Virtual Co-location to Support Remote Assistance for Inflight Maintenance in Ground Training for Space Missions

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Abstract: During training for inflight maintenance procedures in human space missions often several experts need to interact with each other. Unfortunately, it is not always possible to bring a team together to jointly handle a complex situation. This is due to experts' availability, critical timing issues or accessibility of a location. This paper explores whether and how virtual co-location based on augmented reality can be used in such scenarios to bring a team together and allow this team to train for maintenance during space missions.

Key words: *Virtual Co-location, Collaboration in Augmented Reality.*

INTRODUCTION

Nowadays, work environments make use of advanced technologies and equipment to increase the productivity of workers. A unique case is the International Space Station (ISS), a modular structure that provides a platform to accommodate several scientists from different fields conducting scientific research in space. For In-Flight Maintenance (IFM) on-board the ISS, astronauts check, set up, or repair equipment and conduct mission specific procedures such as those involving the completion of scientific experiments. The intrinsic complexity of the equipment and associated procedures makes all human spaceflight operations exhibit a high degree of complexity. Critical situations are typically handled with support from local sources of information and from remote specialists located at the ground base.

The main local source of information is a laptop computer, the Station Support Computer (SSC) which stores complete information about all standardized operations including IFM. To clarify a task, the astronaut has to discuss with on-board members, with members located at User Support and Operations Centres (USOCs) [19] throughout Europe and to access SSC, every time temporarily stopping his current activity. Shifting the attention to other task possibly related to a slightly different physical location may distract and increase the workload on the astronaut. Furthermore, the unavailability of external immediate support in case of emergency situations requires the missions to be carried on with extra caution and under the lowest possible error rate of human operation.

The remote assistance during ground training operations can be improved using new and emerging technologies. Therefore, the use of virtual co-location to enable ground personnel and astronauts to interact with each other is explored for the ground training of payload related procedures.

Virtual co-location allows users to engage in spatial remote collaboration. It entails that experts are virtually present at any place of the world and interact with others that are physically present to solve complex problems as if being there in person. Virtual co-location relies on augmented reality (AR) to create spaces in which people and other objects are present. AR technology already proved to have a significant impact in various domains [3]. Due to the capability to enhance reality, to assist collaboration, to support spatial cues and to allow interaction between the virtual and augmented worlds, AR support promises to successfully support novel types of interfaces for face-to-face and remote collaboration [2].

Related to the AR technology, the use of lightweight Head Mounted Displays (HMDs) with attached cameras requires more attention, in order to explore the potential of becoming a standard equipment in training for space missions. In this line, Markov-Vetter and Staadt [12] present MARSOP (Mobile AR for Space Operation Procedures), a non-collaborative system that provides AR-oriented guidelines via a binocular video-see-through HMD for astronauts conducting operations inside the International Space Station. The system integrates a marker tracker of a re-locatable resource pad, a tangible AR interface, as well as optical flow for 3D model-based, marker-less tracking.

This paper explores the use of virtual co-location during training for space missions and presents a roadmap for implementation. The next section presents related work on AR systems that enable collaboration. Then, the scenario for applying the AR technology for collaboration by virtual co-location is discussed. Subsequently, analysis of AR collaboration support for training and ground simulation with specificity to payloads is presented. Some short discussion about the evaluation and finally the conclusions are also presented.

RELATED WORK

Moeslund et al. [13] propose Arthur, an AR meeting system that permits multiple users wearing HMDs at a round table, to interact with objects specific to architecture and urban planning domain. The interaction with the augmented world is realized in two ways, using physical objects – placeholder objects and a wand, and by hand gestures.

Dong et al. [8] propose ARVita, an advanced collaborative AR tool with problem solving capabilities to be applied in classroom and in professional practice. In these scenarios, multiple users wearing HMDs and sitting around a table are able to perform interaction and to visualize dynamic simulations of engineering processes overlaid on the surface of the table.

The work of Wang and Dunston [17] advances two AR based systems for remote collaboration and a face-to-face co-located collaboration in the scenario of detecting design errors.

Jailly et al. [11] presents an AR system for enhancing the comprehension of the manipulated remote devices in distance learning domain that allow for communication between both students and teachers.

