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EXECUTIVE SUMMARY OF THE THESIS

Development and Evaluation of a Simple Hologram-to-Patient Registration Method using a Head-Mounted Display and an External Depth Camera

LAUREA MAGISTRALE IN BIOMEDICAL ENGINEERING - INGEGNERIA BIOMEDICA

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1. Introduction

eXtended Reality is a concept which covers a wide spectrum of immersive technologies such as Virtual Reality, Augmented Reality and Mixed Reality. The main subdivision of these three modalities can be performed based on the nature of the surrounding[4].

- Virtual Reality: Technologies based on the use of computer-generated environments through the use of totally occlusive headsets. Interaction between the user and the real world is null.
- Augmented Reality: Its working principle revolves around the superimposition of virtual elements over the real world through the use of external devices, e.g., mobile phones.
- Mixed Reality: Technologies based on the merge between real and virtual world; in other words, the user can interact with both, real objects and holographic elements in a realistic way through the use of Head-Mounted Displays.

While the relevance of VR and AR remains undisputed nowadays, Mixed Reality offers a wider range of possibilities in comparison to the other modalities due to its capacity to provide an immersive experience for the user while allowing the interaction and manipulation of virtual elements as well as the visualization of the surroundings.

As many other technologies, Mixed Reality has found its was into the medical field, many approaches have been explored to integrate this concept to different procedures. So far the most remarkable applications in the healthcare environment correspond to ones in the field of Medical Training, Remote Consultation and Image Guided Surgery[2].

The introduction of Mixed Reality to Image Guided Surgery suggests a major step forward for medical imaging; not only can it provide the user with detailed and accurate 3D anatomical images but it can also be used for the tracking of surgical instrumentation across anatomical structures in real-time. Even with the benefits that MR could potentially bring to Image Guided Surgery, its introduction is a process yet to be completed due to the necessity to prove its feasibility in surgical procedures.

1.1. Related Work

In the context of Mixed Reality for Image Guided Surgery one of the most studied topics is the hologram-to-patient registration. This concept refers to the superimposition of holographic elements over anatomical structures; its importance lies in the necessity of achieving precise and accurate registration to provide a proper holographic visualization of both, anatomical structures and surgical instrumentation. Many approaches for a proper hologram-to-patient registration have been developed; in [3] Kuhlemann et. al. focus on the development of a method for the visualization of patient's surface together with the displacement of a of a catheter inside the anatomical structure through the use of a HMD in combination with an Optical Tracking system for the acquisition of fiducial points for the registration process. von Haxthausen et. al. method is another one worth mentioning; in[1] their proposed solution is based on the use of a HMD together with a handheld scanner for the acquisition of surfaces and fiducial markers for the registration process. Even when both proposed methods provide promising results the use of fiducial markers can be replaced in the registration process in order to avoid another source of uncertainty.
Palumbo et. at. developed in [5] a marker free method for hologram-to-patient registration based on the superimposition of holographic models over anatomical structures through the acquisition of point clouds for the registration process. As interesting as the results reported are, the use of an external depth camera is proposed as the next step of the research in order to provide more stable and robust point clouds for the registration process.

2. Materials and Methods

2.1. System workflow and description

The development of a simple, marker free hologram-to-patient registration method is presented. The main structure of the developed method consists of a holographic interface implemented on a Mixed Reality HMD (HoloLens 2, Microsoft, Washington) in combination with an external depth camera (Azure Kinect, Microsoft, Washington); communication between devices is performed using ROS Noetic. The general work principle of the system revolves around the acquisition of point clouds using HoloLens 2 and Azure Kinect depth cameras; a general description of the workflow implemented in the application is depicted in Figure 1.

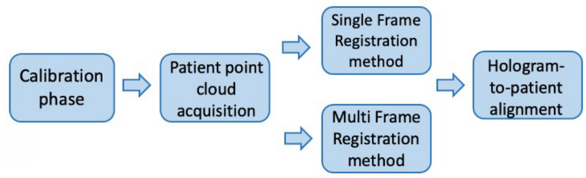

Figure 1: Workflow for the hologram-to-patient registration process. Main steps of the procedure are reported and briefly described here.

A general description of the hologram-to-patient registration is provided below.

