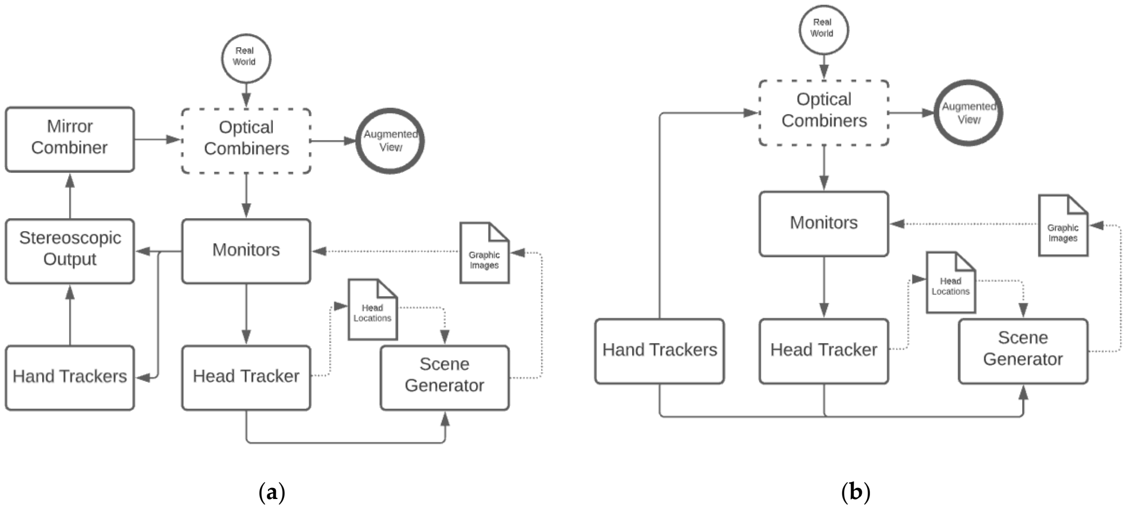

Figure 4. (**a**) Mirror-based AR with Controllers, (**b**) AR with Controllers and no Mirror.

3.2. Integrated Technology Frameworks

The accessibility of AR-capable hardware enables mobile applications, known as Mobile Augmented Reality (MAR) [3]. As its name suggests, MAR offers the user the possibility of integrating virtual information into the physical real environment through a mobile terminal. In other words, the user is not limited to a particular location in order to utilise these systems. Specific aspects of a MAR framework will naturally depend on the purpose of the application. However, some general key aspects of such applications can be identified as suggested by [3,12]. The former describes general foundations of MAR applications regardless of their application domain. The latter aimed to create a MAR framework specific for the agricultural domain.

Specifically, Ming L. et al., propose a framework consisting of four main aspects as depicted in Figure 5, namely (1) Physical layer, (2) Network layer, (3) Decision layer and (4) Application layer. The physical layer is the base of the application. It determines the characteristics of the whole architecture, as it sets the premise for the type of data that is available (or will be available) through the collection process.

In the reviewed examples in Section 2, the physical layer is represented by all the primary sensors that collect and store relevant information for each application. For example, this could be a wireless sensor network (WSN) that collects site condition information for vineyard monitoring [26], databases containing crop diseases information [31] or information relevant to animal husbandry [16] and mission planer system data relevant to agricultural machines [15]. In short, this layer contains the information that will be used for decision-making.

The Network layer enables access and transfer of information in the system. Technologies enabling this transfer include GPRS, microwave and satellite communication [12], wi-fi [13,16,31] and Bluetooth [16]. The last two layers, Decision and Application, are better explained jointly as the former, is the direct (visual) result from the latter. For example, in the application built by Zhao et al., the decision layer is represented by the functions *locate:cow* and *display:cow*, which are triggered by clicking on a cow within the camera view of the mobile device. Similarly, the application presented by Bento et al. [26], displays alerts, management information and geotagging of a specific plant/vineyard (Decision layer) following the interaction between the farmer and the device (Application layer); where the interaction between the user and the application calls from the Application layer.

All the reviewed applications can be expressed by means of this framework. To name one example, Maria et al., [16] developed a MAR application in which farmers use smart glasses to scan QR codes attached to a specific animal (application layer). Thereafter, retrieving information from databases and sensors relevant to animal husbandry (physical layer) through a combination of Wi-Fi and Bluetooth system (Network layer). Finally, the information is displayed as augmented features in the form of videos and a farm information sheet (decision layer) of the selected animal.

