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Augmented Reality for Supervising Multirobot System in Agricultural Field Operation

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Abstract: Agriculture is shifting from farmers manually operating machines to monitoring autonomous machines. Thus, the task of a farmer is fleet management and taking care of safe operation. Situational awareness during the operation is important. Augmented reality (AR) is a powerful tool for visualizing information in real-time. To demonstrate the use of AR in agricultural fleet management, in this paper we present a novel AR system to help the farmer supervise the operation of two autonomous agricultural machines. The paper discusses the requirements for AR application, and we present the architecture of the system and the results of a demonstration carried out in a test field.

Keywords: autonomous vehicles, situational awareness, tractors, wearable headset, mixed reality, MR

1. INTRODUCTION

Highly automated agriculture may be based on autonomous vehicles working in open fields. In general, the agricultural fields are not fenced and this causes safety concerns to enable autonomous systems in this semi-structured environment. Furthermore, the field vehicles must carry out various tasks requiring considerable amount of energy to do, e.g. sowing, spraying and harvesting operations, and this sets constraints on the minimum size of the vehicles.

In our vision, a stepping stone toward fully autonomous operations is a fleet of autonomous vehicles working in the same field and a human operator is sitting onboard of one of the vehicles. The human operator is needed to monitor all vehicles in the area for safety reasons, but also to cope with manual maneuvering, e.g. in case the autonomous units find unexpected obstacles in the field and other rescue tasks. The human operator is also needed in the field in order to refill tanks, handle the logistics of materials across the boundary of the field and move the vehicles from one field to another.

Hence, in this paper, we discuss how to improve situational awareness of the aforementioned operator responsible for monitoring a fleet of autonomous vehicles working in the same field while sitting onboard one of those. In general, the fleet consists of any number of vehicles working in the same field, but in our demonstration, we had to limit the study to two autonomous units available; both of which were weighing around 6000 kg. Our Robots are presented in Fig. 1.

To improve situational awareness, operational information can be communicated to the human operator using virtual technologies. Augmented Reality (AR) is the technology of superimposing virtual objects upon the real world (Azuma, 1997). Commercial technology for Augmented Reality has already reached readiness level of consumer products, but most of the applications are limited to structured indoor environment. In most cases AR is realized with a wearable headset which creates optically superimposed objects on semitransparent surface. Various techniques for optical superimposing and sensors to measure pose of headset are required and in commercial products focus has been on indoor capabilities.

AR has several potential applications areas in agricultural applications and in precision farming (Cupiał, 2011). In this paper, we present a system that uses wearable AR to improve the situational awareness of the human operator monitoring two autonomous vehicles. The AR system interfaces with a Mission Planner (Soitinaho et al., 2019) system that controls the autonomous machines. Necessary information from the Mission Planner is visualized in an AR user interface (UI). Requirements for the AR system are defined in Chapter 3, and the system architecture is derived from those in Chapter 4. The functionality of this system was demonstrated in field

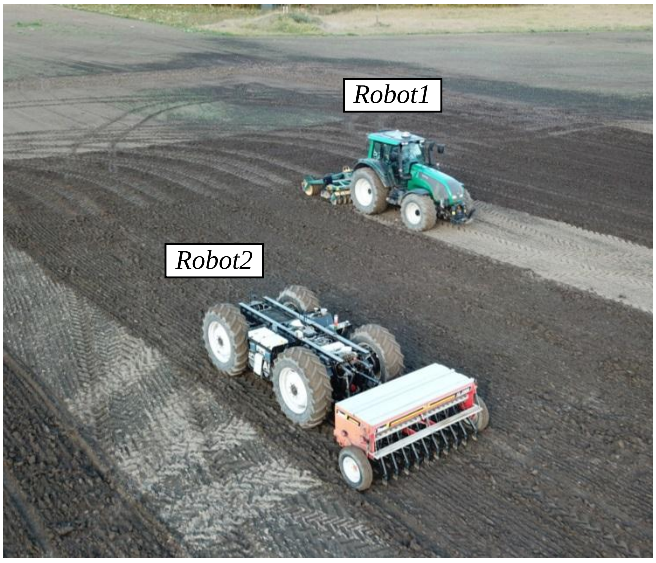

Fig. 1. Autonomous tractors used in the demonstration.

conditions. The system was found to improve the situational awareness of the human operator on the tractor. The demonstration is further discussed in Chapter 5.