1. Calibration phase: Figure 2 provides a graphical representation of the employed calibration procedure. Having two devices operation in different coordinate reference frames a calibration method for the alignment to a common coordinate system is required. Through the acquisition of a point cloud corresponding to a calibration object using both, Azure Kinect and HoloLens 2, and performing a registration process with the CAD model of the mentioned object it is possible to obtain $\mathbf{T}^{\text{AK}}_{\text{CAD}}$ and $\mathbf{T}^{\text{H2}}_{\text{CAD}}$ which allow to position any point in the surface of the object into each of the devices' coordinate reference frame. For the previous mentioned process, a Fast Global registration procedure was used for an initial alignment between point clouds, refinement was performed by means of an ICP registration which produced the final transformation matrixes. The main idea behind calibration procedure consists of the use of correspondence points in the acquired object; knowing the position of these points and transforming them into the coordinate system of HoloLens 2 and Azure Kinect and finding the rototranslation matrix by means of singular value decomposition algorithm which relates both coordinate reference frames through $\mathbf{T}^{\text{H2}}_{\text{AK}}$.

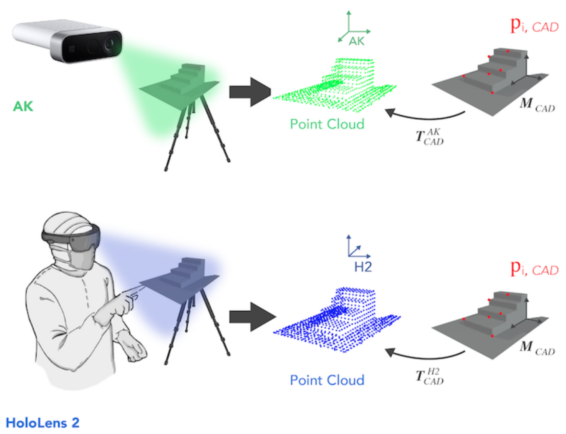

Figure 2: Calibration steps main steps. The acquisition and registration of both point clouds together with the use of known points in the calibration object set the basis for the calculation of the rototranslation matrix.

2. Upon completion of the calibration phase the next step consists of the acquisition of the patient's point cloud using Azure Kinect. For the development of the system, a 3D printed head phantom with its corresponding CT virtual model were employed for this section. Using Azure Kinect, the acquisition of the point cloud of the head phantom is performed; right after this action is completed the registration between the recently acquired Azure Kinect point cloud and the one generated from the virtual CT model is performed by means of the already stated registration method, Fast Global registration followed by an ICP algorithm, which yields $\mathbf{T}_{\mathrm{CT}}^{\mathrm{AK}}$. Figure 3 provides a graphical representation of this process.

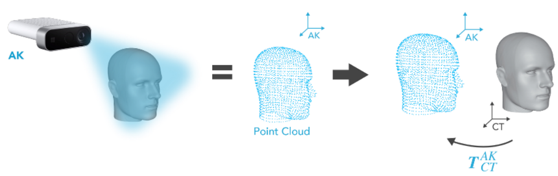

Figure 3: Head phantom point cloud acquisition using Azure Kinect. Through the registration with the point cloud generated from the CT virtual model $\mathbf{T}_{\mathrm{CT}}^{\mathrm{AK}}$ is obtained.

Besides the already mentioned methodology, a second option for the point cloud acquisition of the head phantom is proposed. The method is based on the reconstruction of the surface of the acquired object through the acquisition of various frames from different angles provided by the manual displacement of the Azure Kinect as shown in Figure 4. The aim of this second developed method suggests the theoretical improvement of the registration quality between the virtual model of the head phantom, or any other acquired surface, with the reconstructed surface. The reconstruction process is based on the use of Aruco markers placed around the head phantom, the position of the center of the markers is determined for each acquired frame and through registration all the frames are aligned to a common reference frame for a subsequent superimposition that results in the reconstruction of the object containing all the acquired angles. With the reconstructed surface it is then possible to proceed with the registration procedure with the phantom's virtual model to obtain $\mathbf{T}_{\mathrm{CT}}^{\mathrm{AK}}$.

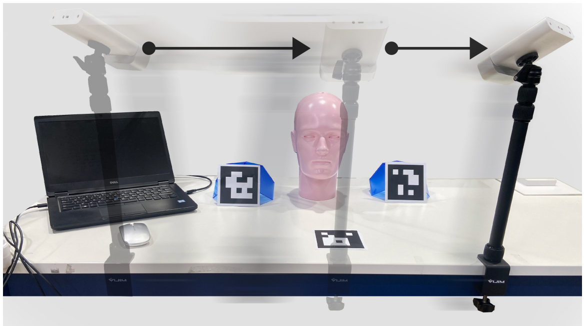

Figure 4: Proposed setup for the acquisition of multiple frames of the head phantom.