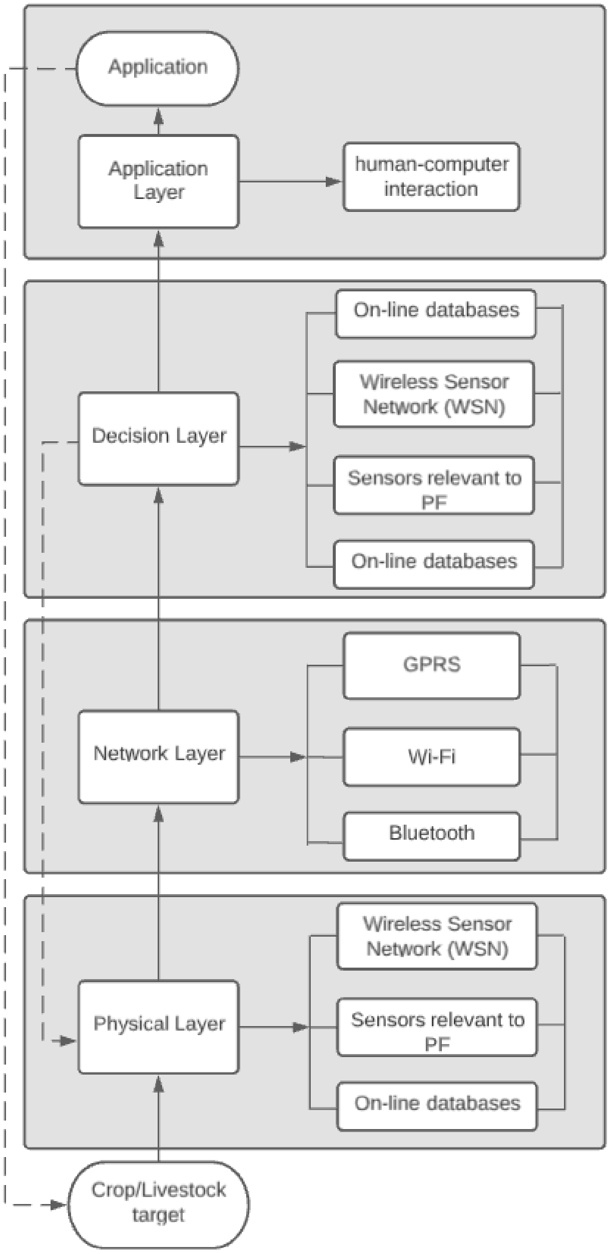

Figure 5. MAR agricultural application framework adapted from [12].

4. Findings

In this section, the focus is on summarising the findings in-line with the research objectives discussed in the Introduction section by reflecting on the findings collated during the survey process. The research questions are employed as sub-headers.

4.1. How Is AR Currently within an Agricultural Setting?

A limitation of this research is that, at the time of writing this article, there is a relatively low number of articles discussing the use of AR within an agricultural setting. Yet, while there is a reduced number of applied examples, there is a clear connections in the nature in which AR is adopted. It is important to reflect on the synergies as the deployment of AR solutions grow with the increasing use of digital twin and precision farming applications.

In terms of how AR is currently deployed within an agricultural setting, it is evident that applications are used to monitor, improve efficiency and to facilitate the scalability of operations within the domain. To summarise, Figure 6 displays a comparison of the discussed related works (both crop and livestock-based articles), the application and the corresponding cross-over in technology between the two within the aforementioned application domains.