Ferrise et al. [9] tackle the domain of maintenance operations of industrial product. In addition to using VR technology to support an operator to learn performing maintenance operations by combining traditional instruction manuals with simulation, AR technology is employed to extend the scenario to tele-assistance. A VR-based skilled operator guides from the distance a trainee that is equipped with AR technology already displaying instructions on top of the real product.

Nilsson et al. [14] propose an AR tool to improve collaboration between actors from different organizations such as the rescue services, the police and military personnel in a crisis management scenario while in the same time sustaining the individual needs.

Yabuki et al. [16] present a system in the early phase of development, aiming at supporting the cooperation between people working outdoor on the environmental issues. The information provided to the users wearing HMDs relates to 3D representations of temperature distribution and wind distribution, velocity and direction.

Alem et al. [1] propose ReMoTe, a remote guiding system that integrates non-mediated hand gesture communication in the mining industry. The work scenario of the system implies the expert remotely assisting a worker using the hands to point to certain locations and to show specific manual procedures. Testing and validation of four early user interface design iterations aimed at maintenance tasks for repairing a photocopy machine, removing a card from a computer mother board and assembling a Lego toy.

Wichert [18] describes a mobile collaborative AR environment that uses web technologies. The collaborative environment allows a 3D game like Tetris to be played in real time by several users wearing HMDs. The players can be located in the same room, with the possibility for extending the collaboration with a remote player. The game setup provides support for studying the two types of AR based collaboration: the co-located cooperative interaction with skilled workers, each having a different view of the AR world and the indirect interaction with remote expert that has the same view as the skilled worker.

In a similar way, Datcu et al. [4][5] propose an AR based scenario of playing a game collaboratively, to simulate the study of complex problem solving between physically co-located and virtually co-located participants. Within the game, the goal of jointly building a tower of coloured blocks represents an approximation of a shared task. Individual expertise is modelled as the possibility to move blocks of a distinct colour and shared expertise is modelled by the possibility of all players to move blocks of a same colour. By scaling down real-life, more complex problems, the study compares presence, workload and situational awareness in real world and AR collaboration scenarios. Additionally, Datcu et al. [6][7] developed a platform for tele-collaboration by AR for supporting teams in the security domain.

Schnier et al. [15] focus on studying the issues around establishing the joint attention toward the same object or referent, in a physically co-located collaboration AR environment.

Gu et al. [10] conduct a study on the impact of 3D virtual representations and the use of tangible user interfaces as support for synchronous design collaboration using AR technology. The results indicate that the change from physically co-located working environment to the virtual co-located scenario encourages the AR users to smoothly move between working on the same tasks and working on different tasks or different aspects of the design process.

The current state of the art on collaboration in AR provides relevant examples for AR based models that support synchronous collaboration among workers in various domains, either being physically or virtually co-located, using free-hands or tangible interaction, static or mobile, or either using HMDs or other display devices. These research outcomes, however, have to be still investigated in the human space flight domain, especially with regard to the remote visualization, spatial interaction and the remote authoring for tele-operation.

SCENARIO

A joint project between the European Space Agency (ESA) and the Delft University of Technology focuses on the training procedures using virtual co-location within the ISS Columbus laboratory. Being the Europe's largest contribution of the ISS programme, the Columbus laboratory (Fig.1, left) consists of a 4.5 meters diameter cylindrical module attached to the ISS (in February 2008). Columbus incorporates 10 flexible racks of research facilities based on the International Standard Payload Racks (ISPRs), one of them being the European Drawer Rack (EDR) (Fig. 1, right). The EDR is a modular and flexible carrier rack specially designed for experiments on a large range of scientific disciplines [19]. The EDR is handled by the Microgravity User Support Centre (MUSC) in Cologne. At a time, three to four payloads are integrated due to the optimized overall design of the facility. The activity of researching and developing the AR system restricts the remote collaboration process to the handling of three payload types, namely KUBIK 6 (Fig. 2, left), GeoFlow Experiment Container (GeoFlow) (Fig. 2, middle) and the Microgravity Science GloveBox (MSG) (Fig. 2, right). KUBIK 6 is a small controlled-temperature incubator or cooler with removable inserts designed for self-contained microgravity experiments [19]. By using a KUBIK Interface Drawer (KID), such a scientific experiment module can be operated inside the Columbus EDR. GeoFlow is used to run experiments for studying the thermal convection in the gap between two concentric spheres to model Earth's liquid core. MSG is a device used to perform a wide range of scientific experiments in a fully sealed and controlled environment, completely isolated from the rest of the station [19].