3. Final step of the process consists of the hologram-to-patient registration using the transformation matrixes acquired during the process. A simple matrix multiplication between $\mathbf{T}_{\mathrm{CT}}^{\mathrm{AK}}$ and $\mathbf{T}_{\mathrm{AK}}^{\mathrm{H2}}$ can be performed in order to produce $\mathbf{T}_{\mathrm{CT}}^{\mathrm{H2}}$, this final transformation matrix will allow the user to visualize the CT virtual model of the head phantom superimposed over the head phantom, as shown in Figure 5.

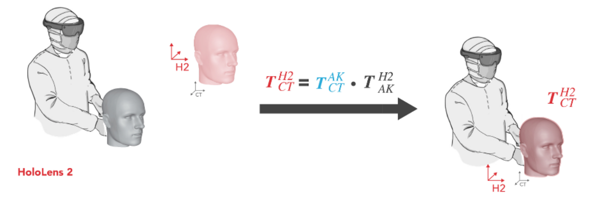

Figure 5: Final step of the process. A matrix multiplication between $\mathbf{T}^{\mathrm{AK}}_{\mathrm{CT}}$ and $\mathbf{T}^{\mathrm{H2}}_{\mathrm{AK}}$ yields $\mathbf{T}^{\mathrm{H2}}_{\mathrm{CT}}$ which allows the achievement of the hologram-to-patient registration.

2.2. Registration Accuracy Assessment

In order to evaluate the hologram-to-patient registration accuracy an experimental setup was developed. An Optical Tracking system(NDI Polaris Vicra) with a trackable probe was used. The concept behind the design of this setup consisted of the use of six fiducial markers located in representative positions of the head phantom; in order to perform a comparison of the accuracy of the hologram superimposition the six points were acquired using the Optical Tracking system by placing the trackable probe in each one of the positions while, for the virtual position of the markers, a virtual sphere was placed on each on the positions so the position could be saved after successful registration. Figure 6 provides a practical example of this procedure.

Figure 6: Experimental setup proposed for the second part of the registration accuracy assessment.

The alignment between the coordinate reference frames of the Optical Tracking system and HoloLens 2 was achieved by using a QR code; the position of the left upper corner of the code was acquired four times in different positions using the trackable probe and HoloLens 2. Upon acquisition of the positions the two sets of points, one for Optical Tracking System and one for HoloLens 2, underwent singular value decomposition algorithm in order to obtain the roto-translation matrix $\mathbf{T}^{\mathrm{H2}}_{\mathrm{OT}}$, which relates both coordinate reference frames and allows the alignment of any point acquired using the Optical Tracking System to HoloLens 2 coordinate system.

2.3. Offset Correction

Due to the intrinsic inaccuracies of HoloLens 2, the superimposition of holograms on real world objects can present an offset in the positioning during the visualization through the HMD. The proposed solution for this issue is based on the development of a correction algorithm which minimizes the difference between the fiducial points position between the holographic scene and its position in the real world. Through the use of the orientation of HoloLens 2 depth camera in combination with a correction factor the algorithm performed a correction in the x, y and z position of the fiducial markers in order to reduce the error between real and virtual world; the correction was performed based on an iterative scheme which gradually reduced the error between corresponding points. The stopping criteria established that the correction was not effective anymore after the error between points increased with respect to the previous iteration.

3. Results and Discussion

Eleven tests were performed to test the precision and accuracy of the developed methods for a total of 22 trials. The results for the testing of each method are presented in this section.

3.1. Single Frame Registration

After the evaluation of the registration accuracy, results are shown in Figure 1. Blue boxes represent the obtained distance differences for each one of the selected fiducial markers between its virtual and physical position in the head phantom; for the six markers, a mean distance of 8.34±0.73mm was calculated. The green boxes in the plot make reference to the achieved distance after offset correction, it is possible to see that the correction not only decreases the distances between corresponding points but also manages to mitigate the dispersion between them; the mean average distance across the six markers in this case is 3.85±0.19mm.

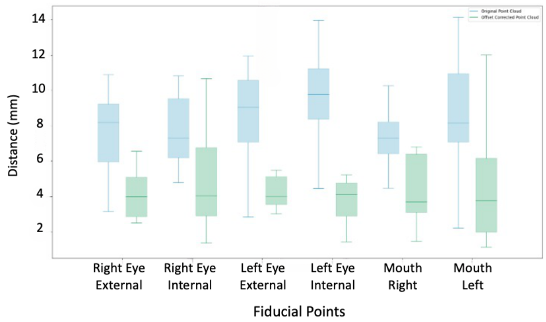

Figure 7: Distance error across the positions of the six fiducial markers in the virtual scene and the real world for Single Frame registration. Blue boxes correspond error before offset correction, green boxes the error post offset correction.