2. MOTIVATION

2.1. Augmented Reality in Agriculture

The use of AR in agriculture has been researched in various studies during recent years. Out of these studies, two utilized AR in a tractor environment. To aid farmers navigate fields optimally, an assisted guidance system was developed using wearable AR technology (Santana-Fernández et al., 2010). Another assisted guidance system was developed to enable night-time farming (Kaizu et al., 2012).

Other research suggests that AR could be used to simulate the growth of crops and livestock and visualize information about agricultural tasks (Liu et al., 2013), in gardening (Okayama & Miyawaki, 2013), in grape production (King et al., 2005) and in a greenhouse (de Castro Neto, 2013). Research also suggests the use of AR in identifying pests (Nigam et al. 2011), plants (Katsaros & Keramopoulos, 2017) and weeds (Vidal & Vidal, 2010). Recently, AR has been used to aid a farmer collect soil samples (Huuskonen & Oksanen, 2018).

2.2. Augmented Reality in visualizing fleets and robots

AR has been used to visualize information about robots and robot fleets. One study used AR to visualize the internal states of robots in a multi-robot system (Ghiringhelli et al., 2014). In another study, an AR system that showcased the sensor data of a robot over the real-world view (Collett & MacDonald, 2006). In addition, one study utilized AR to improve the situational awareness of a human interacting with a robot swarm (Daily et al., 2003). In these studies, the virtual information was superimposed on the robots, to provide users with the necessary data in the correct context.

3. REQUIREMENTS

3.1. General requirements

As the motivation is to improve situational awareness of a single operator responsible for a fleet of robots working in the same field, requirements for the system can be derived both from the user comfort but also from the multi-robot operation itself. In the selected scenario, the operator is onboard one of the robots (in this case in *Robot1*). The user should be able to monitor the correct operation of that vehicle, but also other vehicles in the fleet.

AR technology is available as products, like wearable headsets. For the scenario, a headset was the most natural technology, as the operator environment is a tractor cab that has glasses around and visibility through these glasses is necessary for any operation. A headset enables hands-free operation of the tractor and showcases information to the operator in their field of view without the need to look at a separate monitor. In this paper, the focus is on visual AR content.

3.2. Requirements derived from Operation

To improve the situational awareness of the tractor operator and allow safe operation in the field, the following requirements should be fulfilled by the AR system.

1. The location of *Robot2* should be visible to the operator even if the *Robot2* is not visible, due to being behind a hill for example.
2. The status of each machine should be visible: is the machine functioning correctly or in a faulty state?
3. If a machine is in a faulty state, the cause for that state should be visible.
4. Information about the state of the machine in proper operation should be visible: where the machine is headed, what task it is executing and how long until refill or other service needs to be done.
5. All the information should be updated in real-time.

3.3. Requirements derived from User

In addition to fulfilling operational requirements, the system should have good usability and support work ergonomics. Based on this, further requirements are derived.

1. All the necessary information should be shown, but the view should nevertheless be intuitive to understand and not contain too much information.
2. The UI should have good contrast and be visually easy to perceive.
3. Using the AR system should allow the user to operate *Robot1*; therefore, a wearable headset should be used to allow hands-free operation.
4. The virtual objects in the user interface should be correctly aligned with the physical objects.
5. The AR hardware should be ergonomic to wear for long periods of time, such as in the case of operating an entire field.

