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Smart glasses in the chicken barn: Enhancing animal welfare through mixed reality

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ABSTRACT

Livestock production requires a thorough understanding of animal welfare to increase productivity and ensure appropriate housing conditions. The expanding availability of consumer-grade virtual and augmented reality devices opens new possibilities for precision livestock farming (PLF), where sensor technology traditionally monitors real-time animal data. In poultry farming, monitoring each bird individually is often not economically feasible due to the large flock sizes. To address this issue, we propose a novel method to evaluate housing conditions by focusing on the visual and temperature preferences of domestic chickens, considering these factors within a broader environmental context. Chickens perceive light at a wider range of wavelengths than humans, which significantly influences their behavior. Additionally, temperature variations, such as heat leaks and accumulations, can contribute to stress and negative behaviors in the flock. We developed a device comprising smart glasses equipped with specialized cameras to capture thermal infrared, ultraviolet, and visible RGB (red, green, blue) light, alongside real-time user position tracking. Points of interest (POIs) can be added to the logged tracking data along with captured content. The data collected by the glasses can be used to create virtual tours embedded in a 3D model of the barn, providing a comprehensive view of on-site conditions.

We also introduce a streamlined pipeline for building these virtual tours using the Unity game engine, making the content accessible for agricultural education. This approach enables users to remotely gain insights into the housing conditions of poultry without needing a physical visit, enhancing both learning and engagement in animal welfare practices.

1. Introduction

In recent years, the agricultural sector in Germany and Western Europe has faced increasing demands, particularly in animal husbandry, due to a growing social movement emphasizing animal welfare [12]. Modern environment control strategies are necessary in livestock production for ethical and economic reasons [27]. By introducing new technologies and reducing flock sizes in the barns, many farmers are improving livestock housing conditions. Especially for chickens, the lighting and temperature conditions in the barn are among the most critical factors for animal welfare [43,8,46]. If the optimal conditions are not achieved, productivity decreases, and the animals become stressed, leading to negative behaviors such as feather pecking and cannibalism [40,17]. Facing these issues, we aim to introduce new immersive methods to investigate housing conditions through advanced Mixed Reality technology.

We want to address two different user groups and therefore introduce a system consisting of multiple modules. The main idea behind this distinction and the respective methodology is to keep the count of in-person visits in a barn low. In livestock farming, animal welfare is strongly related to the animal's interaction with the farmer and other humans [63,61]. Animals show an emotional reactivity to the presence of humans [24]. Fear of humans can also be a limiting factor in productivity [6,7,20]. Different studies in the field of human-animal interaction re-

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vealed that chickens can be habituated to environments with human treatment when they experience positive events related to a human visitor from an early age [33,21,22]. However, the way animals perceive humans is not only based on previous experiences, but also influenced by their environment and housing conditions. Especially in large-scale commercial farms, the space for avoidance and escape is typically very limited, which can further increase stress levels [28]. A common guideline for ethical standards in research involving agricultural animals is the Ag Guide [25]. Further ethical aspects in commercial livestock production were investigated by Kunzmann [41], Porter [58], and Macer [48]. Hemsworth [33] recommends that only trained people should interact with farm animals since human behavior can affect animal welfare and productivity. Besides the welfare aspects, hygienic precautions for minimizing health risks and preventing diseases in the flocks are a major challenge, especially for large group visits [66]. We suggest a methodology where only one person is needed to visit the barn physically allowing to share a video stream to persons outside the barn as well as a post hoc localization of events within an off-farm digital map. From an ethical perspective, we are called upon to maximize animal welfare by reducing stress to the animal evoked by persons, especially unknown persons, entering the barn, disturbing the animals, and impacting welfare consequences.

Group A, respectively the expert group, consists of on-site users who visit the barn in person, such as farmers, scientists, or lecturers. For this user group, we developed a head-mounted device (HMD), leveraging Augmented Reality (AR) technology. Although this general idea has already found broad acceptance and use cases in the industry [10], it is still not comprehensively investigated in agriculture and animal sciences. The primary purpose of our device, in the following referred to as smart glasses, is extending the user's perception of the surrounding environment by augmenting supplementary information related to animal welfare. To realize this, we make use of a specific type of AR, called video pass-through AR. Using this technology, the users see their environment on the glasses' screen as a live camera image, contrary to see-through AR, where the users directly see their environment, e.g., through transparent glasses. One major advantage of video pass-through AR is that live streams from the device including its environment are possible. While exploring the barn, the user can then switch to an ultraviolet or thermal infrared perspective. The glasses track the user's position based on structure from motion. Additionally, the smart glasses allow the user to record videos, or save points of interest (POIs).

Users of group B, the non-expert group, are all users who investigate the barn remotely with a computer, such as students or customers. This can be realized either by a live stream from the glasses, or by using the captured data within a virtual environment. In this context, modern 3D visualization techniques offer a solution by providing students with realistic insights into animal husbandry without the difficulties of in-person visits. We propose a pipeline for creating a virtual educational tour platform based on captured data from the smart glasses using the Unity game engine. The ultimate goal is to provide insights into the conditions within a barn in an immersive virtual environment as a tool in agricultural education and knowledge transfer.

To summarize, this article discusses the development of smart glasses enhancing welfare assessments inside the barn, as well as a virtual learning platform focused on poultry production and animal welfare, integrating 3D models with images, and both video and audio data.

We focus on two main research goals, for which the glasses are supposed to be applied, addressing user group A:

1. **Temperature Detection**: Using the glasses' thermal imaging sensor, the user should be able to detect temperature differences as small as 1 °C. A particular emphasis is set on identifying heat accumulations and temperature leaks within the barn.
2. **UV Light Assessment**: The glasses should capture and visualize the presence of UV light in a barn, even at low intensities, and allow the user to identify areas with high UV reflectivity, allowing to determine how UV light may affect chicken behavior.

Addressing user group B, we focus on two more research goals towards assessing housing conditions outside the barn:

3. **Setup of an Educational Platform**: We aim to introduce a toolbox for creating a virtual tour through a barn. The virtual tour should provide insights into the local facilities and ease orientation by allowing the user to freely move and explore. The whole process of setting up the virtual tour should be reproducible by other institutions with reasonable effort.
4. **Spatial Linking of Information**: Particular emphasis is placed on the applicability of a game engine for combining spatial data and knowledge in a virtual tour setting. Captured data from the smart glasses should be accessible intuitively. Therefore our goal is to accurately arrange content within the correct spatial context, and display it in an appropriate way, keeping the whole procedure as simple as possible for the user.

The subsequent section reviews related work in virtual education environments and summarizes the current state of research. Section 3 addresses the hardware requirements and setup of the smart glasses. Section 4 details the software development process in Unity including results of an exemplary virtual tour of the University of Bonn's scientific farm. Section 5 discusses these results, and the article concludes with a reflection on potential use cases for the developed software kit. A detailed technical guideline for applying the glasses is proposed by Baltzer [4].

