COMPUTER AIDED MEDICAL DIAGNOSIS AND SURGERY SYSTEM: TOWARDS AUTOMATED MEDICAL DIAGNOSIS FOR LONG TERM SPACE MISSIONS

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ABSTRACT

The Computer Aided Medical Diagnosis and Surgery System (CAMDASS) is a tool that is aimed at providing medical guidance and automated diagnostic support to non-experts for performing medical procedures, especially motivated by astronauts on long term spaceflights beyond Low Earth Orbit (LEO) where restricted communication makes tele-medicine solutions impractical.

The paper introduces the motivation and various operational restrictions that apply for such a system, and various related work to provide a background. This is followed by a description of the CAMDASS system and preliminary results, as well as a discussion on future work.

1. INTRODUCTION

During space flight, crewmembers will be exposed to a plethora of potential environmental hazards that are vastly different from Earth. Astronauts are prone to injury and illness, and these situations can seriously impair mission outcomes. Trauma on a space mission can involve any of the following conditions (not an exhaustive list): intra-cranial hemorrhage, hemorrhage, airway obstruction, hemo-pneumothoraces and circulatory instability [1]. In addition, lengthy stays in space cause prolonged exposure to microgravity and radiation, and are known to have physiological effects such as muscle mass degradation, reduction in bone density and decreased functioning of the immune system. Additional tasks that astronauts can be assumed to perform on long term interplanetary missions, such as extra-vehicular activities (EVA) and lifting and assembly during surface exploratory missions, are likely to exacerbate the recognized risks (such as bone fracture or decompression sickness).

The variety of specializations covered by possible medical incidents makes it impractical to have a Crew Medical Officer (CMO) who is fully and appropriately trained to handle all possible medical needs. The limited size of human space flight missions implies that it would not be likely to include multiple CMO's in the crew in order to achieve complete coverage of the possible scenarios. Moreover the impracticality of training the CMO's to an acceptable competency remains an issue. Similarly, the availability of manned spacecrafts to temporarily augment the crew with an appropriate expert, or transport the patient back to Earth is highly unlikely, especially in the case of manned missions beyond Low Earth Orbit (LEO).

Additionally, for missions beyond LEO such as those expected under the Aurora Exploration Programme, severe constraints on communication links with Earth (such as lengthy time delays – expected to reach up to forty minutes on Mars for round trip communication – and restricted connectivity – due to line of sight constraints on communication), it would be impossible for crew members to receive any meaningful guidance from experts in real-time. Therefore, for long duration space mission, that is, both LEO and interplanetary mission, enabling technologies for real-time medical procedure support is essential, considering the detrimental effect of disabled crew members to the successful completion of the mission.

Measuring physiological change is also critical to our understanding of human space habitation, and the advancement of appropriate treatment for common symptoms. While a range of payloads have been flown to study changes in cardiovascular and pulmonary states and muscular atrophy in microgravity, with the extension of operations on the International Space Station (ISS) till 2020 and imminent interplanetary missions, such enabling technologies can play the roles of enhancing our understanding of physiology in space, supporting medical diagnostic procedures and even perhaps supporting medical intervention if needed.

The Computer Aided Medical Diagnosis and Surgery System aims at developing technologies that fill the need for an automated guidance system for medical procedures, especially diagnosis, without relying on the presence of a remote expert. The system developed is intended as a prototype of a tool assisting in the medical care of astronauts on long term missions, which is relevant with respect to interplanetary manned missions that are planned in the coming decades.