4. SYSTEM ARCHITECTURE

4.1. Overview

The operator with AR headset is onboard *Robot1*. The system is designed to interface with a Mission Planner system that was developed for two autonomous vehicles operating in a field (Soitinaho et al., 2019). The Mission Planner system receives data from both Robots, including the GPS position and heading of each plus basic data like engine coolant

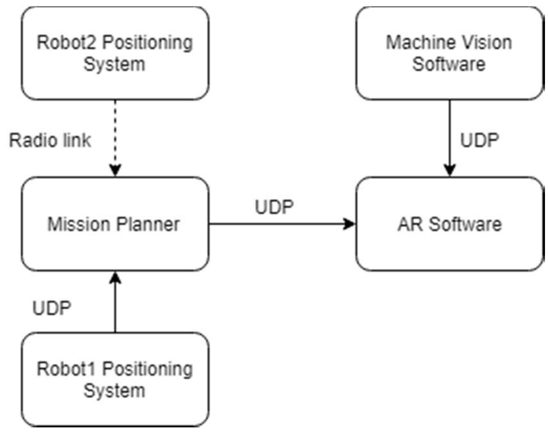

Fig. 2. Data flow diagram and communication systems.

temperature and RPM. In addition to the current state of the Robots, the Mission planner broadcasts the future paths for both vehicles generated by the Mission planner to AR system. The communication was realized using the User Datagram Protocol (UDP).

For the correct overlay of objects, the correct orientation of the AR headset is required. The AR headset was equipped with internal orientation sensors in global coordinates, but the performance was not sufficient for this application and environment. Thus, an external sensing system to measure the orientation of headset in the tractor frame. A camera was attached to the ceiling of *Robot1* to track a visual marker attached to the operator's headwear, these are presented later in Fig. 7, in the top left corner.

The visual marker was a Kanji marker, printed and attached on top of operator's cap. The cap and AR headset were interlocked. The Microsoft LifeCam camera used in the system was connected to laptop computer and the orientation was calculated with a custom software programmed with Visual Studio 2013 .NET, C#/C++ and ARtoolkitX. The orientation from this machine vision system was sent as UDP message to the AR software that fuses the headset-to-frame pose with the heading of *Robot1*.

The overall communication diagram of the software is presented in Fig. 2. The *Robot2* Positioning System sends the position data wirelessly from the *Robot2* to the Mission Planner. The Mission Planner is housed in *Robot1* and connected to the *Robot1* positioning system with UDP. The camera on the roof of *Robot1* is connected to a laptop in the *Robot1*, which houses the Machine Vision software.

4.2. Augmented Reality Hardware

The AR hardware used in this application was a wearable AR headset (ODG R-7 Smartglasses, Osterhout Design Group, San Francisco, USA), Fig. 3. The headset uses optical see-through technology: the virtual content is shown on two see-through displays in front of the user's eyes. Because the virtual content is partially transparent, it is combined with the view of the user's environment. The headset is equipped with a small computer running an Android-based operating system customized by the manufacturer. The ODG Android version used in this system was Android 6.0.1, API 23.

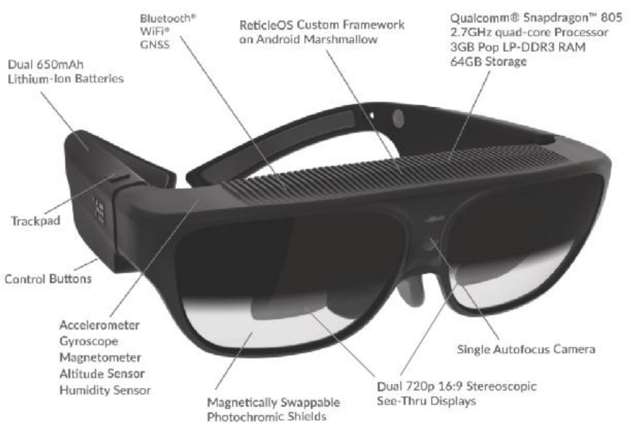

Fig. 3. The Augmented Reality glasses chosen for the application (ODG R-7, Osterhout Design Group, USA).

