Surgical Guidance using Augmented Reality (SUGAR)

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ABSTRACT

Augmented Reality (AR) represents a disruptive technology with the potential to revolutionize minimally invasive surgeries. Procedures such as pedicle screw insertions for spine fusion represent an interesting scenario where AR can augment the surgeon capabilities. Current devices have strict hardware limitations and limited tracking precision which prevent their usage in the intraoperative scenario. SUGAR project aims to develop an AR system integrated with a robotic assistant to overcome such limitations. We propose a streaming architecture to move intensive computational tasks on a remote server, and the usage of a high-precision electro-mechanical device to track the patient position. The final system will provide real-time information to the surgeon, without losing focus of the surgical field.

Augmented Reality: Minimally Invasive Surgery; Percutaneous Screw Insertion; Robotic Surgery.

1. INTRODUCTION

Nowadays, medical images are a key requirement in standard clinical practice, allowing more precise diagnosis, preoperative planning, and intraoperative navigation, especially in Minimally Invasive Surgeries (MIS). In the last decades, innovation has been focused mainly on the introduction of new *acquisition* modalities, protocols, and technologies, while *visualization* did not evolve with same pace [1].

Augmented Reality (AR) provides a disruptive alternative to previous medical image visualization methods, providing digital overlays that *augment* information directly on the real world. AR has the potential to foster the adoption of minimally invasive surgery (MIS), offering to the surgeon to view digital images and data directly overlaid on his or her field of view through the usage of head mounted display (HMD). Despite its advantages, AR devices suffer from technical problems related to insufficient tracking precision, complex workflows, low framerates and high latency, especially visualizing medical volumes in real time, which prevent their usage intraoperatively.

SUGAR project aims to tackle the aforementioned problems, with the objective of reducing the gap between AR technologies and their usage in MIS. In particular, the objective is to provide an AR system for guidance of minimally invasive robotic-assisted spinal surgeries, providing real-time visualization of the patient anatomy and its integration with a high precision electro-mechanical tracking device [2].

To achieve this, we implemented a remote-streaming architecture through Web-RTC protocol and integrated an AR system based on Microsoft HoloLens HMD with our robotic assistant. The final system offers a real-time communication between the robot and the HMD and visualize the patient anatomy performing the volume rendering on a remote high-performance server.

Nonetheless, even if a preliminary prototype has been achieved, we found serious problems during the integration of the whole system, especially trying to achieve a reliable two-way communication between the HMD and the remote server.

2. STATE OF THE ART

In the past years, multiple HMDs have entered the market (e.g. HoloLens, MagicLEAP, ARS by Trivisio, Google Glass and DAQRI). However, their onboard hardware significantly limits the rendering framerate of heavy datasets, requiring a high computational load which may not be suitable for embedded imaging hardware.

Remote rendering is a possible solution. Common streaming technologies -such as HTTP-based Adaptive Streaming (HAS) which encompasses MPEG-DASH or HLS- can have delays in the order of seconds, which are insufficient for an RT AR application. Ultra-low latency technology protocols such as WebRTC and Common Media Application Format are emerging to offer more efficient solutions and have the potential to manage an RT 3D rendering application [3].

Another issue is the imprecise placement of implants during surgery. Due to low accuracies provoked by poor RT patient motion-tracking, negative surgical outcomes may occur. AR systems have shown the potential for intraoperative visualization. In [4], a novel navigation method tailored to run on the HoloLens is developed for lumbar pedicle screw implantation. They report errors of 3.38º±1.73º in trajectory orientation and 2.77±1.46 mm for the insertion points. These results are comparable to other studies done in [5]. Nevertheless, the procedure is performed on a phantom spine, which omits the motion during a real surgery. Similar research was conducted in [6], where they superimposed a Computed Tomography (CT) scan to assist the surgeon with the trajectories, but motion was also dismissed. They reported roughly circular deviation with average radius of 2.52.5±0.44 mm in the registration accuracy.

SUGAR's consortium has developed an innovative electromechanical tracker to overcome difficulties when tracking patients' motion. To the best of the authors' knowledge, none of the existing AR systems for intraoperative guidance of MIS introduce an RT remote volumetric rendering combined with an electromechanical tracker for faster and more reliable motion tracking.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

SUGAR project aims to develop an AR system for MIS, focused on the percutaneous insertion of trans-pedicular screws for spinal fusion. This will provide Real-Time (RT) information to the surgeon during the intervention, without losing focus of the surgical field, in order to make the intervention safer for the patient and to reduce surgery time. As highlighted in Section 2, several problems need to be solved to achieve a reliable and robust AR system, able to augment the information presented to the surgeons. Table 1 reports the main problems identified in the state of art, and the solutions proposed to overcome such limitations.