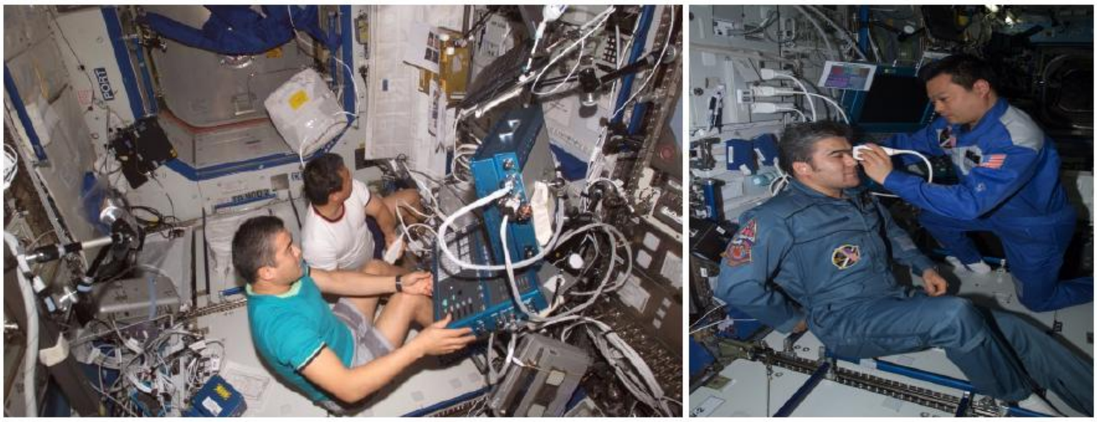

Figure 1: Astronauts using the ultrasound device in the HRF on the ISS (images courtesy of NASA)

2. BACKGROUND

2.1. Telemedicine and Space medicine

Providing immediate access to emergency care has always been of priority in international space programs. The sheer distance between an astronaut who needs trauma or illness treatment and expert medical professionals has constantly posed significant challenges. Careful selection of astronauts based on their personal and genealogical medical history and high level of fitness has been the fundamental method of preventing potential health failures during space flight. However, the National Aeronautics and Space Administration (NASA) and the Eurpean Space Agency (ESA) have initiated significant effort towards making a number of life support systems available on the ISS. For example, the Human Research Facility (HRF) and European physiology modules contain a variety of physiological measurement equipment including pulmonary function, cardiovascular, electroencephalogram (EEG) and ultrasound devices.

Considering the availability of basic medical devices, physicians on Earth are able to view, monitor and recommend actions based on downlinked astronaut data. Techniques such as videoconferencing, uplinking of procedure documents, and tele-stration have been proposed and explored [2]. Tele-stration is of particular interest in space medicine as it allows physicians on earth to use interactive techniques to explain medical procedures to crewmembers. For example physicians can use a tablet and stylus to explain what steps are to be taken in a medical emergency.

In recent years, ultrasound has emerged as a quick and reliable method for trauma diagnosis in extreme environments. The relatively quick setup time and portability of ultrasound along with low bandwidths required for data communication are a few reasons for its use. Dulchavsky and colleagues conducted a number of experiments (Advanced Diagnosis using Ultrasound in Microgravity, ADUM) on the ISS with the ultrasound unit installed on the HRF [3] . With beginnings in parabolic flights, the authors showed that ultrasound can provide fast and reliable diagnosis for a number of situations including pupiliary light reflex[4], pneumothorax [5], retroperitoneal and pelvic imaging [6]. In their study, astronauts used cue cards to obtain sonar images of different physiological structures with support from ultrasound experts on the ground. The authors reported that ultrasound images allow astronauts to perform fast trauma diagnosis, with the ability to obtain expert diagnosis from ground personnel. Astronaut candidates today are all trained on basic ultrasound device usage and data collection. This is a requirement not just from a diagnostic perspective, but is also because ultrasound is used in muscle atrophy studies.

On the Neurolab (STS90) shuttle mission, two astronauts with surgical experience performed different operations on rats [10], demonstrating that surgical procedures can be successfully conducted in space. SRI International demonstrated remote surgery as part of the NASA Extreme Environment Mission Operations (NEEMO) using the M7 surgical robot (http://www.sri.com). The M7 robot has also been demonstrated on parabolic flights.

Software solutions that provide just-in-time (JIT) support have been shown to be extremely beneficial in remote medicine. The addition of virtual reality (VR) and augmented reality (AR) technologies allows such software systems to provide topological cues for tools and sensor positioning. The addition of visual guidance through critical procedures can be tremendously beneficial, especially for non-experts. For example, remote surgeons can be provided with real time support by sharing 3D images with surgeons at other remote sites [7, 8].

Similar AR and VR technologies have been widely explored in other medical domains. The said technologies make use of multimodal sensory immersion to enable users to view, learn and apply relatively new or even unknown skills, and as such provide valuable learning tools. VR simulators are now the *status quo* for surgical resident training [10].

The use of AR and VR technologies in surgical procedures is not new. In case of an inexperienced surgeon, the ability to use 3D anatomical references in VR can be very helpful. AR has been used to register 3D images with the patient site to provide surgeons with see-through capabilities for needle guidance in neurosurgeries [9]. Additionally, VR can be used as a basis for consultation and the exchange of expertise using specific data, allowing procedures to be planned on a collaborative basis.