User input to the device can be given using a trackpad on the right temple of the glasses. For power supply, the device has two Lithium-Ion batteries and can be charged with a USB cable. The headset weighs 170 grams. However, in all demonstrations, a charging cable was connected to extend the battery capacity and allow the full performance of the device.

4.3. Augmented Reality Software

The AR functionality was implemented by using the Wikitude Software Development Kit (SDK) (Wikitude Augmented Reality SDK, Wikitude GmbH, Salzburg, Austria). The SDK includes features such as detecting the user's location and orientation, image recognition and geo-locations: rendering virtual content to GPS coordinates. The SDK has a version specifically designed for the ODG R-7 device (the Wikitude SDK ODG 7.1.0 was used). The AR software was implemented in JavaScript and HTML.

To improve the situational awareness of the supervisor on the tractor, the following information from the Mission Planner system is shown. Operational information for both robots was shown on both sides of the view. For both, a status "OK" or "ALERT" were shown. In case of an alert, the reason for the alert is shown under the status indicator. The purpose of the status information is to quickly indicate when there is a need for intervention by the operator. In addition, the speed of the machine, hitch level, time left its operation and the current segment were shown. For *Robot2*, its location was indicated with a red arrow. Furthermore, the next three waypoints of *Robot2* were shown. For these functionalities, geolocation AR was used. All the information was updated every second. In addition, a small blue arrow appears in the UI when the robot is not in the view, indicating where the user should look to see the robot.

A compass was also visible with *Robot2*'s and the waypoints' locations marked with circles in the compass. The view of the system is seen in Fig. 4. The angle from the camera in *Robot2* is used to correct the orientation of the AR view. The correct orientation of the headset is the angle from the camera application added to the heading of the tractor. This correct orientation compared with the orientation of the headset and a

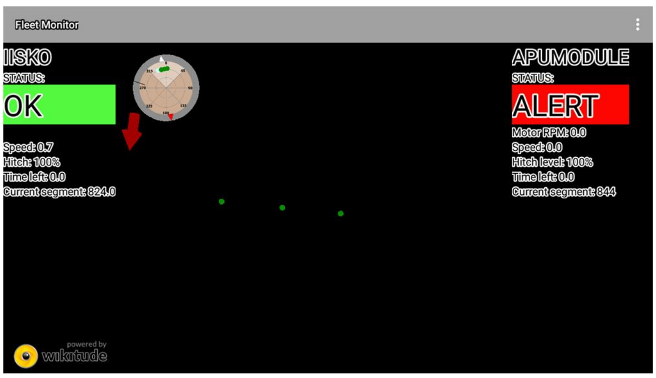

Fig. 4. A view of the AR UI. Information about the robots is shown: *Robot1* (titled "IISKO") on the left and *Robot2* (titled "APUMODULE") on the right. The location of *Robot2* is indicated with a red arrow and its next waypoints with green circles. The screenshot is from the AR headset. The black background is see-through and thus, the physical world is seen with the virtual objects superimposed on it.

correction angle offset is calculated based on the difference. This correction angle is low-pass filtered and inserted into the SDK, which has a function for correcting the compass angle.

5. DEMONSTRATION

5.1. Machine and Field Setup

The use of the system was tested on a field plot in southern Finland. Four users tested the AR headset for monitoring both the tractor and the autonomous field robot while sitting in the tractor. The users were familiar with the Mission Planner system and operating *Robot1*. To evaluate the system properly, it was sensible to limit the movement of the machines in a way that allowed *Robot2* to be in the view of *Robot1* at all times. Thus, for all tests, both machines were configured to repeat a predetermined route. The operation of the machines was autonomous except for changing the direction of the tractor, which required manual operation using the driving direction selector. The field setup is presented in Fig 5.

