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OPTIMIZATION OF LOGISTICS IN AGRICULTURE USING AUGMENTED REALITY – sadjAR

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Povzetek

Kmetijski sektor se vedno bolj usmerja v uporabo naprednih tehnologij, kot je obogatena resničnost (AR), z namenom povečanja produktivnosti in trajnosti. V članku je predstavljena aplikacija SadjAR, ki deluje na osnovi AR, in je v pomoč malim in srednjim kmetijam, saj kmetom omogoča dostop do strokovnih nasvetov in izobraževalnih vsebin v realnem času. Sistem uporablja očala Vuzix M4000, ki omogočajo prostoročno interakcijo in kmetom zagotavljajo takojšnje vodenje neposredno na terenu. S pomočjo poučnih video vsebin in video klicev strokovnjaka SadjAR rešuje ključne izzive, s katerimi se kmetje soočajo, kot so omejen dostop do strokovnega znanja ter potreba po prilagajanju vedno bolj zapletenim kmetijskim praksam.

Sistem vključuje mobilno aplikacijo za AR očala in platformo, ki deluje v oblaku. Testiranje aplikacije na petih kmetijah je pokazalo, da SadjAR izboljšuje produktivnost, pripomore k reševanju problemov in zmanjšuje potrebo po osebnih obiskih strokovnjakov. Kmetje so izrazili zadovoljstvo z enostavnostjo uporabe sistema in njegovim potencialom za izboljšanje upravljanja kmetij.

Aplikacija SadjAR bo v prihodnje nadgrajena z modelom strojnega učenja za samodejno prepoznavanje škodljivcev in bolezni, kar bo še dodatno optimiziralo tehnologijo za odločanje na terenu v realnem času.

SadjAR ima potencial, da zapolni vrzel med tradicionalnimi kmetijskimi praksami in sodobnimi zahtevami preciznega kmetijstva ter zagotovi prilagodljivo in dostopno rešitev za kmetije.

Ključne besede: obogatena resničnost, logistika v kmetijstvu, oddaljena pomoč, odkrivanje škodljivcev, trajnostno kmetijstvo

OPTIMIZACIJA LOGISTIKE V KMETIJSTVU Z UPORABO OBOGATENE RESNIČNOSTI – sadjAR

Abstract

The agricultural sector is experiencing a growing shift toward adopting advanced technologies such as augmented reality (AR) to enhance productivity and sustainability. This paper introduces SadjAR, a pioneering AR-based system that assists small and medium-sized farms by giving farmers real-time access to expert advice and educational resources. The system leverages Vuzix M4000 AR glasses, allowing hands-free interaction and enabling farmers to receive immediate guidance directly in the field. By integrating video tutorials and expert

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consultations, SadjAR addresses critical challenges farmers face, such as limited access to timely, affordable expertise and the need to adapt to increasingly complex agricultural practices.

The system's architecture includes a mobile application for AR glasses and a cloud-based platform for experts to manage content and provide remote assistance. Field tests on five farms demonstrated that SadjAR will improve operational efficiency, facilitate faster problem-solving, and reduce the need for in-person expert visits. Farmers reported high satisfaction with the system's ease of use and its potential to improve farm management.

Future developments for SadjAR will focus on enhancing the system by incorporating machine learning models for automatic pest and disease detection, further optimizing the technology for real-time, field-based decision-making. This innovation has the potential to bridge the gap between traditional farming practices and the modern demands of precision agriculture, providing a scalable and accessible solution for farms of varying sizes.

Keywords: augmented reality, agricultural logistics, remote consultation, pest identification, sustainable agriculture

1 INTRODUCTION

The agricultural sector has witnessed a growing trend toward adopting advanced technologies like automation, data analytics, and smart devices to enhance productivity and sustainability. Among these emerging technologies, Augmented Reality (AR) has shown the potential to transform how farmers interact with agricultural experts and access educational resources. AR facilitates a hands-free, immersive experience that integrates digital information with the physical environment, enabling farmers to gain real-time support and guidance directly on the field.

SadjAR is a pioneering project that explores the application of AR in fruit and vegetable production.

The primary goal of this initiative is to provide farmers with direct, remote access to expert advice from agricultural consultants, and easy access to practical video tutorials and other educational content. By leveraging AR glasses, farmers can receive on-the-spot assistance, facilitating quick problem-solving and enhancing their operational efficiency.

The motivation behind the development of SadjAR stems from the challenges faced by small and medium-sized farms, where limited access to affordable, real-time expertise often hampers productivity. Traditional consulting methods, such as in-person visits or communication via phone and email, are time-consuming, costly, and usually impractical for immediate problem resolution. Moreover, the increasing complexity of modern farming, characterized by the need to adapt to new technologies and sustainable practices, has created a demand for innovative solutions that can bridge the knowledge gap between traditional farming methods and modern advancements. AR technology enhances real-time decision-making and improves task efficiency, which is crucial for agricultural practices (Hameed et al., 2022).