2.2. Augmented Reality for Tele-operation and Guidance

AR techniques not only offer tremendous potential for remote human guidance in medical JIT systems, they have immediate use in human-robot interfaces, particularly with respect to manipulation tasks. There has been a significant effort in applying AR to telerobotic control. Chintamani et al demonstrated the benefits of visual guidance cues for remote robot teleoperation [12]. Their AR interface presented the spatial information of the robot's path (or plan) as overlays on the camera views for the robot operator to guide the end-effector in a cluttered environment. Usability evaluations showed that the AR overlays constrained the robot to safe regions in the cluttered environment. In addition the researcher also investigated the effects of different visual graphic representations of spatial information that could be used in AR interfaces for manual control of space robots [13].

AR techniques have also generated a great deal of interest in guidance and navigation tasks, where super imposition of information onto images of the real world aid in efficient task completion. Schall et al use AR to display underground infrastructure for workers [15]. Reitmar et al describe a mobile AR system for multi user collaboration [16], showing the use of AR techniques for data and information exchange.

ESA has also shown interest in the use of AR to provide JIT support, significantly to support astronauts during in-orbit maintenance tasks. The Wearable Augmented Reality system (WEAR) developed by Space Applications Services is a head mounted display (HMD) based procedure guidance system to support routine maintenance tasks and procedure execution on the ISS. Using WEAR, the astronaut sees graphic markers of spatial locations of interest overlaid on his view of the environment, along with detailed access to maintenance procedure information (displayed on the HMD) in a hands free manner (using speech recognition). The WEAR system was tested on the ISS by Astronaut Frank DeWinne in 2009.

Motivated by the above mentioned works, as well as the rising popularity of AR applications on smart phones such as LAYAR [14], CAMDASS aims at providing an AR based guidance and support system for the execution of medical procedures, as well as assistance for diagnosis. While AR technologies with similar aims exist, a unified approach to remote procedure guidance is still non-existent in literature. Systems with similar objectives include an optical see-through AR method developed by Fuchs et al [11]. The authors showed how overlays of anatomical models on the patient body can help laparoscopic navigation and help enhance surgeon situational awareness.

3. SYSTEM DESCRIPTION

As mentioned above, CAMDASS is a prototype system that aims to provide support to astronauts (as users with basic medical training) in performing medical procedures for diagnosis and surgery.

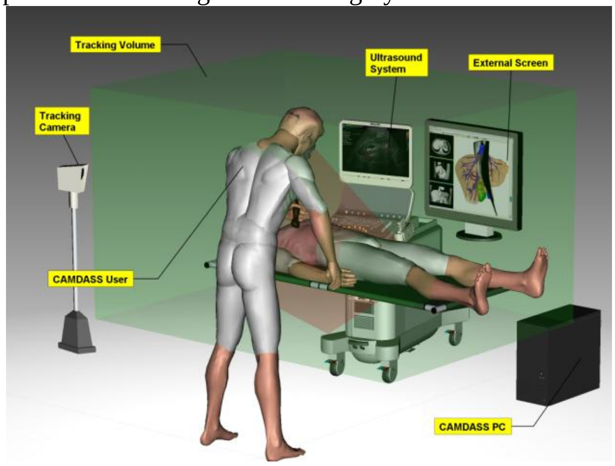

Figure 2: Artistic representation of CAMDASS

CAMDASS utilizes a HMD and tracking of the user, patient and various tools to provide accurate guidance via visual cues that are displayed in and integrated with the user's natural view. Additional information is provided in the form of intuitive cue cards and instructions. Speech recognition is used to enable hands free control, enabling the user to focus on the medical tasks to be accomplished. Using a database to store the medical procedures, as well as acquired medical data and achieved medical results, the system discards the necessity of having a remote expert available.

As a prototype, the current system is intended as a proof of concept, and as such implements limited guidance for specifically chosen medical procedures that are relevant to medical care (and acquisition of physiological data) of astronauts. Due to applicability for diagnosis in case of trauma and data acquisition, ease of use and the availability of such a system on board the ISS, the implemented procedures support an ultrasound device.

The CAMDASS prototype has been designed keeping extensibility in mind. Apart from the easy addition of new procedures via re-use of components, the creation of new components and guidance mechanisms is facilitated by a Service Oriented Architecture (SOA).

This section will briefly describe the hardware components before detailing the salient features of the system.

3.1. Hardware

CAMDASS uses a combination of hardware devices to achieve its goal of procedure guidance using AR.