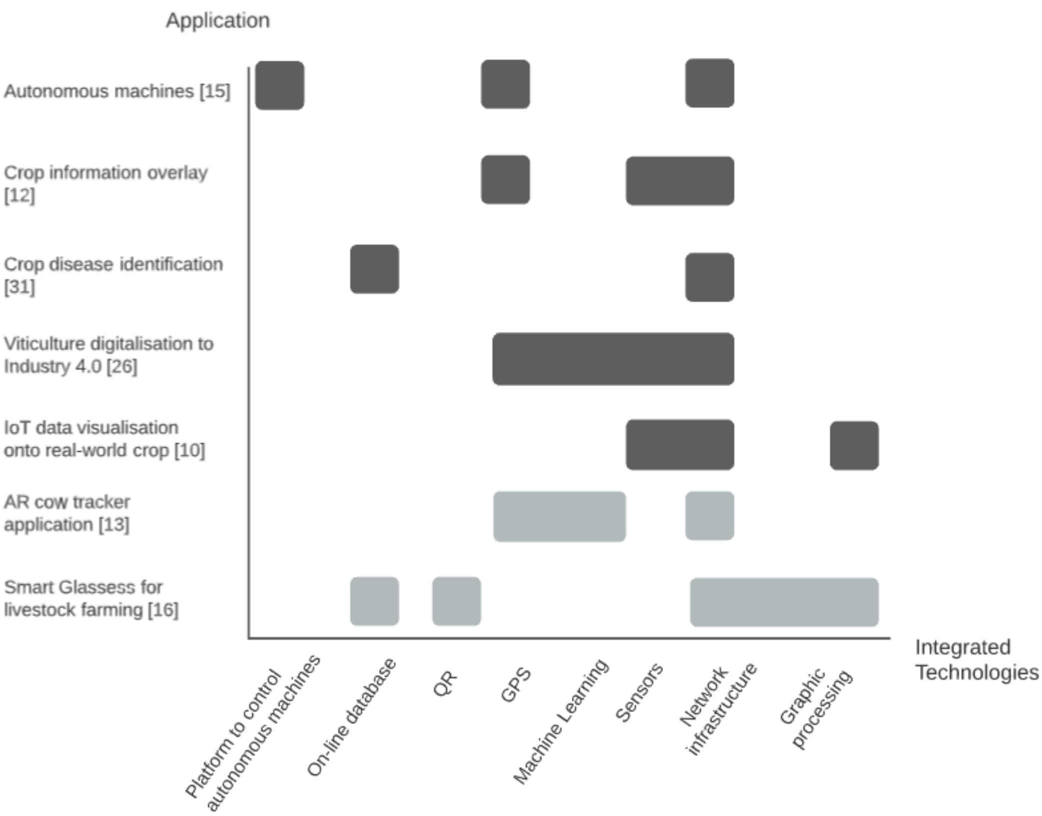

Figure 6. Comparison Analysis of Technologies Coupled with AR in Farming. Dark grey refers to crop-based articles, whereas light grey is for livestock.

In short, AR has been deployed within 7 documented settings, namely to relay data back to the farmer concerning autonomous machinery [15], to provide crop overlay information [12] and crop disease identification [31], viticulture digitalisation [26], IoT data visualisation overlay onto crops [10], cow tracking within livestock management [13] and for use with information overlay onto smart glasses for general livestock management [16].

4.2. What Technologies Is AR Coupled with to Provide a Service for Farmers?

The seamless interaction, and flexibility, between real world and digital content in a real-time deployment makes AR an asset for precision farming. In both application domains (crop and livestock) discussed in Section 2.1, AR provides the farmer with an intuitive metric for the access of real-time data (e.g., per animal, or per tractor) to focalise efforts in potentially problematic subjects. A similar approach for interaction evaluation is discussed in [37]. Each case study focuses on a different deployment of AR. While the work by [16] advocates for the use of wearables for monitoring milking production (of stationary cows). Zhoa et al. [13] focus on a smart phone mobile solution, highlighting the flexibility to implement AR solutions targeted to specific scenarios within livestock farming. Results from both applications demonstrate that technology is no longer a barrier for implementing AR applications in livestock, yet the limiting factors may include the development challenge. However, technologically, response times and computer vision integration (for example differentiating between single animations) are currently able to cater for real-time deployment, flexibility and scalability.

AR solutions have demonstrated a decrease in the time farmers had to spend locating an individual and associating external information (i.e., productivity metrics, health etc.). Despite the differences in specific requirements for crop and livestock management, there is overlap in terms of coupled technologies in the encountered applications.

A common trait between livestock and crop management is the use of AR as means of displaying information. However, it is the combination of AR with at least one but often several other technologies that provides the added value for precision farming application. Furthermore, the examples discussed can be classified into two broad categories. Firstly, those that use markers, either paper or object based to trigger augmentation (marker-based apps) of features in the real world and, secondly, those that use location instead (location-based apps), displayed in Table 1.