2. Related work

The use of virtual 3D environments for education and professional training has gained attention in the Geoinformation community over the past decade, especially following the emergence of more accessible Virtual Reality (VR) glasses starting around 2013-2016. Virtual environments are gaining widespread use across various fields, including emergency simulations [76,71], critical medication [36,52], and digital reconstruction of lost architectural heritage [1,3,5,14,29]. These applications' virtual environments share a common characteristic: accessing their real-world counterparts is often impossible due to possible dangers, health risks, or significant costs. Similarly, the use of virtual environments in agricultural education helps overcome the challenges associated with large group visits to barns, ensuring a safe and stress-free environment for both the animals and the visitors. Virtual environments are increasingly utilized by professionals to facilitate knowledge transfer, potentially reducing the dangers, costs, and logistical challenges associated with real-world training.

Fiorillo et al. [26] proposed a framework for cultural heritage visualization that focuses on knowledge transfer for beginner-level students, incorporating game elements that were designed by more experienced students. The interactive tour was made accessible online, providing an engaging educational experience during the pandemic years (primarily 2020-2022) when in-person class trips and cultural visits were frequently limited.

Sefercik et al. [65] developed a virtual tour of a university campus in Turkey using the Unity game engine. They utilized UAV-based images to generate a point cloud in the initial step and a textured mesh model in the subsequent step, which could be imported into Unity. Finally, a movable first-person player was added to the 3D scene, allowing virtual access to the campus. The virtual scene included buildings with pop-up windows providing additional information, such as size or usage.

Keil et al. [39] published an approach to visualize free spatial data in immersive 3D environments using game engines. To intensify the communication of spatial information, they used digital elevation models and 3D city models from Open Street Map and Open.NRW (open.nrw, last access 22.07.2024) and imported them into a Unity project. In addi-

Fig. 1. User wears the Smart Glasses in a chicken barn on Campus Frankenforst, University of Bonn.

tion to a common display view, they added a virtual reality capability for the use of head-mounted displays. The result was a 3D representation of mostly simple spatial information that allowed viewing the desired location from all perspectives, creating an improved overview compared to common approaches. Virtual reality devices offered additional advantages, especially through the increased field of view and the realistic depth effect.

Caria et al. [15] investigated the use of up-to-date augmented reality applications in livestock breeding and created a link to the emerging topic of precision livestock farming [56]. The authors conducted a study to evaluate AR glasses as a tool for augmenting information live while exploring the barn and were able to point out major advantages for farmers in their daily work. The methodology included industrial-grade smart glasses by GlassUp (Italian startup company) as the primary component for the head-mounted device. Several technical challenges emerged during the experiments, providing valuable insights for refining our approach. One significant finding was that voice commands for controlling the device proved problematic in the presence of background noise. The controls were shifted to a mechanical dashboard to address this issue. Another challenge resulted from lag times of more than 2 seconds between reality and the captured stream. While Caria et al. [15] make use of QR Codes in a marker-based augmented reality approach, we want to develop a marker-less system with continuous position tracking. Another difference is the choice of sensors. Since Caria et al. [15] use an RGB camera only, the device depends on a well-illuminated environment. Our device comprises UV and thermal imaging sensors for assessing animal welfare. If, for instance, temperature differences at nighttime are supposed to be investigated, the smart glasses can be used without the necessity of scaring the animals by sudden changes of the lighting.

The role of computer vision in PLF for welfare monitoring and behavior analysis was investigated in a review by Yang et al. [75]. The authors summarize different innovative approaches which improve productivity as well as animal welfare but also point out open potentials especially for VR technology in poultry farming. Further it is stated that most vision-based methods for welfare analysis are not robust to varying lighting conditions. We address this challenge by applying sensors which are independent from the presence of human-visible RGB light.

The transition between real animals and their digital twins, and vice versa, using AR and similar techniques, was examined in a review by Neethirajan and Kemp [54]. The review highlights a distinction between the physical environment, where data is generated and captured by sensors, and the virtual environment, which operates on a computer and provides information to enhance reality. Among their suggestions, the authors recommend thermal infrared sensors to measure animal body temperatures, feeding this data into digital twins of the animals. However, they also note that digital twins in livestock production are a highly uncharted topic and lack practical application and evaluation. Additionally, it is uncertain whether the concept can efficiently transfer to poultry, given the relatively large number of sensors required and the effort involved relative to the potential benefits.

Halachmi et al. [30] suggest that technologies using one sensor per herd or flock, rather than one sensor per animal, may become more common for poultry and other livestock with lower economic value per individual. Despite these challenges, Neethirajan and Kemp [54] identify high potential in improving animal welfare conditions using digital twins and related technology.

Summarizing recent related publications, there is still a high need for further scientific work in applying VR/AR technology in livestock farming. First approaches showed a general applicability and promising results, but also revealed major issues and research gaps. In our article, we focus on the development of smart glasses combining multiple sensors with respect to relevant aspects in the welfare of chickens. We additionally highlight the importance of using the technology not only on-site but also remotely by suggesting a pipeline to provide the recorded data as a virtual tour.

3. Development of the smart glasses

In this section, we describe the setup of our smart glasses, which are supposed to support expert users at evaluating housing conditions within chicken barns. Syberfeldt et al. [69] conducted a comprehensive review of available augmented reality products and key selection criteria. We decided on a head-worn solution to fulfill most of the proposed prerequisites. We developed a device based on Pico 4 VR glasses and three different camera modules to record video material while going through a barn. The VR glasses feature a pass-through video stream captured by their built-in cameras allowing the user to move around safely while wearing the head-mounted display (HMD). Fig. 1 illustrates the glasses in practical application within a barn.

Compared to Caria et al. [15], we use the standard Pico controllers to navigate the menu instead of developing an additional physical dashboard. This feature simplifies the controls, as the controllers are specifically designed for AR applications. It also reduces the amount of hardware needed in the barn. A live image from the chosen additional camera is displayed as an overlay on the pass-through stream of the glasses' screens. The user can choose between thermal infrared (IR), ultra violet (UV), or the human-visible color spectrum (RGB) with an extended field of view (FOV) (cf. Fig. 2). The theoretical background in chicken vision leading to the choice of these specific cameras is explained in detail in the following subsections.

Each stream can be recorded after choosing an icon. Additionally, the user can take screenshots of each stream and record audio. During

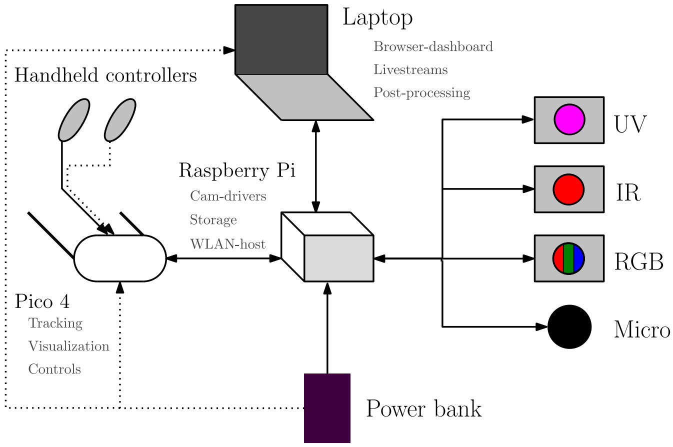


Fig. 2. Smart glasses overview including supplementary components. Right side contains the sensors; UV - Ultraviolet, IR - Thermal Infrared, RGB - Red Green Blue (visible light for the human eye), Micro - Microphone for audio input along with all optical sensors.

the recording session, the device uses built-in cameras to track its position and orientation in a local coordinate system by a structure from motion algorithm [57], which is based on visual pattern detection. The Pico 4 application responsible for the tracking was created using Unreal Engine. It establishes a wireless local area network (WLAN) connection to a Raspberry Pi mini computer, which works as an interface between the VR glasses and cameras. The Raspberry Pi contains the necessary drivers, and hosts a dashboard on a local server, offering all camera controls.