By providing farmers with a tool that enables real-time communication with experts and hand-free access to instructional videos and resources, SadjAR aims to make modern agricultural practices more accessible, practical, and efficient.

This paper explores the development, implementation, and benefits of the SadjAR system, demonstrating how AR technology can be a game-changer in the agricultural sector by promoting better communication, education, and knowledge exchange in a practical and feasible manner.

2 STATE OF THE ART

Effective pest management is crucial for maximizing crop yield in agriculture, but excessive pesticide use can harm plants and animals. Machine learning algorithms and image processing techniques for pest detection and control have already been implemented in a mobile application built using the Flutter framework, which captures pest images via a smartphone camera. These images are analyzed using transfer learning models based on a Kaggle dataset for pest identification (Soni et al., 2022).

Another smart mobile application was developed to identify and manage pest infestations more accurately than manual methods. A Convolutional Neural Network (CNN) was used for classification, achieving 90% accuracy in determining pest types and plant damage stages. Additionally, the system provides information on organic pest prevention methods, helping to minimize pesticide use while maintaining crop health and yield (Mahenthiran et al., 2021).
In recent years, augmented reality (AR) has garnered attention for its applications within the agri-food sector, particularly in precision farming and food supply chains. Despite the high development costs, AR's potential to revolutionize agricultural practices through enhanced information access and decision support has been widely recognized (Xie et al., 2022; Chai et al., 2023).

The 2019 study explores integrating augmented reality (AR) with the Internet of Things (IoT) to enhance precision farming. AR improves IoT data visualization by overlaying virtual objects on real-world crops. The system uses a multi-camera platform to measure 3D coordinates and display IoT data, enabling real-time interaction with crops. Despite improving crop monitoring and decision-making, challenges like camera calibration and environmental factors affecting AR visibility persist (Phupattanasilp & Tong, 2019).

While research has advanced AR applications in agriculture, challenges remain. Most studies focus on pest management, crop monitoring, and automated harvesting, using AR, machine learning, and image processing to improve efficiency. Successful applications include combining AR with deep learning for pest identification and strawberry harvesting. However, limitations such as environmental impacts on AR visibility, high costs of AR devices, and computational demands hinder accessibility for smaller farms (Chai et al., 2023).

Our work addresses these issues by focusing on the accessibility and adaptability of AR for smaller farms, specifically in fruit and vegetable production. Our solution, SadjAR, aims to improve real-time communication between farmers and experts through AR, providing hands-free access to expertise and educational resources. This approach tackles technological challenges and emphasizes cost-effective, scalable solutions for diverse farm sizes, bridging the gap between technological innovation and everyday farming practices.

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3 TECHNOLOGIES

The Vuzix M4000 AR glasses were chosen in our study, and they are suitable for agricultural applications due to their robust design, high-quality video display, and efficient interaction features. The Vuzix M4000 (see Figure 1) provides a durable, hands-free experience with easy input options, making it ideal for real-time consultations and on-field tasks. This allows farmers to access digital information seamlessly while maintaining focus on their activities, even in challenging conditions (Sara et al., 2024).

Figure 1. Vuzix M4000 are powerful smart glasses weighing only 95 grams (TeamCreative, n.d.)

The system consists of two core components. The first is a mobile application developed using the Unity game engine, designed to run on Android-based AR smart glasses. This enables farmers to interact seamlessly with the system while performing hands-on tasks in the field. The second component is a web-based application hosted on a cloud server, which serves as a platform for agricultural experts to provide remote guidance via video calls and a robust content management tool. This web application allows users with the appropriate roles to upload and manage educational video content, ensuring farmers can access up-to-date learning materials directly on their smart glasses.

The system is supported by a centralized cloud database, ensuring continuous data synchronization across devices. This architecture guarantees real-time connectivity and facilitates the accumulation of valuable data, such as pest and disease identification records, for long-term agricultural research and improvement.

By combining AR with cloud-based infrastructure, our solution provides a scalable and efficient approach to precision farming. Future developments, including machine vision integration for automatic disease recognition, will be built on these technological foundations, further enhancing the competitive edge of sadjAR.

One of the innovations lies in developing an interactive disease and pest library integrated into AR glasses. This library enables farmers to visually compare crop symptoms with a pre-existing database of diseases and pests, which is directly accessible in the field.
The system's current research focuses on improving the accuracy of pest and disease identification by incorporating machine learning models, which will enable automatic recognition of crop diseases based on real-time images captured by the AR device. This machine vision feature is one of the most innovative aspects, and it is poised to revolutionize diagnostics in agriculture.