Table 1. AR Applications and Supporting Technologies.

AR Application	Technology Integration	Agriculture Domain	Medium
Real-time information about autonomous machines [15]	Platform to control autonomous machines *	Crop	Wearable: smart glasses
Crop information overlay [12]	Sensors, (e.g., humidity, wind, temp.), network infrastructure (e.g., GPRS, Wi-Fi, etc.)	Crop	Mobile phone
Crop disease identification [31]	Online database *	Crop	Mobile phone
Viticulture digitalisation to Industry 4.0 [26]	Smart sensors, machine-learning *	Crop	Mobile phone
IoT data visualisation onto real-world crop [10]	IoT sensors, graphic processing	Crop	Unknown
AR cow tracker application [13]	GPS, machine-learning (computer vision)	Livestock	Mobile phone
Smart Glasses for livestock farming [16]	QR (Quick Response) code scanning, VoIP (Voice over Internet Protocol), video streaming, (Wi-fi)?	Livestock	Wearable: smart glasses

* In some cases the specific technologies cannot be provided as they are not implicitly discussed in the referenced article, Unknown is stated when this cannot be inferred from the manuscript.

Both types have advantages and disadvantages in their implementation in the field. Namely, adopting a QR code process limits the farmer to specific locations to use the AR, however tracking and the physical to digital integration process is improved. The non-QR code approach provides greater flexibility for the deployment of the AR, yet physical to digital integration may be more problematic.

4.3. What Hardware Frameworks Are Used to Deploy AR Technologies in an Agricultural Setting?

Recent AR interaction models demonstrate advancements through the integration of mirrors, gyroscopes, wireless connectivity but the original foundations discussed in Figure 2 remain core. Reflecting on the related articles discussed in Section 2.2, Table 2 presents an overview of the hardware technologies employed for agricultural solutions in the aforementioned articles.

Whilst distribution and access to AR is made possible by means of different hardware-based solutions (e.g., smart glasses, head-mounted optical see through or video see-through), some could be considered as impractical for farmers within an everyday setting, where sensorial perception is crucial. There are, of course, multiple versions of AR glasses with varied screen size, ambience and depth recognition, as discussed in the article by Szanja et al. [18]. However, within this investigation the main type discussed is F4SG in [16], where primary control of the headset is achieved through an external joypad (via wi-fi and Bluetooth). Two main advantages specific to the F4SG device were identified in the study; namely (i) low impact on video and audio quality communication of background noise in the field and (ii) prolonged battery life of the device that enables the farmer to perform tasks uninterrupted throughout the working day.

Table 2. AR Hardware Approaches *.

Article	Agriculture Domain	Medium *
Huuskonen et al. [15]	Crop	Optical see-through HMD
Liu et al. [12]	Crop	Video see-through
Salve et al. [31]	Crop	Video see-through
Bento et al. [26]	Crop	Video see-through
Phupattanasilp et al. [10]	Crop	Monitor-based
Zhao et al. [13]	Livestock	Video see-through
Maria et al. [16]	Livestock	Optical see-through HMD

* In some articles, as the hardware model is not implicitly discussed, the authors infer the actual hardware model or list as Unknown when not evident.

Hardware solutions should also be ergonomic to cater for use over long periods of time [15]. Coupled with the hardware approach, consideration should be given to use of either a marker-based or marker-less approach. They have a higher up-front cost to develop but over time are more efficient with the resource use than traditional methods. There is a gap in agriculturalists' understanding of technological aspects [38], which may also mean that AR is an ideal approach because the technology integrates with systems and processes they are familiar with. Many article emphasise the work is on AR, but actually AR is typically employed as a visual outlet for the data processing or displaying the aggregated information.

4.4. Further Reflection and Validity

Based on the findings, this sub-section reflects on precision farming and AR in a wider (global) context. To address some of the world's current environmental, economic and social challenges, the United Nations put forth the Sustainable Development Goals (SDGs) [39]. The 2030 agenda completion has been a significant topic for the scientific community over the past years. From the SDGs implementation there are two key lessons. Firstly, scarcity of reliable data can frustrate a country's ability to optimize investment, create policy, make decisions and measure progress. Secondly, even though significant progress has been made, such progress has been unequal amongst countries and areas. Some of those inequities are attributed, amongst other things, to different technological capacities and data availability [40]. Within the agricultural domain, this is especially relevant for Goal 2 which aims to end hunger, improve achieve food security and nutrition whilst promoting sustainable agriculture; particularly target 2a that focuses on increasing investment through an enhancement of international cooperation opportunities, namely in rural infrastructure and agricultural research. Furthermore, 2a emphasises technology development to enhance agricultural productive capacity in developing countries.