Tracking: A **Polaris Spectra** from Northern Digital Inc is used to track multiple objects. The Polaris Spectra is an optical tracking system that uses passive infrared reflective markers that are illuminated by the device, which then uses two factory calibrated cameras to track each marker with a root mean square (RMS) error of 0.3 mm. Multiple markers are rigidly grouped to create a tracking tool, enabling accurate tracking of 6 Degree of Freedom (DOF) position and orientation.

Head Mounted Display: The **nVisor ST** from NVIS Inc is used to display AR, as well as User Interface (UI) elements displaying procedural data, in the user's field of view. The nVisor ST provides high resolution stereoscopic see through capabilities, that is the augmented reality and UI elements for each eye are displayed on a transparent prism, and are implicitly overlaid on the environment on the retina. This allows the user to maintain direct visual contact with the environment, retaining a more natural visual interface.

Ultrasound: The **Logiqbook XP** from General Electric Healthcare is the selected Ultrasound device. While the choice of specific Ultrasound device is independent of CAMDASS, and does not affect the functionality, an important factor is the ability to interface with and capture images from the device. This is currently supported using a video capture card that is connected to the Ultrasound device.

While the hardware mentioned above is used in the current CAMDASS prototype, they can be replaced by devices offering similar functionality with minimal effort.

3.2. Software

CAMDASS is implemented using the Medical Imaging Toolkit (MITK) from the German Cancer Research Center (DKFZ). MITK (www.mitk.org) is an open source framework that integrates visualization and imaging functionality provided in two toolkits, namely the Visualization Toolkit (VTK) and Insight Segmentation and Registration Toolkit (ITK) from Kitware (www.kitware.com).

Modularity: CAMDASS has been designed in a modular fashion, enforcing the primary design goal of easy extensibility. Core functionality has been implemented in the form of services using the Service Oriented Architecture introduced in MITK. This allows core functionality to be accessed as and where needed, without needing explicit integration and initialization by the central system. Additionally, UI elements are generated and activated using string identifiers, and are controlled via the procedure definition.

Procedure Definition: A medical procedure is formalized into a workflow, and used to generate an XML based procedure that is used to drive the procedure execution via a generated state machine. Each state in the state machine represents a step of the medical workflow, with attributes specifying the UI's to be displayed, and various data inputs and outputs that are applicable for the current step. This allows easy creation of new procedures, and allows re-use of UI's and procedural constructs. Goals and patient data are defined with respect to a generic 3D human model.

Patient Body Registration: To achieve accurate guidance, especially with respect to positional guidance, the goals must be defined in a manner allowing the procedure to be used humans with varied physiology. This is allowed in CAMDASS via the use of a Patient Body Registration module that allows conversion of reference (position) data between the reference model and the current patient, and vice versa.

The currently implemented Patient Body Registration module tracks a number of markers positioned on the appropriate region of interest on the patient body, and registered the tracked point set with a similar set of points defined with respect to the reference body model to generate an affine transform that allows real time tracking of the patient body. While this follows a simplistic registration algorithm, it is implemented in a modular manner to allow easy exchange with more advanced (and possibly specialized) registration algorithms that have been studied in detail.

HMD Calibration: Another factor that is crucial to accurate guidance of the user, especially for positioning of medical tools such as the ultrasound probe, is the accuracy of the AR representation to the environment. This is decided by the positioning and parameters of the 'virtual camera' used to generate the AR, the 'virtual camera' being the equivalent of the vision system formed by the display prism and the human eye. As the image of the AR overlaid on the environment is formed directly on the human retina, it is not possible to have a fully automated procedure for the calculation of the parameters that characterize the vision system, user involvement is required. The selected mechanism used for the calibration process is the Single Point Active Alignment Method detailed by Tuceryan et al [17], which has been shown to achieve excellent results in a workspace that closely resembles those applicable to CAMDASS.

