Biomechanical Modeling And Pre-Operative Projection Of A Human Organ Using An Augmented Reality Technique During Open Hepatic Surgery

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***Abstract*— Augmented Reality (AR) technology offers innovative ways in order to visualize and manipulate a 3D model of an object by superimposing computer-generated images onto another object interactively. The ability to interact with digital and spatial information in real-time offers new opportunities to manipulate and process medical data easily and efficiently. During surgical interventions, surgeons face various challenges dealing with digital patient data. Several methods are used to visualize the operative areas, such as fluoroscopy and ultrasound techniques. These techniques have several limitations. Thus, the augmented reality technique could serve as a better alternative to project a three-dimensional model of the target organ into the surgeon's perspective and field of view to improve the accuracy and efficiency of the medical intervention intraoperatively. In this paper, a new AR method is proposed in order to visualize and simulate the biomechanical model of the liver organ during open hepatic surgery. In this regard, the 3D model based on the patient's preoperative CT scans is first reconstructed. Then, the reconstructed model is projected using the AR headset. After that, the biomechanical model is generated and prepared for the simulation. The proposed approach is validated using acquired CT scans of the human organ.**

Keywords— Augmented Reality, 3D modeling, Medical intervention, open hepatic surgery, Biomechanical model, CT scans, human organ.

I. Introduction

According to the World Health Organization (WHO)[1], more than 325 million people worldwide suffer from a hepatitis infection, which is a liver disease that can cause serious infections leading to fatal health problems. The increasing death rate due to liver diseases led medical experts and the research community to find potential and effective solutions to reduce this number. The technological advancement led to the emergence of a new surgical technique such as the Minimally Invasive Surgery (MIS). This technique involves the use of an endoscope, a thin tube attached with a camera inserted into natural openings of the body. Although this technique reduces the risk of infection and offers a faster recovery time, it comes with various limits that can hinder the surgical process. It usually requires steep learning curves due to the highly offered advanced technological features. In addition, the used instruments have a limited range of motion, which produces poor visual feedback on the monitor. In order to establish better observations, the research community investigates the use of the Augmented Reality technology during open surgery offering a wider field of view of the subject organ and direct interaction compared to other techniques.

In fact, AR offers wider and global visual feedback and provides crucial surgical information, by improving the accuracy and efficiency of the surgical intervention. This work focuses on the implementation of an AR technology that guides surgeons during the intraoperative intervention in open surgery. The generation of a biomechanical model corresponding to the liver organ, as well as its simulation using AR technology, remains a challenging task.

This paper is organized as follows: In the second section, previous works and approaches have been analyzed and discussed. Then, the developed algorithm to generate the biomechanical model is detailed and the original approach to simulate the biomechanical model using Meta 2 AR headset is described. Conclusion and perspectives are presented at the end.

II. State of the Art

In the last decades, technological advancement in the medical field led to the emergence of new techniques such as Minimally Invasive surgery (MIS), which helps surgeons to manipulate organs in a direct way using specialized instruments. This technique help researchers to investigate new possibilities to implement new technologies such as Augmented Reality (AR) in operations rooms. Multiple researchers investigated the usage of this technology during surgical procedures and its application in the medical field in general. AR offers wider and global visual feedback and provides crucial surgical information, thus improving the accuracy and efficiency of the surgical intervention.

One of the first image-guided surgery implementations has been performed by Rasssweiler and. al [2]. Their approach evaluates the feasibility of a mobile computer-assisted Percutaneous Nephrolithotomy (PCNL). The iPad-based system uses a tracking server for image processing and a tablet

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to record the captured images, which were transferred back and forth with the server via Wi-Fi. The system proved its capability in assisting PCNL interventions through its intuitive navigation process, which solved various limitations encountered when using ultrasound and fluoroscopy techniques. In a conducted experiment, the proposed system proved its efficiency by accelerating the procedure by 20% compared to fluoroscopy. Although, this approach provided solid results, a lack of guidance information was noticed and the absence of a real depth view led to difficulties in reaching the target areas in multiple cases, which explains the high radiation exposure compared to the ultrasound technique. Besides that, the proposed framework was tested on a prepared gelatin mixture, which is not distinguishable from kidney tissues.