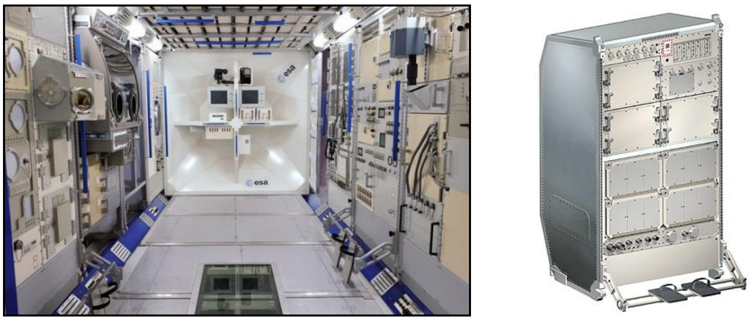

Fig. 1: ISS Columbus mock-up at the European Astronaut Centre (EAC) in Cologne, Germany (left) and the EDR (right).

Experiments relate to research on material science, biotechnology, fluid science, combustion science and crystal growth, and are manipulated via the glove access points.

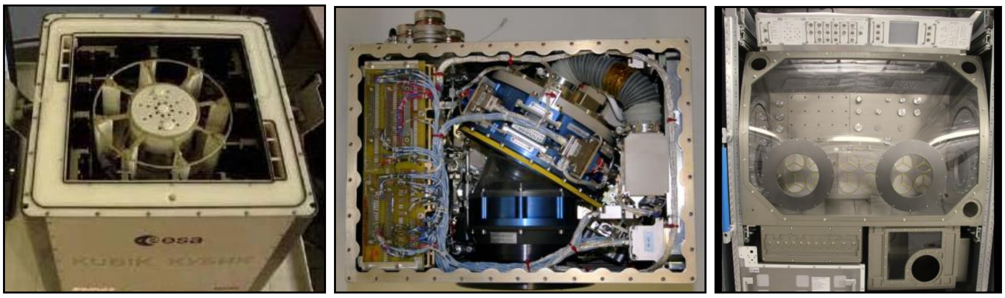

Fig. 2: KUBIK 6 Incubator inside EDR (right), GeoFlow Experiment Container (middle) and Microgravity Science GloveBox (MSG) (right)

Supporting virtual co-location using an AR system targets different operational objectives on the three before mentioned types of payloads on ISS/Columbus (Table 1). The goal, however, is to develop a generic AR system that can easily be extended to also support additional operational objectives of other EDR payload equipment. For this purpose, two scenarios are considered for the current study. First, the virtual co-location support focuses on the training of procedures for the aforementioned payloads. A scenario is defined and analysed to clearly identify the role and functional requirements for an AR system supporting virtual co-location.

Table 1: AR collaboration support objectives on different payloads.

Payload	Objective
KUBIK	▪ Kubik 6 preparation ▪ Functional Check of KUBIK 3 stand-alone. ▪ Check KUBIK 3 cable connections and KUBIK 3 status in case of anomalies. ▪ Prepare KUBIK 3 for the experiment
GeoFlow	▪ FSL optical target 2 replacement
MSG	▪ Remove and replace the MSG Facility Front Filters

Analysis of virtual co-location for training procedures

In order to identify the key concepts to be supported within an AR system for virtual co-location, a scenario for ground training of procedures is defined. A minimum of four actors are considered for this scenario: Trainee, Trainer, Payload Expert and Operations Expert.