The basic system configuration aligns with [47], who proposed a mobile augmented reality application for agriculture consisting of an optical sensor (video camera), mobile terminal, server, and positioning system (GPS). The dashboard can also be accessed via a computer or any other device connected to the WLAN network, allowing the barn tour to be shared live, for example, through a video conference. Before the hardware compilation, we set a total price limit of 5000 € to keep the costs reasonable concerning the applications and user groups. The goal is to offer the device as a toolbox consisting of hardware and software, primarily for evaluation purposes in educational institutions focused on animal husbandry. The primary use case for our smart glasses is to create virtual tours of chicken barns for agricultural education, with a specific emphasis on understanding of housing conditions from the animal's perspective. To achieve this, we conducted extensive literature research on chicken eye anatomy and behavior. The most important findings we considered mandatory to include in the smart glasses are outlined in the following sections.

3.1. UV light

Chickens exhibit tetrachromatic vision, possessing four types of cone photoreceptor cells in their eyes, unlike humans, who have three [31,32,70,11]. Chicken eyes include cones sensitive to long (red), medium (green), and short (blue) wavelengths, as well as a fourth cone that is sensitive to very short (violet/ near-ultraviolet) wavelengths [31,32,45]. The additional violet-sensitive (VS) cones enable chickens to perceive a broader and richer spectrum of colors, including wavelengths in the near UV range, which are invisible to humans [31,32]. This advanced color vision facilitates their navigation and interaction with their environment in ways beyond our comprehension [44].

Research has shown that UV light influences chickens' behavior, likely due to their unique color vision [37,67,49,40]. According to [68], the presence of UV light plays a major role in the welfare of chickens. Our project emphasizes the importance of capturing this spectrum, enabling us to visualize and analyze objects with heightened sensitivity, similar to how chickens perceive their environment. Therefore, we chose a camera

Fig. 3. Image taken with the 360° camera at Campus Frankenforst, Königswinter, and edited with post-processing methods to simulate chicken vision.

filter focusing on the UV-A range (315-400 nm).

For our UV sensing capabilities, we utilize an XNiteUSB8M camera with an 8 MP resolution (3264×2448 @ 15 fps) and a Sony IMX179 sensor with a detection limit of around 300 nm. This system is complemented by a Llewellyn Optics Silica lens (6mm F/2.8) capable of detecting light below 200 nm, along with UV and IR filters (XNite 330C and XNiteBP1, respectively). The total light range of this system encompasses 320-380 nm, targeting the UV-A spectrum. However, challenges associated with this sensor include its relatively heavy weight and low frame rate at maximum resolution.

3.2. Temperature

Temperature regulation is crucial in maintaining animal welfare, particularly in preventing heat stress, often exacerbated by high stocking densities in barns. Heat stress can lead to reduced productivity, impaired growth rates, changes in behavior, increased susceptibility to disease, and higher mortality rates [2,73,35,9]. Additionally, localized temperature drops caused by leaks or inadequate ventilation can negatively impact animal comfort and increase the risk of health problems [13]. To effectively identify and address these critical temperature variations, we selected the FLIR Lepton 3 thermal infrared camera. While its spatial resolution of 160×120 pixels is modest compared to other models, it provides sufficient detail to detect temperature differences at close range, with a high temporal resolution of 50 mK. This reduction makes it a cost-effective solution for monitoring barn environments at around $350. To facilitate the data transmission to a host device, we integrated the camera with the GroupGets PureThermal 3 circuit board, allowing for seamless image streaming via a USB-C connection. This setup not only enables real-time detection of heat accumulations and cold spots but also supports the implementation of customized drivers for enhanced functionality.

3.3. Field of view

An essential aspect of simulating the animal perspective in our project is understanding the field of view (FOV) of chickens. Given that birds' eyes are on the sides of their heads rather than forward facing, their visible field is naturally different from that of humans. As prey animals, chickens have evolved specialized visual adaptations to help them detect and evade predators [74]. One of their primary adaptations is the lateral positioning of their eyes, which expands their FOV. This positioning allows for expansive visual coverage, estimated to be around 300°, though exact values may vary based on breed and individual anatomy [60]. Birds are known to have a small binocular overlap of 10-30° [50,51], while their monocular field extends much wider, covering 120-140° per eye. Even with the latest methods for visual field analysis, such as automatic eye tracking [38], accurately determining the boundary between the monocular and blind sectors remains a challenge. Since a chicken's eyes are relatively immobile within their sockets, they rely

Fig. 4. 3D model of a chicken barn on research farm Campus Frankenforst, Königswinter.

on rapid head movements, supported by their long, flexible necks, to make significant shifts in view [59]. Previous research has shown that chickens move their heads frequently to recognize objects but often fail to do so at certain angles and distances [18,19]. This suggests that while chickens have a much wider field of view than humans, their ability to perceive sharp details and depth (stereoscopic vision) is limited.

Although the VR glasses used for our device already contain 5 front-facing RGB cameras, these are only used as a live pass-through video for user navigation in the barn, and position tracking, but they are not suitable for animal welfare assessments. To simulate chickens' visual characteristics, we implemented a 360° camera system using two fish-eye lenses mounted on opposite sides of a circuit board. Since the camera records a full omnidirectional panorama, post-processing methods have to be applied to approximate the actual perception of a chicken (cf. Fig. 3). The blind spot of 60° towards the back is therefore removed. Across the monocular field of approximately 270°, a blur filter is applied to create the impression of reduced visual capabilities. The ultimate goal is to improve the understanding of how chickens perceive the environment by simulating their vision for human eyes.

The 360° camera is a prototype and not in mass production, so it is not as readily available on the market as the other two cameras. The expense was around $150. Although consumer-grade 360° cameras are becoming more widely available, most lack a UVC (USB Video Class) interface. That interface is essential for our device, limiting our choices. The camera produces a single video stream that combines both lenses into a widescreen format with a resolution of 1920×1080 pixels.

4. Development of the educational tour platform

In this section, the pipeline for creating a virtual educational tour is presented, addressing non-expert users, remotely engaging with captured material from the smart glasses. Creating a virtual tour requires distinguishing between different types of data. According to [64], it is essential to differentiate between real-world data and artificial data to effectively combine them. In the previous section, the hardware setup used for capturing real-world data was outlined, while this section focuses on artificial data, specifically virtual 3D models that represent real objects.