As agriculture systems around the world strive to become more productive and less wasteful, in other words yield more by using smart city technologies with less input, sustainable practices must be pursued from a holistic perspective and integrated perspective [41], which directly links to the purpose of precision farming. In the SDGs documents it is regularly highlighted that data influx should be time-driven and available for decision making, this is one of the arguments used to advocate the importance of novel technological approaches, like earth observation products [42]. One could argue immersive technologies fall within these novel technological approaches and therefore could be of interest for SDG monitoring workflows. Literature testing the application of AR technology in agriculture within the SDG context (e.g., SLR-based methodologies) is to the best of our knowledge not yet available due to the limited volume of published works of AR in Agriculture from 2016–2021. However, other domains, for example education have found advantages in the use of AR to meet their corresponding SDG [43,44], which may signify an impending growth in the uptake of AR in farming the near future.

Another notable aspect for succeeding in SDG monitoring is the way in which data is communicated. Information and monitoring results should be adequate for their application. Moreover, the results should be interpretable by different stakeholders. Since SDGs are often broad, complex and large-scale, it is idyllic to find a way to show results locally (i.e., what does it mean for the farmer?) in a live, data-driven, format. In that sense, immersive technologies, such as AR, could speed-up information delivery and retrieval for decision making, ultimately aiding in the process of achieving SDGs monitoring and evaluation. As such, the findings discussed in this article, serve as a demonstration of applied AR-based solutions within agriculture and outline the constraints and benefits of using the technology when couple with precision farming.

5. Conclusions and Future Work

The mixed reality technology domain, of which AR resides, is a constantly evolving field [33] and as Papadopoulos et al. discuss, new innovations tend to define new interaction methods. Evidence suggests AR will become vital for the success of precision farming, particularly as there is a migration towards the use of data-driven farming and autonomous agro-robotics in the endeavour to produce more with fewer resources. The autonomy that wearable-based hardware provides farmers makes AR especially suitable for precision livestock farming, both when monitoring individuals through large spaces [13] or during more static practices like the milking process [16]. In this article, related literature was discussed regarding only applied AR solutions within agriculture. In all the articles discussed, AR has demonstrated a significant impact for the end-user stakeholder, yet there may be applications for other stakeholders beyond the investigation of this study (within a wider agriculture setting), such as in the supply chain as evidenced in [23]. It is also clear in the findings that AR must be coupled with other technologies for a beneficial impact; namely sensors, networking, machine learning and location-based communication technologies. The limitations of this work include the aforementioned reduced level of existing articles on AR for agricultural application. AR is a relatively young technology for use within both livestock and crop-based farming, and this is evident in the low number of articles published on this topic between 2016 and 2021. This also meant that a systematic literature review process was not possible, instead a snowballing approach was adopted to investigate the articles referenced.

Future directions for this research could include extending the survey outside of agriculture to related domains within the food supply chain (e.g., transport, shipping, manufacturing/processing, etc.) to reflect on the wider benefits of AR within the entire food supply network. Furthermore, this article also did not conduct a user experience (UX) or human-computer interaction-based investigation, as this was outside the scope. Rather the intention was to focus on applied agriculture projects and discuss the hardware in place and potential benefits of emerging solutions could have for precision farming. However, both considerations are possible areas of investigation for a further extension of this research.

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Abbreviations

AR	Augmented Reality
F4SG	GlassUp F4 Smart Glassess
GPRS	General Packet Radio Service
GPS	Global Positioning System
HMD	Head-Mounted Display
IoT	Internet of Things
LMS	Livestock monitoring systems
MAR	Mobile Augmented Reality
QR	Quick Response
RFID	Radio frequency identification devices
SDG	Sustainable Development Goals
SDK	Software Development Kit
SLR	Systematic Literature Review
UX	User Experience
VR	Virtual Reality
WSN	Wireless Sensor Network

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