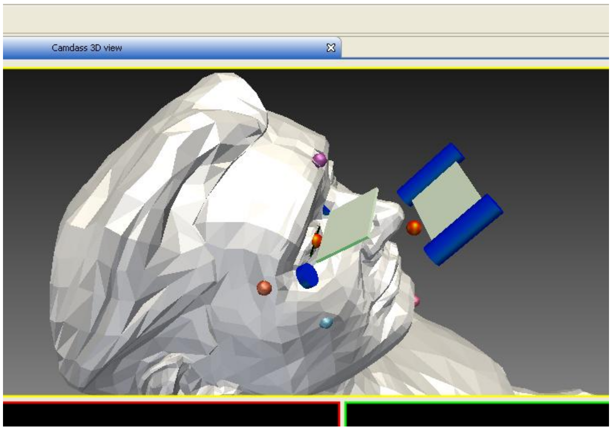

Figure 3: Position and orientation guidance

Position and Orientation Guidance: An important aspect addressed by CAMDASS is the ability to guide a user to place a medical probe (or similar device) at the appropriate position and orientation (defined by an azimuth and elevation) on the patient's body. This is done by using the Patient Body Registration to calculate the goal point with respect to the current patient, and tracking the probe. A number of visual cues are used to guide the user to place the probe correctly, and a tolerance value is used to evaluate when the user has reached the required position. The visual cues are also depicted in a VR representation on a screen, allowing user guidance even if the user chooses not to wear the HMD.

Reference Image Based Guidance: Due to the differences in individual human physiology, especially discrepancies that can be caused in low gravity environments, it is not always easy or appropriate to define exact positional guidance cues for procedural steps that involve the acquisition of medical images (for example an ultrasound image of the vena cava). In such cases, the user can be guided to acquire an appropriate image (after approximate positioning) by the use of a reference image with important features that have been clearly identified.

Hands Free Control: Hands free control has been implemented for specific parts of the procedural flow where it is expected that the user will need to use both hands for comfortable execution of the procedure step. Hands free control has been realised using 'Command and Control' based speech recognition (only a specified subset of words or commands are recognized) using the Microsoft Speech Engine that is freely available for Microsoft Windows operating systems.

4. CONCLUSION & FUTURE WORK

Apart from work that is needed to extend various aspects of the CAMDASS software, as well as increase the compatibility in terms of procedures and medical devices supported, a number of tasks have been identified in order to leverage the potential of CAMDASS.

4.1. Usability Evaluation

A pilot end-user evaluation is planned using a two group design. The first group will perform simulated Muscle Mass measurement procedures using the ultrasound unit with procedure cues cards. The second group will be guided through the same procedure by CAMDASS. All experimental participants will be trained using a simplified Corneal Diameter measurement procedure on a mannequin head.

The objective of the evaluation run is to understand the advantages and disadvantages of CAMDASS over conventional methods. All data pertinent to analysing user performance, such as sub-procedure step timing, probe position and orientation error, image acquisition quality, will be collected and analysed.

4.2. Training tool

Extensions are envisioned to adapt CAMDASS for use as a training (both pre-mission and just-in-time) tool. The corresponding on-ground scenarios that have been identified are training staff or medical experts instructing astronauts on the use of a device or a specific procedure, or astronauts working independently to review or practice. Similar flight scenarios could be imagined, that is astronauts working with or without remote support.

For use in the on-ground scenario with an instructor, AR is anticipated as an optional tool, and trainees can use only the desktop interfaces to train. However, with respect to individual learning, AR based guidance will need to be more involved than in the respective medical procedure, in the form of graphic cues detailing steps to be taken, and additional mechanisms for feedback and evaluation. While readily apparent, the benefits of using a CAMDASS based tool for on-ground training applications will need to be assessed.

A spaceflight version of the CAMDASS training tool would necessarily follow the ground training scenario, due to restricted communication. However in recognition of the fact that astronauts might face unanticipated medical situations, remote instructors or experts could collaborate with the user to provide feedback or modify the executed procedure to simulate anomalies.

4.3. Automated Diagnosis and Workflow Control

As CAMDASS currently guides the user through a series of procedural steps to acquire relevant medical data, where transitions through the procedure is manually controlled, the integration of Intelligent Decision Support (IDS) systems is one of the next logical steps towards achieving support for automated diagnosis. Such an IDS could also be leveraged to autonomously identify the successful completion of a procedural step, and initiate transition to the next step.

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6. REFERENCES

1. A. Kirkpatrick, C. Ball, M. Campbell, D. Williams, S. Parazynski, K. Mattox, and T. Broderick, "Severe traumatic injury during long duration spaceflight: Light years beyond ATLS," *Journal of Trauma Management & Outcomes,* vol. 3, p. 4, 2009.

2. K. McFarlin, A. E. Sargsyan, S. Melton, D. R. Hamilton, and S. A. Dulchavsky, "A surgeon's guide to the universe," *Surgery,* vol. 139, pp. 587-590, 2006.