4.1. Data integration

The main objective of this project is to integrate video footage from the inside of chicken barns with an artificial 3D model of the building into a unified virtual environment, spatially linking these different data types. The goal is to allow users to navigate through the 3D model and access video recordings at their respective locations within the barn. As they play a video, the trajectory of the smart glasses used for recording will be represented by a simplified path within the model, visible

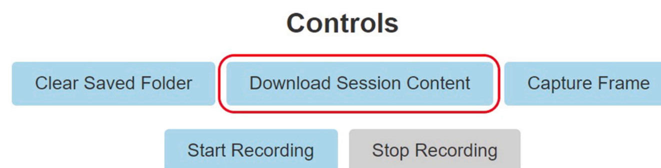


Fig. 5. Browser dashboard of the smart glasses with download option.

simultaneously to help users trace the recordings in the virtual environment. While various software packages can meet these objectives, it is crucial to streamline the process from raw data to the final virtual tour to ensure that even users without advanced programming knowledge can create their virtual tours without extensive training.

For the development of the software mainly two different resources are needed:

1. **3D model**: When aiming to create the most realistic 3D model, the ideal approach would involve using a professional terrestrial laser scanner [42]. This method includes scanning the coops from multiple viewpoints and generating a textured mesh through applicative post-processing software. Although this technique offers a high level of detail, it is also complex, requires specialized knowledge, and involves costly equipment. For this reason, we will discuss a simpler alternative using standard 3D modeling software, which is also effective, albeit with less emphasis on intricate details. For the example in this article, we utilized SketchUp [16] and Blender [34]. One significant advantage of SketchUp is its extensive library of textures and sample models, which can be easily imported. While SketchUp generally requires a paid subscription, it offers a free browser-based version with limited capabilities. The basic procedure in SketchUp involves drawing or importing ground plans and then giving them heights to create 3D models.
   The level of detail in the 3D model can vary greatly depending on the user's objectives and the amount of effort invested. For this project, we modeled a building containing multiple chicken coops on the University of Bonn's Campus Frankenforst (see Fig. 4). Manual measurements were taken using a measuring tape and laser range finders, achieving accuracy within a few centimeters. The primary structures, such as walls, doors, and windows, were measured meticulously. However, we omitted technical equipment and interior details since these details are not critical for orientation and can be observed more thoroughly in the video recordings.
2. **Video footage:** The most crucial element for any virtual barn tour is the video footage, capturing the housing conditions. While exploring the barn with the smart glasses, any important information can be captured in the form of photos, videos, and audio. The three cameras introduced in Section 3.1 can record videos and images in different light frequencies. After a recording session, the session

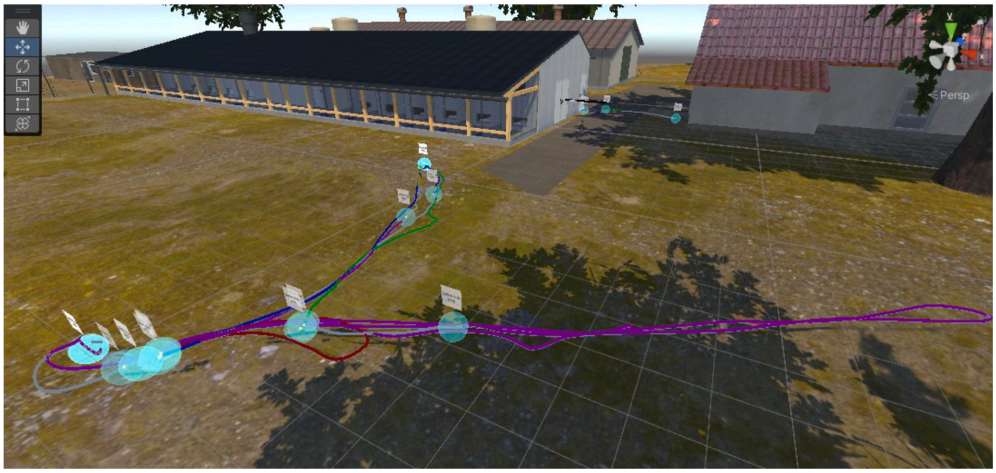
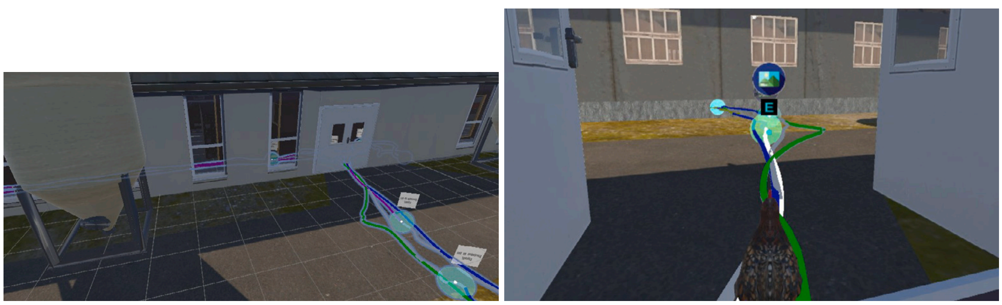


Fig. 6. Recording trajectories and POIs in the 3D model.



(a) Recording paths leading through doors of a building in the virtual environment.

(b) Doors in the virtual environment that open automatically when approached by the user.

Fig. 7. Interaction with doors in the virtual environment.

content can be downloaded as a zip archive from the smart glasses. Accessing the data can be done via a browser dashboard on a computer connected to the Raspberry Pi's WLAN network (cf. Fig. 5). Recordings that capture ultraviolet and thermal infrared light are converted to color channels visible to the human eye, making them viewable using standard video players. The folder structure and naming convention were chosen to match the requirements of automatic importing in Unity. Additionally, a JSON file is generated to log the tracking data from the session. This file acts as the directory for the virtual tour, guiding the user through the barn.

4.2. Development of a virtual barn tour in Unity

Unity has long been established as a leading development environment for 3D games. However, its capabilities extend beyond gaming, as it has become an increasingly popular tool for developing serious educational applications in the scientific community. Unity supports various platforms and input formats and has a vast library of pre-written scripts to facilitate object movement and interactivity within virtual environments.

The development of a virtual chicken coop tour in Unity requires the following steps:

1. **Create a New Unity 3D Scene:** Start by creating a new scene in Unity and import the 3D model of the chicken barns, which will serve as the foundation for integrating additional content.
2. **Import Our Toolbox:** Incorporate our toolbox [4], which includes scripts and materials for animating a virtual chicken, viewing trajectories, managing camera movements, and displaying videos and images.

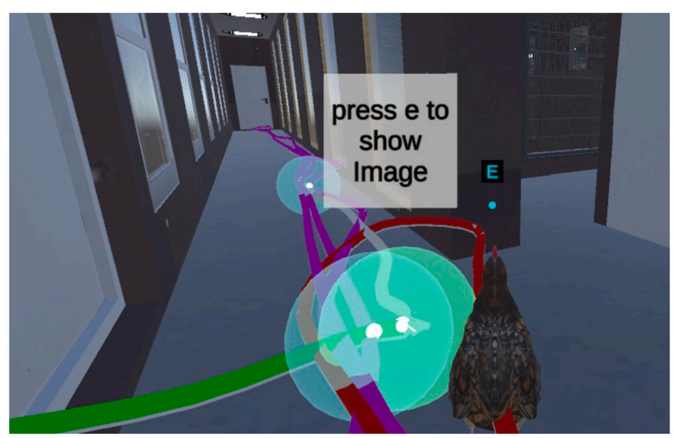


Fig. 8. When approaching a point of interest, a small menu appears, offering the user the option to play the content by pressing a button.