Tab. 1. Solutions and advantages proposed by the developed system, with respect to typical problems identified in the state of the art.

State of the Art Problems	SUGAR proposed solution
Limited computation power of HMDs	Off-load computer intensive tasks on remote servers
Low framerate and high latencies	WebRTC-based streaming architecture
Insufficient tracking precision for MIS	Integration with a high precision electromechanical device
Complex workflow and set-ups	Integration of AR marker into the robotic assistant workflow

The remote streaming architecture would allow to take advantage of Graphical Processing Units (GPUs) available on high-performance servers, reducing the computational load of HMD. Consequently, efficient volume rendering techniques can be used to visualize the patient anatomy overlaid on the surgical site, without requiring any pre-processing pipeline. The AR system would be integrated with the robotic assistant developed by Cyber Surgery, allowing the visualization to be updated in real-time taking into account the position of the HMD, the robot position and the patient position continuously tracked by a high-precision electromechanical system. Finally, to avoid a complex set-up for the AR system, the detection of an AR marker rigidly attached to the robot allows the initialization of the scene and the identification of the position of the devices.

4. PROJECT RESULTS

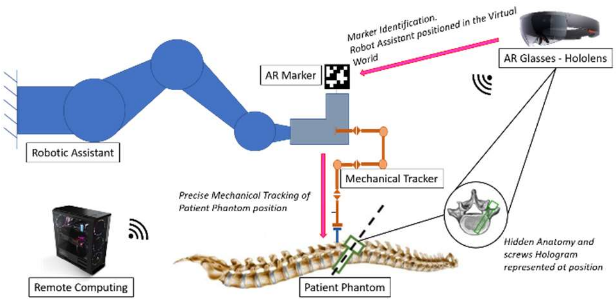

Fig. 1. Schematic view of the designed system. An AR marker allows to identify the position of the HMD, which is streamed remotely to the server. The server merges the information provided by the robot, the electromechanical tracker device and the HMD to correctly visualize the patient anatomy, and stream-back the volume rendering result to the HMD.

The physical set-up, shown schematically in **Figure 1**, is composed by:

- A robotic assistant (Robot Staübli TX2-40), which guides the surgeon by aligning surgical tools with the trajectory planned;
- An electromechanical tracking device (named Robotracker), represented by a 6 degree of freedom (d.o.f) passive arm with redundant encoders in each joint;

- Microsoft HoloLens[1] device as HMD for holographic rendering;
- A dedicated router and a remote server which centralize the communication and performed all the computational calculous;
- An AR marker [7] rigidly attached to the robot, used to synchronize the rendered scene with the real position.