The research is highly original due to its novel AR and machine learning combination in a real-world agricultural setting. Most existing technologies in agriculture focus on data collection via sensors or remote monitoring, but sadjAR enhances human interaction by

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allowing experts to provide live, tailored guidance. Moreover, integrating real-time data, historical knowledge, and expert support is a first in this field.

3.1 Modules

As seen in Figure 2, the application consists of three key modules: a video call feature for real-time consultation with agricultural experts, a gallery of educational videos, and a comprehensive pest and disease handbook systematically categorized by region.

Figure 2. The main menu in the application

The application is designed to be intuitive, requiring no prior training. The menus are straightforward, as demonstrated in Figure 3.

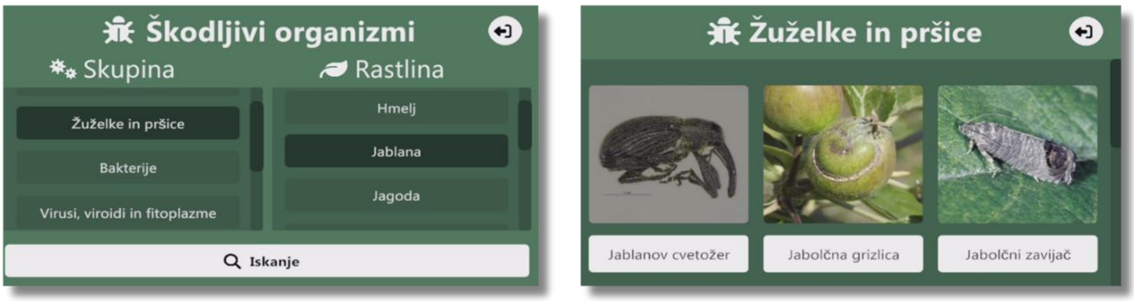

Figure 3. Submenu for pest and disease search

The primary advantage of the application is the video call feature (Figure 4) with an agricultural advisor. The high-quality camera gives the advisor a perspective as if they were physically present on the farm. This allows for a detailed examination of the environment, such as the proximity to forests or other factors that may influence farming conditions. The real-time video consultation also reduces the need for in-person visits, thereby minimizing logistical challenges and associated costs. Farmers can receive immediate advice and solutions by streamlining the consultation process, leading to quicker decision-making and enhanced productivity. As a result, the application not only optimizes operational efficiency but also contributes to the overall sustainability of the farm by enabling more informed and timely actions.

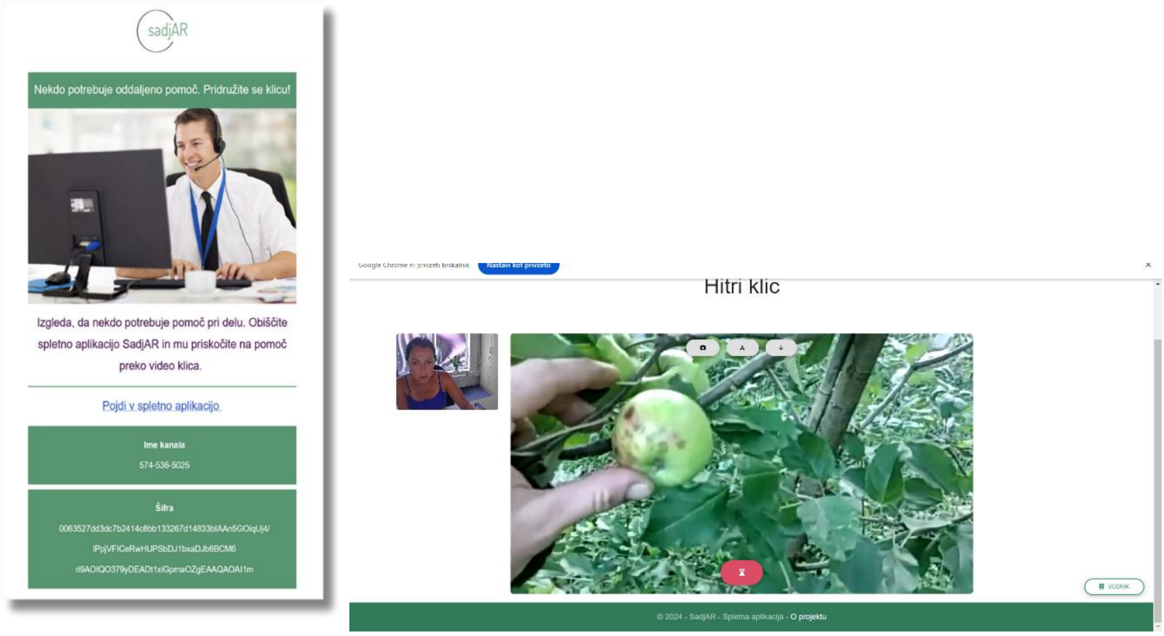

Figure 4. A video call module

3.2 Development of Key Functionalities

From the technical perspective, the development of SadjAR combined multiple external frameworks and SDKs (Software Development Kit). The application was built in Unity game engine. Integration of external services was achieved via Unity assets, Firebase Realtime Database/Firestore, and Agora SDK for real-time communication.