3. **Import Tracking Data and Recordings:** The smart glasses track their position with a frequency of 1 Hz as they move through the barn. During the recording session, all positions and orientations are logged into a JSON file using a local coordinate system. Additional points of interest (such as spots where photos were taken or a video recording began) get a reference to the respective media file in addition to the positional information. To import the data of one recording session into Unity, we developed a tool called Data Path Factory. By simply dragging and dropping the JSON file into the tool and pressing the 'Create Data Path' button, the script reads the JSON data and generates Unity Game Objects, which include all crucial information like positions and linked media files. Gen-

Fig. 9. When viewing recordings from the smart glasses, a media player appears in fullscreen mode, with the position in the 3D environment still visible in a small window in the top right corner.

Fig. 10. Thermal infrared video display alongside a smaller window for orientation.

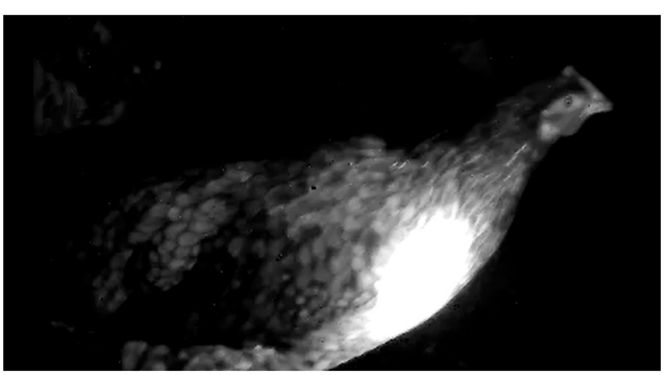


Fig. 11. UV image of a chicken inside the barn with artificial UV light.

Fig. 12. UV image of a chicken flock outside under sunlight.

erally, individual POIs contain a single image, while trajectories can include videos. The video length and the distance covered between tracking timestamps determine the movement speed during playback. However, even when users stand still while recording, the tracked position may vary slightly due to small movements and tracking inaccuracies. To address this, we implemented a filter that merges consecutive points within 10 cm of each other to single points. This approach helps prevent sudden and unexpected movements of the model, ensuring minimal simulated movement when recording from a fixed viewpoint. Additionally, we introduce Beziér curves between time stamps to smooth the movement, since the measuring frequency of 1 Hz would otherwise result in discontinuous movement with abrupt turns every second.

4. **Registration of the trajectories:** To fit the recorded trajectories into the 3D model, manual adjustments can be made if needed. Each SubPath element represents a trajectory corresponding to a video recording. The paths are color-coded depending on the cam-

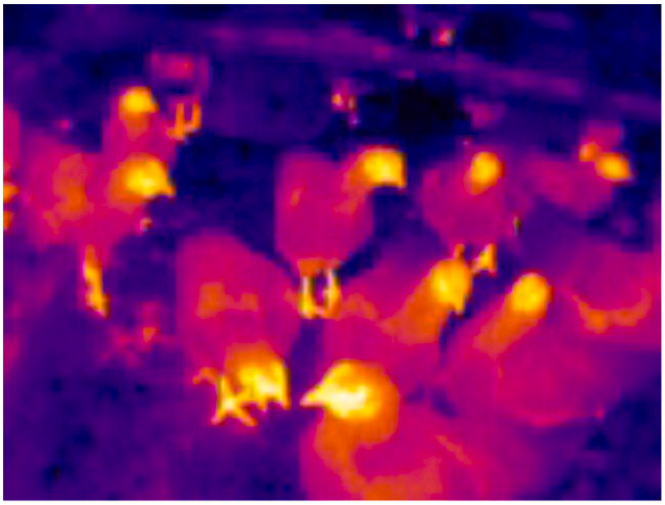


Fig. 13. Thermal image of a chicken flock inside the barn, showing the head and feet as the warmest exposed parts of the body (bright yellow).

era used: green for RGB, violet for UV, and red for thermal images, making the content easily distinguishable. Since the relative spatial relationship of all SubPaths remains consistent regardless of the global coordinate system, all SubPaths can be collectively moved, rotated, and scaled by applying transformations to the DataPathFactory parent object.

5. **Export the application:** Select an appropriate format and platform for the final virtual tour, and export the application accordingly. We recommend using WebGL for browser-based applications when addressing a large remote audience. Although it is possible to render 3D models and high-resolution videos in a web browser on modern computers, this approach might not deliver the highest possible quality. For optimal performance and visual fidelity, we suggest exporting the application as a local executable file, which can also be distributed remotely via file-sharing platforms. Additionally, it is possible to export the application for mobile operating systems, such as Android, but in this case, the control bindings need to be adapted for touch screen interactions.

Comprehensive step-by-step instructions for setting up the virtual tour in Unity are provided in our technical manual [4]. To highlight the most important features, the following section will demonstrate the setup of a virtual tour using recordings from the agricultural research farm Campus Frankenforst at the University of Bonn.

4.3. Results – virtual tour of Campus Frankenforst

In this section, we showcase the primary functionality of the virtual tour platform using data collected from chicken barns at Campus Frankenforst, the agricultural research farm of the University of Bonn. Once the data from the smart glasses is imported and integrated into the 3D environment, POIs that have been captured are automatically marked as circles, with colored Bézier curves on the ground connecting these points. In the example shown in Fig. 6, violet curves predominate, indicating that recordings with the UV camera were used along these paths.

A key consideration in designing the tour is the transition between indoor and outdoor environments. Since video recordings may involve transitions through doorways (cf. Fig. 7a), users might encounter closed doors within the virtual tour. To address this, we included interactive doors in the 3D model that automatically open when the user approaches. As illustrated in Fig. 7b, this feature allows the user to seamlessly continue its path from the inside of the barn to the outside environment.

When launching the application, the user appears in the virtual environment as a chicken, with movement similar to that in a third-person role-playing game. The default view places the camera behind the character, but it can easily be adjusted to a first-person perspective or other angles. The chicken avatar can be controlled using the W, A, S, and D keys for movement, the Space bar for jumping, and the Shift key for running. Users can interact with objects, such as opening doors, by pressing the E key. Initially, users can freely explore the 3D model to gain an overview of the space. During this exploration, they will encounter POIs and trajectories marked on the ground (cf. Fig. 8). When near a POI, a popup label will provide information about its content, and an icon preview may be displayed if it has been preselected. This preview can be a real photo taken by the smart glasses at the POI or a simplified icon representing the content type.

Users can switch from free exploration to media viewing mode by approaching POIs and pressing the ‘e’ key. This mode displays a minimap of the 3D model, facilitating navigation (cf. Fig. 9).