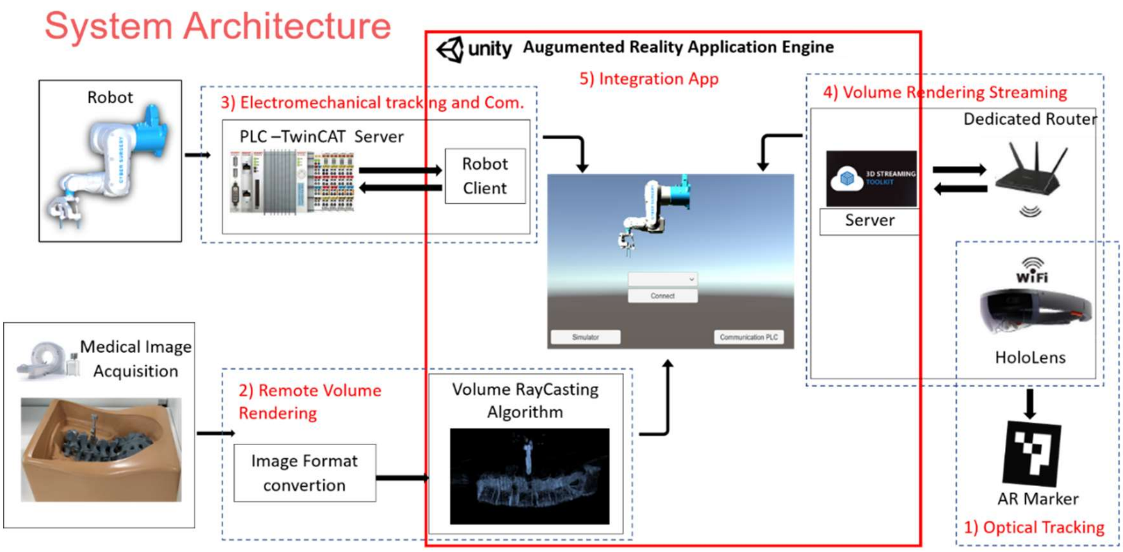

Fig. 2. SUGAR system architecture: the complete application is composed by different modules which allow the communication between the robot, the HMD and a remote virtual reality scene which combines the information provided by all the systems, perform the volume rendering by exploiting GPU capabilities and stream the visualization of the patient anatomy to the HMD.

A spine phantom with a mechanical clamp attached to the L3 vertebra is used for experiments. A Computed Tomography (CT) scan is performed simulating an intraoperative acquisition, allowing to identify the position of the volume with respect to the clamp through a registration procedure developed by proprietary software. The clamp has a so-called *kinematic coupling*, representing the attaching point between the phantom and the Robotracker and allowing a precise RT tracking of the patient [8].

The system architecture is presented in **Figure 2**. We defined a modular architecture to allow independent development of different parts. The system is composed by 5 modules:

1. An optical marker tracking application deployed on the HMD, to identify its position with respect the robotic assistant;
2. A direct volume rendering technique routine of a medical volume, which take advantage of the GPU capabilities of the server;
3. A socket-based server-client communication system between the Robot PLC and the virtual scene;
4. 3D Streaming server-client application running on the server side and the HMD respectively, which allows a two-way communication between the virtual scene and the HoloLens;
   A virtual scene developed in Unity, which provide a virtual representation of all the physical devices, simulate the point of view of the HMD with respect to the robot and position the patient volume at correct position. The result of the volume rendering is streamed back to the HoloLens for visualization.

Each system component was tested individually, but only a partial integration could be achieved. Indeed, we could successfully communicate our virtual scene with the robotic assistant by implementing a Socket TCP/IP communication between the robot PLC (server side) and the virtual scene (client side). The virtual scene is updated with the position of the Robot and the information provided by the Robotracker. Accordingly,

[1] We could not buy any model of Hololens since Microsoft stopped the commercialization of model 1 and we could not buy model 2, which is commercialized only in few states. The device used in this project was kindly shared by our research partner, but this and the Covid-19 lock-down have been a major limitation for the development of the project.

we could locate and orient coherently the CT scan simulating the real environment.

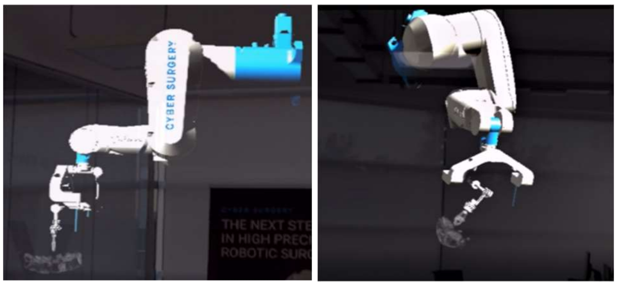

Fig. 3. Holographic visualization on HoloLens device, streaming the CT scan volume rendering attached to the robot. The rendering is performed remotely from the HMD point of view, and updated based on the user position.

A second simulation step implied the usage of the streaming architecture, simulating the initial position of the HMD and streaming to the HoloLens the volume rendering of the spine phantom tracked by the robot, seen from the HMD point of view (**Figure 3**). The rendering of both, robot and spine phantom, is updated in RT while the user is moving around the scene.

It has to be noticed that we could not achieve a reliable two-way communication between the HoloLens and the remote server, able to detect the AR marker to initialize the HMD position in our virtual scene. Complications have been found to achieve a stable communication, and we found that the HMD used has serious hardware limitations to run the marker tracking application jointly with the streaming client.

5. FUTURE PROJECT VISION

Despite the problems faced, we believe that the AR prototype achieved (TRL 3-4) has the potential to be rapidly scaled and improved to be integrated in our core application. AR systems represent a promising technology with the potential to revolutionize the clinical practice but require further development and advancements in order to be welcome in the surgical routine.