The trainee is assigned a specific task by the trainer on the payload equipment, for which the standardized procedure has to be followed precisely. Apart from using her prior knowledge on the procedure, in the standard approach the trainee is allowed access to the expertise of the remote payload expert and to a laptop computer, the Station Support Computer (SSC). The SSC contains the procedural description of the task stored in form of an Operations Data File (ODF). In this scenario, AR based collaboration support system has to enable synchronous collaboration with the remote payload expert and the access to ODF for a given task. The AR software system runs either on a mobile computer or on the SSC. During the training, the trainee wears an HMD connected to the AR system. The HMD will be either connected by wire or wireless to the computer running the AR system. The diagram in Fig. 3 (right) represents the different interaction relationships between the actors of the training/simulation process.

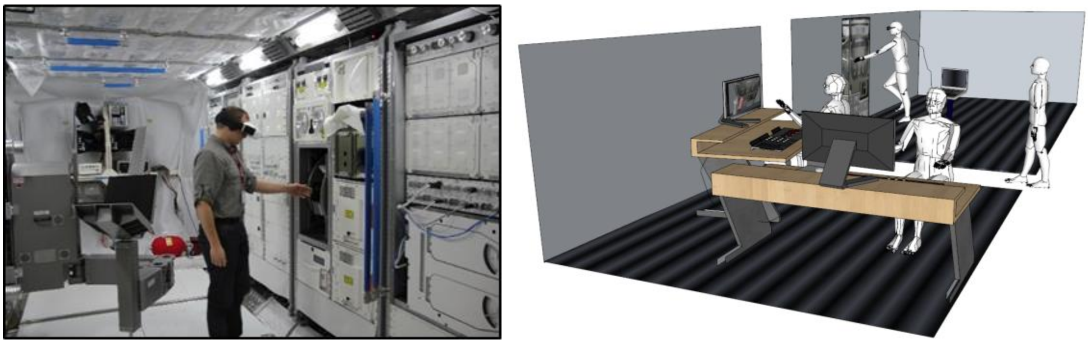

Fig. 3: Trainee wearing a HMD inside ISS/Columbus mock-up (left) and interaction relationships between the actors of the training/simulation process (right).

The access of the trainee to the two types of resources (human-oriented and computer-oriented, automatic guidance) can be supported simultaneously. The trainee is informed about the task objective and the current procedural step within the task in form of visual displays in the HMD. The current task step can be set by the trainer or can be automatically assessed by the AR system. Secondly, the AR system facilitates the virtual co-location of both the trainee and the payload expert at the physical place of the trainee, with the option for the trainee to access also concise information from the task ODF. In this situation, the automatic guidance would be minimal, the AR system being mainly set on fully supporting the collaboration process. This is achieved in two ways namely by securing the transfer of instruction of the remote payload expert to the trainee and the transfer of the local trainee actions to the payload expert. In this way, the role of the AR system for automatic assessment of trainee actions are passed to the remote expert, the guidance being generated remotely and further transferred locally, back to the trainee.

There are two cases regarding the collaboration between the payload expert and the trainee. In the first case, the remote expert interacts with the AR system through her laptop computer. The interaction relies on the use of a standard mouse and keyboard. The visualization is screen based. In a second case, the remote expert wears a HMD for Virtual Reality (VR), e.g. an Oculus Rift. Then, the interaction of the remote expert with the AR system is done by hand gestures and the visualization of the shared VR scene is on her HMD. Fig. 4 illustrates the VR-AR mixed collaboration model for the training/operation process.

Apart from defining the task objective, the trainer can dynamically switch the task step and other inherent parameters of the task. This is done by voice instructions and by manually controlling the AR system. A special interface of the AR system has to be designed on the side of the trainer. Although in the typical scenario the trainer, the payload expert and the trainee are located in separate physical environments (with the trainee inside the ISS Columbus replica), practically the trainer and her equipment can be located in the same room as the payload expert. The role of the operations expert is to observe the activity of all participants engaged in the training and simulation session. Her participation allows her only a limited influence on the activities, indirectly by giving specific suggestions to the trainer. In her observations, she spots flaws on the remote AR-supported collaboration, training and simulation procedure for guidance, misleading and erroneous feedback from the automatic AR system. The findings of the operations expert will later lay the basis for further improvements of the AR system prototype for astronaut training.