The development process started with implementing gesture and button recognition on the Vuzix M4000 device. A universal input-mapping system was created by overriding Unity's `Update`() method to continuously capture `KeyCode` values from the touchpad and physical buttons. These signals were then redirected to the `HandleKeyPress`() function, where each input triggered a specific application event (e.g., menu navigation, call initialization, or video playback). The mapping also supported short and long presses, as well as swipe gestures.

The AR video call module was implemented using a hybrid approach: Firebase Firestore served as a signaling and session management layer, while Agora SDK ensured low-latency audio-video streaming. During a call, Firestore stored channel metadata, tokens, and state variables, which the Unity client subscribed to via real-time listeners (`ListenForChannelUpdates`()).

The educational video module was realized by integrating 3D WebView for Android/iOS into Unity's Canvas system. A script (`YoutubeCollectionManager`) retrieved video metadata (Title, URL) from the Firestore collection `YoutubeCollection` and dynamically instantiated UI buttons at runtime. The digital library of pests and diseases was developed primarily with Unity's UI toolkit (Canvas, Panels, ScrollView, Button events). Content was organized into categories (e.g., "Insects", "Diseases"), with OnClick events used for toggling between panels (SetActive(true/`false`)). Each entry contained structured data: description, typical symptoms, images, and recommended countermeasures. Finally, the photo

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capture module utilized the integrated AR camera of the Vuzix M4000. Captured images were stored locally on the device and could later be synchronized with the Firebase database.

4 RESULTS

Five farms tested the application (see Figure 4), and the feedback received was overwhelmingly positive. Since the project is still in the pilot testing stage, the system has not yet reached the highest Technology Readiness Levels (TRLs).
The goal of these tests was to evaluate usability, technical performance, and the practical benefits of the system in everyday farming activities.

Farmers reported that the AR glasses required a short adaptation period, especially regarding image focusing, since the display is limited to one eye. Initial discomfort diminished after a few uses, and participants generally described the technology as intuitive, simple to operate, and highly practical in field conditions.

The hands-free operation was highlighted as one of the main advantages, particularly during mechanical repairs and orchard work, where both hands are needed. Farmers emphasized that the ability to follow instructions from a remote advisor or video tutorial while continuing physical work represented a significant improvement compared to traditional consulting methods.

Figure 5. Testing of the application in a real-world setting – in the orchard and during machinery repair

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In terms of content, the digital library of pests and diseases was regarded as a useful educational tool. Farmers valued the ability to compare plant symptoms with visual references directly in the orchard. However, they also noted the need for expanding the library beyond fruit production to other sectors such as viticulture and vegetable farming.

Participants provided numerous suggestions for future enhancements and additional functionalities. Farmers unanimously agreed on the potential of augmented reality (AR) technology within the agricultural sector, emphasizing its future role in improving farm management practices. They highlighted the value of AR in offering practical, hands-free solutions and expressed confidence that this technology will become an indispensable tool in modern farming. The insights gathered from these tests will be crucial for the continued development and refinement of the application.

Field tests confirmed that SadjAR is an effective tool for improving farm logistics and knowledge transfer. Farmers consistently underlined that AR-based solutions shorten the time between problem identification and resolution, reduce the need for on-site expert visits, and provide a unique learning experience directly in the working environment. SadjAR is therefore positioned not only as a research prototype but also as a technology-ready solution with clear potential for commercialization and long-term application in precision agriculture

5 CONCLUSION

The SadjAR project represents a significant step forward in integrating augmented reality (AR) technology with practical agricultural applications, particularly for small and medium-sized farms. The system enhances operational efficiency and facilitates more informed decision-making by providing farmers with real-time access to expert advice and hands-free educational resources. The results from field tests demonstrate the potential of AR to transform traditional agricultural practices, offering a scalable, adaptable, and cost-effective solution for modern farming challenges.

As AR technology evolves, solutions like SadjAR will likely become indispensable tools in precision farming, bridging the gap between traditional methods and the demands of a technologically advanced agricultural sector. Future research and development will focus on expanding the system's capabilities, particularly on machine learning for automatic pest and disease detection, ensuring that AR continues to drive innovation in farming.

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