The performance of the offset correction algorithm is also reported in this section. Illustrated in Figure 8, the general tendency indicates that the majority of the corrections applied stopped after 15 iterations for a total correction of 7.5mm. The distance shown in the y-axis refers to the mean distance difference between the hologram representation of the head phantom and the model used in the real world across the 6 fiducial points.

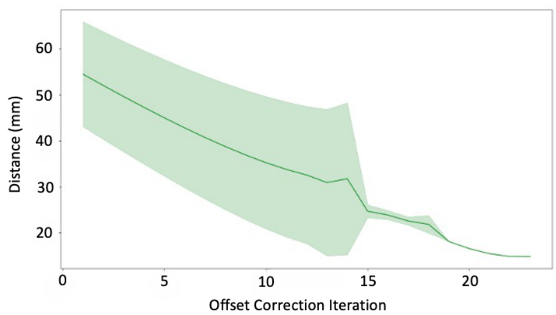

Figure 8: Single Frame registration offset correction. Distance error is reduced through each iteration.

3.2. Multi Frame Registration

Results corresponding to the performance of the Multi Frame registration method are presented in the section.

Figure 9 shows the achieved distance difference for the fiducial points in the virtual scene with it corresponding pairs in the head phantom. Once again, blue boxes show the distances before the offset correction; the increase with respect to the Single Frame registration is evident, a mean of 9.83±1.04mm across the six markers was obtained; these results suggests a worse performance in regards to the hologram-to-patient registration. The first apparent reason could in fact be the quality of the achieved reconstruction since the displacement of the Azure Kinect was performed in a manual and unstable manner. After offset correction the registered mean was equal to 7.15±0.87mm.

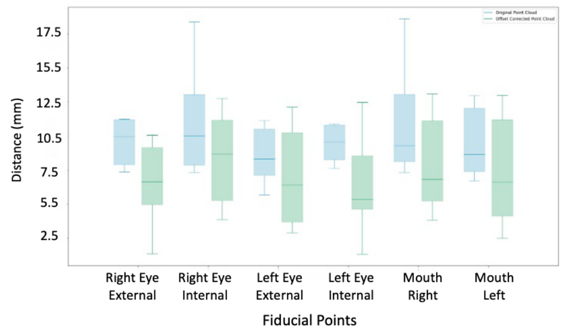

Figure 9: Distance error across the positions of the six fiducial markers in the virtual scene and the real world for Multi Frame registration. Blue boxes correspond error before offset correction, green boxes the error post offset correction.

As for the offset correction performance, Figure 10 shows that the number of iterations before meeting the stopping criteria revolved around 13 iterations, which would suggest an average correction of 6.5mm. Nevertheless, the issue with this method responds to the fact that the initial alignment provided a large difference between corresponding fiducial points, therefore, even when the offset correction was applied the distanced remained significantly large.

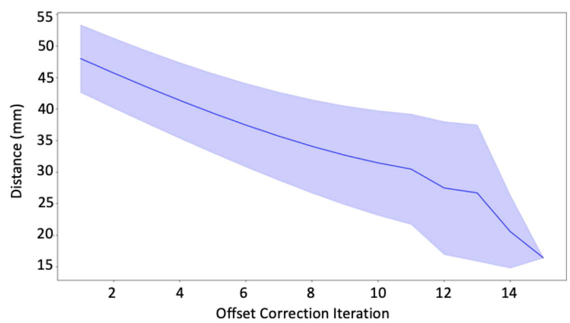

Figure 10: Multi Frame registration offset correction. Distance error is reduced through each iteration.

4. Conclusions

Two methods for a simple and marker free hologram-to-patient registration method have been presented. As interesting as the results presented are, the Single Frame registration method presents a better accuracy when compared to the Multi Frame registration method; the hypothesis referring to an improvement of the registration quality can be them rejected not without mentioning that many factors can be still improved for this method, starting from the manual displacement of the Azure Kinect and the use of a more robust setup for the positioning of the Aruco markers.

Nevertheless, the presented Single Frame registration method shows promising results towards laying the groundwork for the development of hologram-to-patient registration techniques which can be implemented in real case scenarios. Future work should now focus on the correction of the offset for HoloLens 2 in real-time since it would massively improve the quality of the hologram superimposition. In regards to the Multi Frame registration method, the improvement in the reconstruction process could deem it as a useful solution not only for this case, but also for working will larger anatomical surfaces.

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