5.1. Technology Scaling

To achieve higher Technology Readiness Level (TRL), some algorithmic steps needs to be reimplemented to increase its robustness and efficiency, and part of the hardware updated to more recent technologies. In the near future, we envision the following tasks:

1. Improve HMD hardware to increase its computational and connectivity capabilities (we plan to buy HoloLens 2 model when available);
2. Implement advanced shaders and transfer functions for the volume rendering algorithms to improve visualization;
3. Increase the connection robustness and include encryption in our communication system;
4. Enhance the information displayed to the user by visualizing the implanted screws and the robot trajectory in RT;
5. Validation trials on phantoms and animals to evaluate the overall system precision. User-experience evaluation comparing the usage of the robotic assistant with and without the AR system.

In the medium-long term, we plan to add gesture recognition and/or a voice-control system to switch between different visualization modalities and to use the AR system to guide the surgeon during the different steps of the surgery.

5.2. Project Synergies and Outreach

The current consortium is formed by Cyber Surgery, a start-up company that is focused in the development of a surgical robot for spine surgery with the goal of having a certified product for the European market in the forthcoming years (CE mark), and Vicomtech, an applied research centre specialised in advanced interaction technologies, computer vision and data analytics that is actively collaborating with Cyber Surgery in the development of the robotic assistant.

Future developments would require the collaboration with hospitals and clinical centres to validate our prototype, involving surgeons with experience in using robotic assistants and/or AR to perform percutaneous screw insertions. The results obtained and the presentation of the complete system would be object of scientific publications in journal and conferences to share our experience with the scientific community.

Finally, our prototype is based on commercially available HMD, which are general-purpose AR devices. AR for MIS may require a specific hardware to improve the user-experience and match with surgeons' requirements. Consequently, an AR glasses manufacturer could be a valuable partner to achieve this goal.

5.3. Technology application and demonstration cases

The proposed project would make a positive impact on the Health, demographic change and wellbeing societal challenge identified by the Horizon 2020 research programme. Successful adoption of the proposed technologies would change the way in which minimally invasive surgeries are performed allowing safer and more efficient procedures. Surgeons would become capable of performing interventions with less distractions, more quickly and with less mental workload. Risk of surgical damage would be reduced, as well as time under anaesthesia. Reduction in surgical time would also translate into monetary benefits, as hospitals would be able to employ their ORs more efficiently and increase revenue.

Concrete demonstration cases will be focused on spine interventions on phantoms and animals combining the AR system with the robotic assistant developed.

5.4. Technology commercialization

Cyber Surgery is currently focused in developing and obtaining the CE mark for a robotic assistant for spine intervention, which have already received funding and interests by stakeholders. Nonetheless, we believe that an AR system could be a great advance to include in future versions of our system, as well as an intraoperative device or a surgical training tool, and a differentiation factor with respect to the competitors. Once started the clinical trials, the AR prototype developed would be a key-factor to involve old and new stakeholders.

5.5. Envisioned risks

Potential risks are mainly related to the introduction and acceptance of such systems in the operating room, and to match the safety requirements of MIS. To mitigate its introduction, the AR system will be first presented as an advanced visualization feature, without any real control in the operation workflow. Therefore, the surgeons' feedback would guide future developments and the possibility to use the AR device to increase the human-robot interaction along the operation. Preliminary identified risks and mitigation action are reported in **Table 2**.

Tab. 2. ATTRACT Phase 2 identified risks and mitigation actions

Potential Risk	Mitigation Strategy
HMD are uncomfortable to wear during the operation	Focusing the AR system on training and surgical planning, outside the operating room.
It is not possible to guarantee a reliable communication between the remote server and the HMD	Substitute the remote-streaming architecture with a robust segmentation pipeline, to upload patient anatomical models on the HMD

5.6. Liaison with Student Teams and Socio-Economic Study

The development of the prototype has directly involved MSc. Level students from surrounding universities, which collaborated with the project coordinator and its partner. The current Consortium actively collaborates with Universities and students, training and guiding them in their career development. In ATTRACT phase 2, the project coordinator will provide materials, slides and examples to allows MSc students participating more actively and generate ideas for the future developments of our systems.
To contribute to the socio-economic study of ATTRACT Phase 2 we plan to provide interviews with researcher and developers which can give the idea of the technical load related to such systems. Additionally, end-user feedback will be collected though usability questionnaires, which would be provided to the community under the form of scientific articles and would reflect the societal impact of the project.

6. ACKNOWLEDGEMENT

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