In the case of liver organ surgery, one of the challenging tasks encountered during the minimally invasive surgery was the partial surface view captured by the laparoscopic camera, which limits access to internal structures such as tumors and vessels. To overcome this problem, Plantefévet and al. [3] proposed an interesting approach based on non-rigid registration of preoperative and intraoperative data. The collected pre-operative data is used to reconstruct a biomechanical method that describes the behavior of the deformable organ. The registration process employed a three-dimensional point cloud generated from stereo-endoscopic camera-view. This method involves a semi-automatic liver segmentation and automatic generation of the behavior model. For evaluate their approach, the authors used two sets of data corresponding to a healthy and cirrhotic liver, registration results demonstrated good accuracy by obtaining a mean error below 3 mm in almost cases. Despite the efficiency and the robustness of the system, the usage of a high number of parameters might complicate the registration process and cause latency in the overall pipeline. In addition, the better depth perception of the internal vascular network could improve the visualization of the superimposed images.

Among different registration methods, biomechanically based registration seems to be the method of choice since it can handle large organ deformations [4]. Therefore, a precise biomechanical model is essential to perform an efficient registration. In [5], Planteféve and al. investigate the impact of implementing a homogenous model as an input for the registration method proposed in [3], instead of a heterogeneous liver model which is composed of three parts: the parenchyma, Glisson's capsule, and the internal vascular network, they tested the usage of the homogenous model which is composed only of the parenchyma. The results show that using the heterogenous model does not improve the registration process but increases the computational time. Thus, for a better simulation, authors recommend using a homogenous model which less complicated but more effective. For such hyper-elastic organ, the liver usually undergoes a large elastic deformation due to pneumoperitoneum [6] (CO2 gas insufflation) which can be challenging for an automatic initial alignment. In [7], Haouchine et al. address this problem by proposing a method for estimating simultaneously the elastic transformation of the liver and the transformation of the endoscopic camera. It involves automatic detecting of target area boundaries by segmenting the intra-operative 3D point cloud, which serves to generate the pneumoperitoneum model. Conducted experiment on real in-vivo data of human hepatic surgery and synthetic data proved the efficiency of the approach by obtained lower mean errors compared to related works and relatively lower computational time which make it efficient and practical during surgical operations. As far as the validation process goes, a revision of the patient-specific parameters could be addressed to improve the estimation process.

In the context of intraoperative image tracking, a marker-based solution is still the choice of many researchers. Adagolodjo and. al [8] presented a registration approach using the real-time tracking system based on tracking markers captured in real-time by infrared cameras.

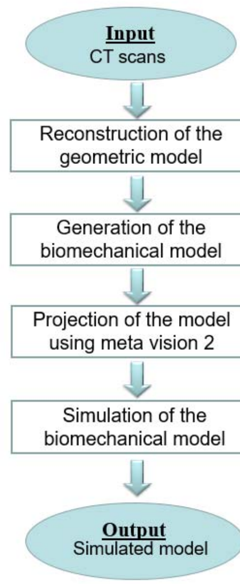

Fig. 1. Flowchart of the proposed approach.

Manual intervention was needed to place the landmarks intraoperatively. The method involves a tracking system that relies on a Finite Element Model (FEM), which is driven by the displacement of a set of markers tracked by the infrared cameras. In order to compute a consistent coordinate system frame between monocular and infrared cameras, the Perspective-n-Point problem is solved by providing the projection matrix M that maps 3D points to 2D image coordinates. During intraoperative tracking, a significant deformation is observed due to the mobilization of the organ, which led to the exploit of a modified ICP method to determine correspondences between tracked markers and the deformable model. To validate the results of this approach, a biomechanical model composed of 1900 tetrahedral elements has been generated from the preoperative CT and 7 markers of 0.5 mm of diameter have been sutured on the liver of the patient randomly around the area of the tumor. The tracking method provided convincing registration results for large deformations and occlusions when the organ is subject to modifications by the surgeon. Despite the robustness of the system, manual intervention by the medical surgeon is performed in order to segment visible contours of the organs, which halt the registration process and the overall procedure in general. In the literature, most of the registration methods rely on tracking markers to identify the target area. Golse et al. [9] proposed a markerless non-rigid approach using preoperative 3D scan segmentations integrating a physics-based elastic model of the liver. The deformations computations are solved using tetrahedral FEM models applying hard constraints such as collision models, gravity, and rest shape constraints. The registration process is based on the RGB-D data that provides color images and a 3D point cloud of the real scene. A mounted camera positioned above the operation table captures the intraoperative data. In-vivo experiments were performed on four patients, the generated models were correctly superimposed with the organs. The visualization pipeline appeared acceptable since the computation time was relatively low, with a frequency of 15 Hz, ensuring a smooth AR visualization. According to the authors, such a technique could not be used under laparoscopy due to the limited percentage of visible surface area, which could prevent ideal registration. However, the AR technologies used are limited and not practical during the simulation of a hyper-elastic organ like the liver.