To evaluate how effective the AR system was, two measures were developed. Firstly, the system should function in real-time. Secondly, the virtual objects should be aligned with the corresponding real-world objects – in this case, the virtual red arrow should be aligned with the *Robot2*. To enable the users to evaluate the alignment, physical markers were planted on the test area. The markers were placed perpendicular in a driving direction of the tractor and parallel to the *Robot2*'s movement on the straight segments. Thus, an approximate angle error can be calculated based on the physical marker corresponding to the red arrow, if there is an error. In this

Fig. 5. The routes of the autonomous tractors in the demonstration. The route of *Robot1* is marked in red, and the route of *Robot2* in blue. Physical markers indicating angle errors are marked as 'x' within the robot's route.

Fig. 6. The AR system in operation. Information about the robots is shown: *Robot1* (titled "IISKO") on the left and *Robot2* (titled "APUMODULE") on the right. The location of *Robot2* is indicated with an arrow and its next waypoints with green circles. This footage from the demonstration field was acquired using a Wikitude SDK version for regular Android devices, which sets the view from the camera as the background of the application, enabling screenshots that show the view of the real world as seen by the user.

case, each marker corresponds to an 8.53-degree shift when looking at the robot from the end point of the test route.

For each test, the *Robot1* traversed the route one time. At the end point, *Robot1* was stopped and the user was asked to evaluate the operation by answering questions posed by the test conductor.

The questions were:

Q1: Estimate visible lag in the system in seconds.
Q2: Estimate the difference between the red arrow and the robot by using the physical markers on the ground.
Q3: Do the waypoints demonstrate where the robot is headed? (Yes/No)
Q4: Did the overall solution improve situational awareness? (Yes/No)
Q5: What comments does the test user have?

The question Q1 addresses the real-time requirement and the question Q2 the requirement for correct alignment of the real and virtual objects. The rest of the questions are used to evaluate the overall functionality of the system and its features.

At the beginning of each test, the AR headset was calibrated using a figure-8 movement according to the initialization and startup guideline of the headset manufacturer.

5.2. Results

The answers to questions Q1 to Q4 are seen in Table 1. For the yes/no questions Q3 and Q4, 0 indicates no and 1 indicates yes. As seen from the table, only *User 3* experienced that the system was lagging 1.3 s.

For question Q2, almost all users reported some misalignment between the real and virtual objects. However, the misalignment was 8.53 degrees at maximum, corresponding to one physical marker distance. For this application, the error was considered acceptable.

All the test users found the waypoints to demonstrate the direction of the robot (Q3). Finally, all test users said that the system improved situational awareness (Q4).

In addition, comments were received from the test users. *User 2* and *User 4* reported that the UI was difficult to see due to sunlight. In addition, *User 2* said that the application would be useful in the dark.

The waypoints did not function optimally according to *User 1* and *User 3*. Both users said that the waypoints did not always fit into the AR view when looking at *Robot2*, making perceiving of the situation difficult. In addition, both users reported that the waypoints malfunctioned when the robot was viewed from afar; the waypoints were either not visible or they seemed to be below the ground, under the robot. A similar effect is seen in Fig. 6, in which the waypoints rise from the ground upwards. However, *User 1* commented that the waypoints were a good addition when they did fit into the view with the robot.

Table 1. Answers to questions by test users.

	Q1 [s]	Q2 [markers]	Q3	Q4
User 1	0	1	1	1
User 2	0	0.5	1	1
User 3	1.3	0	1	1
User 4	0	1	1	1

With respect to the hardware and ergonomy, *User 3* reported that the view in the headset was too small and that the headset was hot, which caused discomfort. In addition, *User 4* stated that the headset was uncomfortable to wear with regular eyewear. Comfort in the current commercial products for AR headsets is not yet optimal.