3. C. M. Foale, A. Y. Kaleri, A. E. Sargsyan, D. R. Hamilton, S. Melton, D. Martin, and S. A. Dulchavsky, "Diagnostic Instrumentation Aboard ISS: Just-In-Time Training for Non-Physician Crewmembers," *Aviation, Space, and Environmental Medicine,* vol. 76, pp. 594-598, 2005.

4. A. Sargsyan, D. Hamilton, S. Melton, D. Amponsah, N. Marshall, and S. Dulchavsky, "Ultrasonic evaluation of pupillary light reflex," *Critical Ultrasound Journal*, vol. 1, pp. 53-57, 2009.

5. S. A. Dulchavsky, K. L. Schwarz, A. W. Kirkpatrick, R. D. Billica, D. R. Williams, L. N. Diebel, M. R. Campbell, A. E. Sargysan, and D. R. Hamilton, "Prospective Evaluation of Thoracic Ultrasound in the Detection of Pneumothorax," *The Journal of Trauma*, vol. 50, pp. 201-205, 2001.

6. J. A. Jones, A. E. Sargsyan, Y. R. Barr, S. Melton, D. R. Hamilton, S. A. Dulchavsky, and P. A. Whitson, "Diagnostic Ultrasound at MACH 20: Retroperitoneal and Pelvic Imaging in Space," *Ultrasound in medicine & biology,* vol. 35, pp. 1059-1067, 2009.

7. H. R. Abbasi, R. Weigel, C. Sommer, P. Schmiedek, and M. Kiessling, "Telepathology in neurosurgery," *Studies in Health Technology and Informatics,* vol. 62, pp. 1-7, 1999.

8. M. D. Ross, I. A. Twombly, C. Bruyns, R. Cheng, and S. Senger, "Telecommunications for health care over distance: the virtual collaborative clinic," *Studies in Health Technology and Informatics,* vol. 70, pp. 286-291, 2000.

9. A. Pandya, M. Siadat, G. Auner, M. Kalash, and R. Ellis, "Development and human factors analysis of neuronavigation vs. augmented reality," in *Medicine Meets Virtual Reality.* Newport Beach, California, 2003.

10. B. M. A. Schout, A. J. M. Hendrikx, F. Scheele, B. L. H. Bemelmans, and A. J. J. A. Scherpbier, "Validation and implementation of surgical simulators: a critical review of present, past, and future," *Surgical Endoscopy,* vol. 24, pp. 536-546, 2009.

11. H. Fuchs, M. A. Livingston, R. Raskar, D. n. Colucci, K. Keller, A. State, J. R. Crawford, P. Rademacher, S. H. Drake, and A. A. Meyer, "Augmented Reality Visualization for Laparoscopic Surgery," in *Medical Image Computing and Computer-Assisted Intervention-MICCAI '98*. vol. 1496: Springer-Verlag, London, UK, 1998, pp. 934 - 943.

12. K. Chintamani, "Augmented reality interface improve human performance in end-effector controlled telerobotics," in *Mechanical Engineering*. vol. Doctor of Philosophy Detroit: Wayne State University, 2010, p. 187.

13. K. Chintamani, A. Cao, R. D. Ellis, C. A. Tan, and A. K. Pandya, "An Analysis of Teleoperator Performance Under Conditions of Display-Control Misalignments With and Without Movement Cues," *Journal of Cognitive Engineering and Decision Making (Under Review),* 2009.

14. S. J. Vaughan-Nichols, "Augmented Reality : No Longer a Novelty ?" in *Computer*. Vol. 42, Issue 12, pp. 19-22, 2009.

15. G. Schall, E. Mendez, E. Kruijff, E. Veas, S. Junghaus, B. Reitinger and D. Schmalstieg, "Handheld Augmented Reality for Underground Infrastructure Visualization" in *Personal and Ubiquitous Computing*. Special Issue on Mobile Spatial Interaction, Springer, 2008.

16. G. Reitmayr and D. Schmalstieg, "Mobile Collaborative Augmented Reality" in *Proceedings of International Symposium on Augmented Reality*. Pp. 114 - 123, 2001.

17. M. Tuceryan, Y. Genc and N. Navab, "Single-Point Active Alignment Method (SPAAM) for Optical See Through HMD Calibration for Augmented Reality" in *Prescence : Teleoperators & Virtual Environments*. Vol. 11 Issue 3, Pp. 259 - 276, 2002.