In this paper, a new approach based on the AR headset (Meta 2) is proposed to simulate and manipulate the reconstructed biochemical model of the liver from CT scan images.

III. Proposed Approach

The need to design 3D models of real objects is always present [10], with more detail and good accuracy. In general, these models can be designed using two methods. The first method is based on the modeling of the object according to a specification, using the design functions within the design software (CAD). Its disadvantage lies in the difficulty of obtaining the desired model without resorting to modification and adjustment phases to meet the imposed geometric and functional constraints, which leads to very long processing times. The second method is based on the reconstruction of a model from a 3D scan or 2D images. This method is used in cases where the objects are specific and cannot be designed within a CAD software. This approach has become a very common practice today, as it reduce the design time of customized models, especially in the medical field. With the increasing use of AR in the medical field, the generation of 3D models of human organs is very important. This operation can be done either by a 3D scan of a human part in the case of an external part or by the reconstruction method in the case of an internal organ. The reconstruction of a 3D model of a human organ can be done from CT scan images of a patient acquired using 2D scanners. The computed tomography (CT) scan is the standard imaging technique used as a diagnostic and surveillance tool to determine a patient's body structure and extract characterizations into 2D images. In this work, the Meta 2 headset is used to simulate and manipulate a reconstructed model of the liver organ. Different steps are followed in order to simulate the corresponding biomechanical model. The following figure (Figure 1) presents the steps of the proposed approach. These steps are detailed in the following sections.

A. Reconstruction of the 3D model

The aim of the proposed approach is to simulate and manipulate a specific 3D model of a human organ using AR headset technologies during open surgery. The input data for our simulation are extracted from the patient's pre-operative CT scan images. In this step, the patient's specific 3D model is reconstructed. In this paper, INVESALIUS 3 [11], an open-source software for the reconstruction of computed tomography (CT) and magnetic resonance images (MRI), is used to generate the 3D model from an imported dataset. This software provides manual segmentation tools for the reconstruction of computed tomography images and has the ability to import DICOM or Analyze files, export files to the STL, OBJ, and volume rendering. To generate a 3D model of the liver organ, a 2D CT-scans dataset is used. The dataset is created by the IRCAD research institute [12]. It provides information about different hepatic tumor cases of anonymized patients in DICOM format. In order to generate the 3D customized model, the INVESALIUS libraries are applied to extract specific areas from the provided labeled images to be able to segment and localize the organ in the subject. After the generation of the 3D model, the model is saved as an OBJ file. This exported file will serve to generate a biomechanical model.

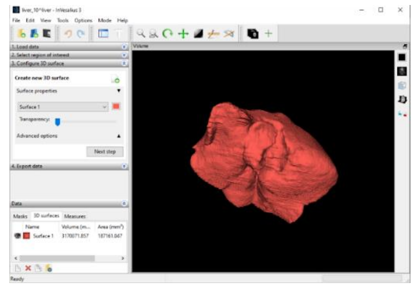

Fig. 2. Reconstructed 3D generic model from 2D CT scans using INVESALIUS 3.

B. Generation of the biomechanical model

In order to manipulate the model of the liver, a collision model should be defined. As the model has a complex geometry nature, a set of convex primitive colliders are created to obtain a global group of convex colliders that fit the exact geometry of the mesh. In order to apply an acceptable deformation, rigid body properties have to be set: the mass, the drag, the gravity parameters, and the collider model properties. The collider will be the subject of any interaction behavior originated from the hand's input position. Applying deformation will result in the recalculation of the biomechanical model geometry, which includes mesh triangles and normal remapping, colliders regeneration and dynamic frequent updates to visualize the deformations. The generated biomechanical model will be projected using Meta 2 headset within Unity game engine.