While the small window showing the position within the 3D model is less crucial for viewing standard RGB media, it is indispensable for thermal infrared and UV recordings. Orientation and object recognition are significantly more challenging based solely on these videos. As shown in Fig. 10, thermal images lack patterns, borders, or color differences if there are no temperature variations, making them unsuitable for orientation. In contrast, the RGB image in Fig. 9 provides a clear analogy between the recording and the model, facilitating user navigation.

5. Discussion

The methodology we propose for understanding poultry housing conditions from the animal’s perspective integrates custom smart glasses with a development pipeline for creating virtual educational tours. Contrary to most current augmented reality approaches, our focus extends beyond the live augmentation of additional information within the real environment. We also emphasize capturing data for later use in knowledge transfer at home in a virtual tour.

The duality of our developed technology and workflow (on-site visit and remote learning) leads to major benefits for animal welfare. Since a virtual tour made of captured data from an on-site visit can display many aspects of farming practices, we propose that a substantial share of group visits could be replaced by virtual visits, similar to other vocational fields such as medicine [52]. According to the [23], the system introduced here is capable to mitigate stress (e.g. handling stress or any other stress associated with the interaction with humans) and, therefore, to decrease the risk of negative affective states and increase the probability of positive animal welfare. Applying our smart glasses in the barn does not harm animals since all sensors are contactless, enabling an -as far as possible- undisturbed insight into poultry housing and welfare. The impact on the animals can be expected as comparable to any other human visit, while the positive effects on animal welfare predominate.

The UV camera allows us to assess the adequacy of UV lighting inside the barn. If the camera detects insufficient or no UV light, the user must manually introduce an appropriate light source (cf. Fig. 11). Our results demonstrate that our system reliably delivers insights into the lighting situation, which is an important achievement with respect to our research goals. A comparison with a handheld UV light sensor, which is commonly used for welfare assessments in barns, confirmed that the camera’s sensitivity meets the requirements for analyzing housing conditions.

Fig. 12 shows that the UV camera can capture high-quality images in outdoor areas, leveraging the UV component of sunlight.

The thermal infrared camera effectively detects animals by their body heat, making it possible to distinguish them from their surroundings, even in low-light conditions. This capability allows the camera to function independently of lighting, enabling recording at night or in barns without artificial illumination, thereby reducing stress caused by light exposure. As shown in Fig. 13, the warmest areas of the chickens

Fig. 14. Hatch within a wall in the barn in RGB and Thermal Infrared.

are typically their heads and feet. According to the camera's technical specifications, it can reliably detect animals with abnormal body temperatures by comparing them to baseline values.

Fig. 14 shows a hatch on a barn wall captured by the RGB camera (left) and the thermal infrared camera (right). Because the hatch is thinner compared to the solid brick wall, it heats up more quickly during summer. Therefore, a noticeable temperature difference is visible in the thermal image, with the colder areas appearing as dark purple. In winter, the hatch may be a source of heat loss, causing the area to be colder than the surrounding wall. This comparison demonstrates the capability of the thermal infrared camera to detect temperature leaks in the barn, which is one of the primary functionalities of the smart glasses.

The main advantage of our approach compared to the use of single sensors is the automatic linking of qualitative content with spatial information in form of POIs and tracking paths. The datasets can be used in education or in spatial decision support systems in industrial PLF [55]. One of the current limitations of our device is that it can only record one camera stream at a time. While this is manageable for static environments by capturing sequentially with different cameras, dynamic scenes involving moving animals cannot be recorded identically. Also, the resolution of the cameras is limited. However, depending on the budget, they can be replaced by other models with higher resolution if needed.

Considering the use of our device in an educational context, a promising concept would be to provide a virtual tour of a typical chicken barn as a supplementary teaching tool in a lecture series. In this scenario, the teacher or lecturer would use the smart glasses in the barn, while students remotely engage with the captured data afterwards. The virtual tour is not intended to replace traditional lectures and textbooks but can be used to enhance practical knowledge and deliver immersive learning experiences. Besides the virtual tour, also a live stream from the glasses in the barn to students at home can be realized.

Our example of an educational virtual tour based on tracking data and recordings of the smart glasses is a promising proof of concept for applying game engines in agricultural education. A follow-up study is planned to evaluate the effectiveness of this method for knowledge transfer within a lecture series.

6. Conclusion

Main goal of this article is to introduce a new method to enhance the understanding of housing conditions in chicken barns and improve knowledge transfer. The smart glasses, designed to capture content in RGB, thermal IR, and UV light, in combination with the pipeline for developing virtual educational tours, serve as a comprehensive toolbox for educational institutes. While individual components, e.g., thermal cameras for detecting temperature leaks, are not new, the main advantage of our system is the integration of multiple functionalities into a single device with accurate indoor position tracking. The resulting virtual tours not only present aspects of animal welfare in isolation but also allow the user to explore the environment, understand spatial relations, and gain a broader contextual view of the content. With our proposed research goals in retrospect, we were able to design the hard- and software for detecting critical temperature spots and the presence of UV light in the barn, as well as a method for providing educational tours for remote learning. Since typically only one person has to visit the barn in person using relatively small portable hardware, the impact on the animals during the investigation is kept at a minimum. The proposed technology is therefore highly promising to increase animal welfare and improve agricultural knowledge transfer, while remaining feasible from an ethical point of view.

7. Outlook

The video material captured by our smart glasses could also be utilized for more in-depth analysis of chickens' physical activity, such as by employing a neural network trained to recognize different behaviors [53]. Additionally, integrating artificial intelligence to assess individual chickens' health and welfare, following the approach of Tong et al. [72], would be a valuable extension. Potential environmental sensors for further monitoring could measure humidity, solar radiation, and airspeed. Physiological and behavioral metrics from the animals, like body weight, heart and respiration rates, food, water intake, and activity levels, could be tracked [27]. Since these metrics typically require different sensors than cameras, integrating them into our current system would necessitate additional interfaces. However, incorporating more diverse data sources could provide a more comprehensive understanding of the barn's housing conditions. A further enhancement could include enabling the device to record multiple camera and sensor inputs simultaneously.

It is essential to evaluate user acceptance to facilitate the broader application of our smart glasses in commercial livestock production [62]. Conducting a study that tests the device in various real-world environments would be an appropriate step toward achieving this.

CRediT authorship contribution statement

Dorian Baltzer: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shannon Douglas:** Writing – review & editing, Validation, Investigation. **Jan-Henrik Haunert:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Youness Dehbi:** Writing – review & editing, Resources, Conceptualization. **Inga Tiemann:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dorian Baltzer reports financial support was provided by Federal Ministry of Food and Agriculture. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] F. Agnello, F. Avella, S. Agnello, Virtual reality for historical architecture, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-2/W9 (2019) 9–16, https://doi.org/10.5194/isprs-archives-XLII-2-W9-9-2019.

[2] O.O. Apalowo, D.A. Ekunseitan, Y.O. Fasina, Impact of heat stress on broiler chicken production, Poultry 3 (2) (2024) 107–128.

[3] R. Argiolas, V. Bagnolo, S. Cera, et al., Virtual environments to communicate built cultural heritage: a HBIM based virtual tour, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLVI-5/W1-2022 (2022) 21–29, https://doi.org/10.5194/isprs-archives-XLVI-5-W1-2022-21-2022.