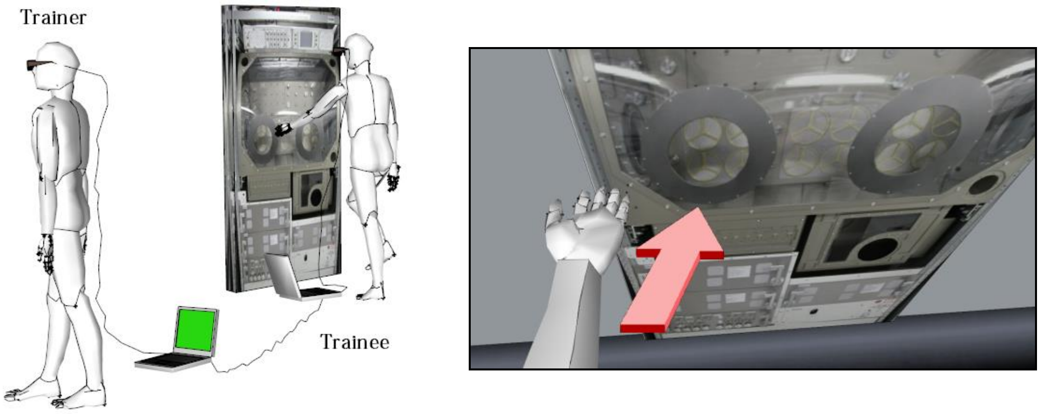

Fig. 4: Trainer-trainee collaboration scenario with the trainer using a VR device (left). Shared view for trainer (VR) and trainee (AR) (right).

EVALUATION

The project has an incremental life-cycle, starting from the simple scenario and moving on to more complex scenarios involving several persons. At every stage, the implementation effort will be evaluated to with regard to the efficiency of support or technical characteristics like bandwidth and latency. Some quantitative indicators are to be derived from interaction data stored in form of AR system's logs during the experiment session. Such indicators are used to measure the quality of interaction of the user with the system user interface, especially by measuring the time necessary for fulfilling specific tasks (i.e. the time required for authoring actions like adding a 3D text component, an arrow, or removing a component from the shared AR view) (Fig. 5).

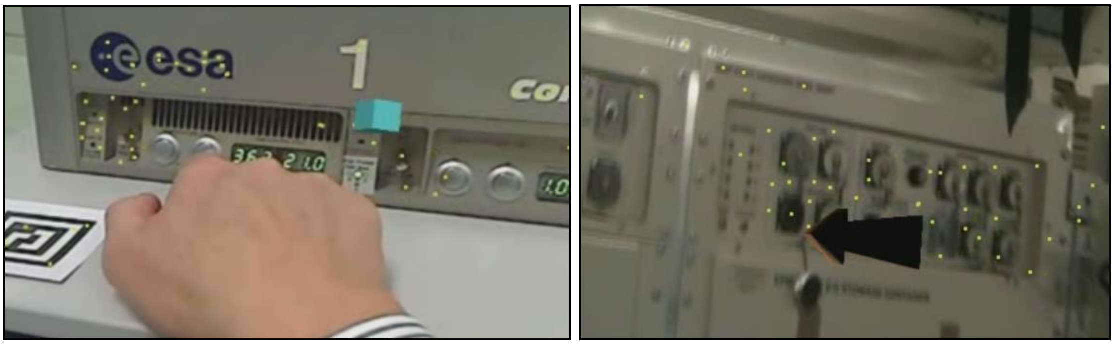

Fig. 5: AR support points and annotation in form of arrows (placed by the remote expert).

Secondly, qualitative indicators aim at measuring the subjective feedback of the participants at the experiments. These indicators rely on the use of individual questionnaires that address different categories of questions targeting quality of interaction (NASA TLX questionnaire), presence questionnaire, spatial interaction, etc. Thirdly, the video recordings represent one more source for investigation, leading to specific indicators based on qualified evaluation by the external expert investigators, during or after the experiments.

CONCLUSIONS AND FUTURE WORK

The paper describes a scenario for training procedures in relation with different payloads using virtual co-location supported by an AR system. It further highlights the requirements an AR system has to address in order to be applied for the actual ground training of typical space maintenance operations. Currently, we are in the process of implementing the AR system. Next, an experiment will be realized at the site of ISS Columbus mock-up at the European Space Research and Technology Centre, The Netherlands.

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