The users also gave feedback on the overall UI. According to *User 1*, the red arrow could be used to track the position of *Robot2*, and it was surprisingly well aligned with the robot. In addition, *User 1* stated that all the data visualized from the *Robot2* was helpful, and it was useful to have the data in the same view with the robot instead of looking for the information elsewhere, such as a laptop. *User 2* commented that the state of the *Robot1* was visualized nicely. *User 3* commented that while the numbers in the UI were too small, the contrast was good. The blue arrow helped with localizing the robot according to this user. In addition, the user commented that the alert sign was good, and it was easy to perceive the overall situation from the UI, such as when *Robot2* had shut down unexpectedly.

5.3. Assessment

The setup fulfills all the operational requirements defined in Chapter 3.2. The location of the *Robot2* is visualized with the red arrow, a marker in the virtual compass and a blue arrow indicating the direction where the robot lies if it is not in view. The virtual objects enable perceiving the location of the *Robot2* even if it is hidden from view. All the status information for both machines was visualized and the real-time requirement was met in the demonstration.

With respect to user-related requirements in Chapter 3.3, the test users gave positive feedback to the informational value of the UI and did not comment that the UI would have been hard to understand. One user commented that the UI had good contrast; however, the UI was not easy to view in the sunlight. The hardware was specifically chosen to fulfill the third requirement of hands-free operation. The fourth requirement, stating that the virtual objects should be aligned with the real ones, was measured in the demonstration and was found satisfactory for this application. The final requirement for ergonomic hardware should be improved based on the feedback from the test users. Thus, almost all of the requirements were met by the developed setup.

6. CONCLUSIONS

In this paper, we derived the requirements of an AR system to be used in an agricultural multirobot system of two robots to improve the situational awareness of a human supervisor. From these requirements, we further derived a system design including the hardware, software and communications. The implementation required the real-time communication system from both robots to the AR system and in addition, an external camera system was required to measure the orientation of headset in the tractor frame. The internal sensor system of AR headset was not sufficient for the purpose.

The implemented system was tested on an agricultural field and evaluated by users. Based on the user evaluations, the AR system improves the situational awareness of the human supervisor on board of one of the robots. Situational awareness for the operator of multiple large mobile robots working in the same region was found crucial. An operator sitting onboard in one of the vehicles of the fleet is multitasking and alerting in AR view on abnormal situations is helpful.

Most of the requirements were fulfilled by the system. We conclude that it is possible to implement an AR system interfacing with a system that manages a fleet of robots. However, even if the AR system was demonstrated as a part of real life operation, commercial AR headset technology in outdoor conditions still requires advanced before the required overall usability is achieved.

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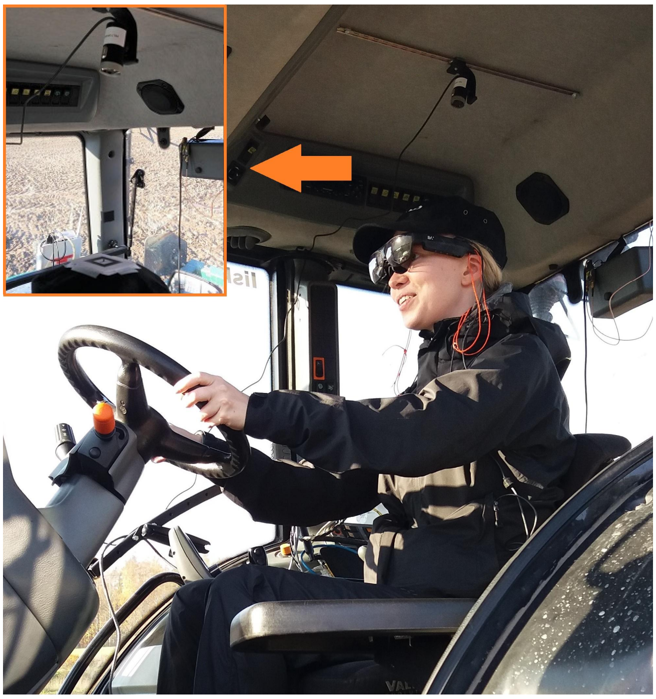

Fig. 7. A test user in the tractor, a.k.a. *Robot1*.

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