[4] D. Baltzer, VisioChick: smart glasses for assessing poultry housing conditions - technical instruction manual, https://doi.org/10.5281/zenodo.13833373, 2024.

[5] F. Banfi, A. Mandelli, Interactive virtual objects (IVOs) for next generation of virtual museums: from static textured photogrammetric and HBIM models to XR objects for VR-AR enabled gaming experiences, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLVI-M-1-2021 (2021) 47–54, https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-47-2021.

[6] J. Barnett, P. Hemsworth, E. Newman, Fear of humans and its relationships with productivity in laying hens at commercial farms, Br. Poult. Sci. 33 (4) (1992) 699–710.

[7] J. Barnett, P. Hemsworth, D. Hennessy, et al., The effects of modifying the amount of human contact on behavioural, physiological and production responses of laying hens, Appl. Anim. Behav. Sci. 41 (1–2) (1994) 87–100.

[8] M. Baxter, N. Joseph, V. Osborne, et al., Red light is necessary to activate the reproductive axis in chickens independently of the retina of the eye, Poult. Sci. 93 (5) (2014) 1289–1297.

[9] R.M. Bilal, Hassan Fu, M.R. Farag, et al., Thermal stress and high stocking densities in poultry farms: potential effects and mitigation strategies, J. Therm. Biol. 99 (2021) 102944.

[10] E. Bottani, G. Vignali, Augmented reality technology in the manufacturing industry: a review of the last decade, IISE Trans. 51 (3) (2019) 284–310.

[11] J.K. Bowmaker, L. Heath, S. Wilkie, et al., Visual pigments and oil droplets from six classes of photoreceptor in the retinas of birds, Vis. Res. 37 (16) (1997) 2183–2194.

[12] H. Buller, H. Blokhuis, K. Lokhorst, et al., Animal welfare management in a digital world, Animals 10 (10) (2020) 1779.

[13] N. Burlinguette, M. Strawford, J. Watts, et al., Broiler trailer thermal conditions during cold climate transport, Can. J. Anim. Sci. 92 (2012) 109–122.

[14] G. Büyüksalih, T. Kan, G.E. Özkan, et al., Preserving the knowledge of the past through virtual visits: from 3D laser scanning to virtual reality visualisation at the Istanbul Çatalca İnceğiz caves, J. Photogramm. Remote Sens. Geoinf. Sci. 88 (2) (2020) 133–146.

[15] M. Caria, G. Sara, G. Todde, et al., Exploring smart glasses for augmented reality: a valuable and integrative tool in precision livestock farming, Animals 9 (11) (2019) 903.

[16] A. Chopra, Introduction to Google Sketchup, John Wiley & Sons, 2012.

[17] C.L. Daigle, Controlling feather pecking and cannibalism in egg laying flocks, in: Egg Innovations and Strategies for Improvements, Elsevier, 2017, pp. 111–121.

[18] M.S. Dawkins, How do hens view other hens? The use of lateral and binocular visual fields in social recognition, Behaviour 132 (7–8) (1995) 591–606.

[19] M.S. Dawkins, What are birds looking at? Head movements and eye use in chickens, Anim. Behav. 63 (5) (2002) 991–998.

[20] E. De Haas, B. Kemp, J. Bolhuis, et al., Fear, stress, and feather pecking in commercial white and Brown laying hen parent-stock flocks and their relationships with production parameters, Poult. Sci. 92 (9) (2013) 2259–2269.

[21] L. Edwards, N. Botheras, G. Coleman, et al., Behavioural and physiological responses of laying hens to humans, Anim. Reprod. Sci. 50 (6) (2010) 557–559.

[22] L.E. Edwards, G.J. Coleman, K.L. Butler, et al., The human-animal relationship in Australian caged laying hens, Animals 9 (5) (2019) 211.

[23] EFSA Panel on Animal Health and Welfare, Welfare of broilers on farm, EFSA J. 21 (2) (2023), https://doi.org/10.2903/j.efsa.2023.7788.

[24] A. Favreau-Peigné, L. Calandreau, P. Constantin, et al., Emotionality modulates the effect of chronic stress on feeding behaviour in birds, PLoS ONE 9 (2) (2014) e87249.

[25] Federation of Animal Science Societies (FASS), Guide for the care and use of agricultural animals in research and teaching, vol. 4, American Dairy Science Association®, American Society of Animal Science, Poultry Science Association, https://www.adsa.org/Portals/0/SiteContent/docs/AgGuide4th/Ag_Guide_4th_ed.pdf, 2020.

[26] F. Fiorillo, G. Rizzi, C. Achille, Learning through virtual tools: visit a place in the pandemic era, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLVI-M-1-2021 (2021) 225–232, https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-225-2021.

[27] S. Fournel, A.N. Rousseau, B. Laberge, Rethinking environment control strategy of confined animal housing systems through precision livestock farming, Biosyst. Eng. 155 (2017) 96–123.

[28] C. Graml, K. Niebuhr, S. Waiblinger, Reaction of laying hens to humans in the home or a novel environment, Appl. Anim. Behav. Sci. 113 (1–3) (2008) 98–109.

[29] S. Günay, Virtual reality for lost architectural heritage visualization utilizing limited data, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLVI-2/W1-2022 (2022) 253–257, https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-253-2022.

[30] I. Halachmi, M. Guarino, J. Bewley, et al., Smart animal agriculture: application of real-time sensors to improve animal well-being and production, Ann. Rev. Anim. Bbiosci. 7 (2019) 403–425.

[31] N.S. Hart, The visual ecology of avian photoreceptors, Prog. Retin. Eye Res. 20 (5) (2001) 675–703.

[32] N.S. Hart, D.M. Hunt, Avian visual pigments: characteristics, spectral tuning, and evolution, Am. Nat. 169 (S1) (2007) S7–S26.

[33] P.H. Hemsworth, Human–animal interactions in livestock production, Appl. Anim. Behav. Sci. 81 (3) (2003) 185–198.

[34] R. Hess, The Essential Blender: Guide to 3D Creation with the Open Source Suite Blender, No Starch Press, 2007.

[35] R. Hirakawa, S. Nurjanah, K. Furukawa, et al., Heat stress causes immune abnormalities via massive damage to effect proliferation and differentiation of lymphocytes in broiler chickens, Front. Vet. Sci. 7 (2020) 46.

[36] J.A. Hunt, M. Heydenburg, S.L. Anderson, et al., Does virtual reality training improve veterinary students' first canine surgical performance?, Vet. Rec. 186 (17) (2020) 562.

[37] C. James, J. Wiseman, L. Asher, The effect of supplementary ultraviolet wavelengths on the performance of broiler chickens, Poultry Sci. 99 (11) (2020) 5517–5525.

[38] M. Josserand, O. Rosa-Salva, E. Versace, et al., Visual field analysis: a reliable method to score left and right eye use using automated tracking, Behav. Res. Methods 54 (2021) 1715–1724.

[39] J. Keil, D. Edler, T. Schmitt, et al., Creating immersive virtual environments based on open geospatial data and game engines, J. Cartogr. Geogr. Inf. 71 (1) (2021) 53–65.

[40] H.H. Kristensen, N.B. Prescott, G.C. Perry, et al., The behaviour of broiler chickens in different light sources and illuminances, Appl. Anim. Behav. Sci. 103 (1–2) (2007) 75–89.

[41] P. Kunzmann, Ethics in the poultry industry-answering moral questions of society, Lohmann-Inf. 46 (1) (2011) 3–9.

[42] M. Lemmens, M. Lemmens, Terrestrial laser scanning, in: Geo-Information: Technologies, Applications and the Environment, 2011, pp. 101–121.

[43] P. Lewis, T. Morris, Poultry and coloured light, World's Poult. Sci. J. 56 (3) (2000) 189–207.

[44] O. Lind, K. Delhey, Visual modelling suggests a weak relationship between the evolution of ultraviolet vision and plumage coloration in birds, J. Evol. Biol. 28 (3) (2015) 715–722.

[45] O. Lind, M. Mitkus, P. Olsson, et al., Ultraviolet vision in birds: the importance of transparent eye media, Proc. - Royal Soc. B, Biol. Sci. 281 (1774) (2014) 20132209.

[46] T.J. Lisney, D. Rubene, J. Rózsa, et al., Behavioural assessment of flicker fusion frequency in chicken gallus gallus domesticus, Vis. Res. 51 (12) (2011) 1324–1332.

[47] M. Liu, X. Li, X. Lei, et al., Research of mobile augmented reality technology applied in agriculture, in: 2013 International Conference on Advanced Computer Science and Electronics Information (ICACSEI 2013), Atlantis Press, 2013, pp. 311–314.

[48] D. Macer, Ethical poultry and the bioethics of poultry production, J. Poult. Sci. 56 (2) (2019) 79–83.

[49] S.A. Maddocks, I.C. Cuthill, A.R. Goldsmith, et al., Behavioural and physiological effects of absence of ultraviolet wavelengths for domestic chicks, Anim. Behav. 62 (5) (2001) 1013–1019.

[50] G.R. Martin, Visual fields and their functions in birds, J. Ornithol. 148 (Suppl 2) (2007) 547–562.
[51] G.R. Martin, What is binocular vision for? A birds' eye view, J. Vis. 9 (11) (2009) 14.
[52] C. Moro, Z. Štromberga, A. Raikos, et al., The effectiveness of virtual and augmented reality in health sciences and medical anatomy, Anat. Sci. Educ. 10 (6) (2017) 549–559.
[53] A. Nasiri, Y. Zhao, H. Gan, Automated detection and counting of broiler behaviors using a video recognition system, Comput. Electron. Agric. 221 (2024) 108930.
[54] S. Neethirajan, B. Kemp, Digital twins in livestock farming, Animals 11 (4) (2021) 1008.
[55] P. Niloofar, D.P. Francis, S. Lazarova-Molnar, et al., Data-driven decision support in livestock farming for improved animal health, welfare and greenhouse gas emissions: overview and challenges, Comput. Electron. Agric. 190 (2021) 106406.
[56] T. Norton, C. Chen, M. Larsen, et al., Precision livestock farming: building 'digital representations' to bring the animals closer to the farmer, Animal 13 (12) (2019) 3009–3017.
[57] O. Özyeşil, V. Voroninski, R. Basri, et al., A survey of structure from motion*, Acta Numer. 26 (2017) 305–364.
[58] D.G. Porter, Ethical scores for animal experiments, Nature 356 (6365) (1992) 101–102.
[59] N. Prescott, C.M. Wathes, J. Jarvis, Light, vision and the welfare of poultry, Anim. Welf. 12 (2) (2003) 269–288.
[60] N. Prescott, J. Jarvis, C. Wathes, Vision in the laying hen, in: Welfare of the Laying Hen. Papers from the 27th Poultry Science Symposium of the World's Poultry Science Association, Bristol, UK, July 2003, CABI Publishing Wallingford UK, 2004, pp. 155–164.
[61] J.L. Rault, S. Waiblinger, X. Boivin, et al., The power of a positive human–animal relationship for animal welfare, Front. Vet. Sci. 7 (2020) 590867.
[62] A. Rese, D. Baier, A. Geyer-Schulz, et al., How augmented reality apps are accepted by consumers: a comparative analysis using scales and opinions, Technol. Forecast. Soc. Change 124 (2017) 306–319.
[63] J. Rushen, A.A. Taylor, A.M. De Passillé, Domestic animals' fear of humans and its effect on their welfare, Appl. Anim. Behav. Sci. 65 (3) (1999) 285–303.
[64] H. Schumann, W. Müller, Beschreibung der Daten als Ausgangspunkt einer Visualisierung, in: Visualisierung: Grundlagen und Allgemeine Methoden, 2000, pp. 27–59.
[65] U.G. Sefercik, T. Kavzoglu, M. Nazar, et al., UAV-based 3D virtual tour creation, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLVI-4/W5-2021 (2021) 493–499, https://doi.org/10.5194/isprs-archives-XLVI-4-W5-2021-493-2021.
[66] L. Sims, Risks associated with poultry production systems, in: Proc. Inter. Conf.: Poultry in the 21st Century, 2007, pp. 355–356.
[67] E.B. Sobotik, J.R. Nelson, G.S. Archer, How does ultraviolet light affect layer production, fear, and stress, Appl. Anim. Behav. Sci. 223 (2020) 104926.
[68] B. Spindler, T. Weseloh, C. Eßer, et al., The effects of UV-A light provided in addition to standard lighting on plumage condition in laying hens, Animals 10 (6) (2020) 1106.
[69] A. Syberfeldt, O. Danielsson, P. Gustavsson, Augmented reality smart glasses in the smart factory: product evaluation guidelines and review of available products, IEEE Access 5 (2017) 9118–9130.
[70] C. Tedore, D.E. Nilsson, Avian uv vision enhances leaf surface contrasts in forest environments, Nat. Commun. 10 (1) (2019) 238.
[71] J. Tichon, R. Burgess-Limerick, A review of virtual reality as a medium for safety related training in mining, J. Health Saf. Res. Pract. 3 (1) (2011) 33–40.
[72] Q. Tong, J. Wang, W. Yang, et al., Edge AI-enabled chicken health detection based on enhanced FCOS-lite and knowledge distillation, Comput. Electron. Agric. 226 (2024) 109432.
[73] S. Wasti, N. Sah, B. Mishra, Impact of heat stress on poultry health and performances, and potential mitigation strategies, Animals 10 (8) (2020) 1266.
[74] D. Wood-Gush, The Behaviour of the Domestic Fowl, Heinemann Educational Books Ltd, London, 1971.
[75] X. Yang, R.B. Bist, B. Paneru, et al., Computer vision-based cybernetics systems for promoting modern poultry farming: a critical review, Comput. Electron. Agric. 225 (2024) 109339.
[76] Y. Zhu, N. Li, Virtual and augmented reality technologies for emergency management in the built environments: a state-of-the-art review, J. Saf. Sci. Resil. 2 (1) (2021) 1–10.