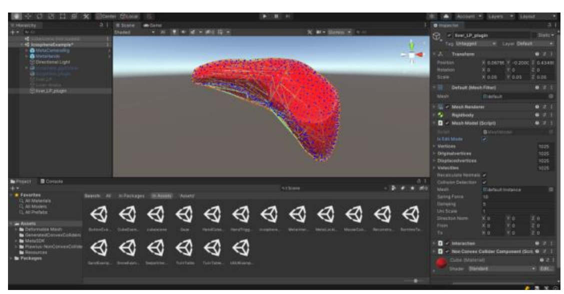

Fig. 3. Biomechanical model geometry preview.

C. Projection of the 3D model using Meta 2 AR Headset

he proposed approach is developed within the Unity environment. Unity is a cross-platform (Windows, Android, IOS, Mac, Game Consoles, and web) game engine developed by Unity Technologies. It is one of the most used engines within the industry (cinema, architecture, engineering…) due to the harmonic interface, accessibility, and fast rendering of complex scenes. The used language for developing within Unity is C#. It is an Object-Oriented Programming Language (OOP), simple, modern, and secure. Many of the C# functionalities contribute to the creation of a robust and reliable application. The Unity Engine was targeted as the main tool for testing and running the application using the Meta2 AR headset.

The Augmented Reality headset is composed of a sensor array that makes positional tracking possible to see, grab and move holograms just like physical objects. Meta 2 provides a new kind of operating environment where personalized holographic objects could be arranged. This AR headset offers various capabilities: the wide field of view (of 90 degrees) delivers efficient AR use and facilitates collaboration, design, and creation of personalized AR models. Along with a 2.5K resolution and 60Hz refresh rate which delivers a comfortable and immersive augmented view, it also offers the most intuitive support of direct hand interactions and engagements. Overcoming the limits of many other AR technologies that require specific hand input and gestures. The Meta2 headset package delivers an SDK that gives various tools to develop Augmented Reality applications within Unity, with its latest SDK version 2.7.0.38. As part of the proposed methodology, this Meta2 SDK was imported within the Unity environment to incorporate specific scripts in the scene to run applications with the AR Meta2 headset. The main SDK components are described in the table below.

TABLE I. META2 SDK BUILD-IN COMPONENTS AND FEATURES

Component	Description
MetaCameraRig prefab	A set of graphical components that allow the integration and linking of Meta features with Unity-developed applications.
SLAM	Meta's tracking system - Simultaneous Localization and Mapping.
Sensors Data	Provide access to raw data from the Meta 2's onboard sensors to do any sort of advanced scripting
Meta Gaze	An interaction technique that gives the possibility to interact with objects in the center of the view.
Meta Hands prefab	A system that allows users to add a variety of hands interaction features to objects within the scene (such as GrabInteration, GrabScale, GrabRotate ...) and implement custom interactions.
Meta 2 Webcam	A virtual device that exposes two feeds, one is a composite view containing both AR content from the Unity scene and the RGB camera feed simulating what the user is seeing, while the other shows just what the RGB camera sees.
Surface Reconstruction	A feature that defines the surrounding surface environment and its reconstruction as a model.

D. Simulation of the biomechanical model

In order to simulate the biomechanical model using the Meta2 SDK within Unity, the main scene should include the key components such as: the MetaCameraRig and MetaHands to access various Meta interfaces, events, and data that locate the active hand's positions, environment calibration, RGB camera, and sensors that define rules of projection of the objects in the scene onto the Meta field of view.

Also, the biomechanical model of the liver organ is present in the scene alongside the developed interaction deformation script to deform according to hands input gestures.

In this section, the different steps followed in order to simulate the biomechanical model are detailed:

1. Generation and recalculation of the group of convex Mesh Colliders from the visual mesh vertices, the colliders represent the surface of the mesh by adding physical properties such as gravity and the object's mass for realistic physical interaction.
2. Meta interaction using the "Deform method" which first computes the deformation direction normal from the Meta hand world position and the raycast hit onto the visual mesh. Then, this method calculates the list of affected vertices and their next velocity values. Thus, the final positions of displaced vertices are obtained at the end of the simulated action.
3. Simulation of the model using the method "Fixedupdate": This method computes the next velocity value for each affected vertex, which is dependent on different properties (model scale, mass, physics time step, spring force, damping resistance value, which decreases over time.
   In this step, a condition should be verified in order to update the interactive model (the biomechanical model) during the simulation: if the velocity values are not null (there is an interaction with the model), the displaced vertices should be set, the mesh is updated, and its corresponding normal should be recalculated.

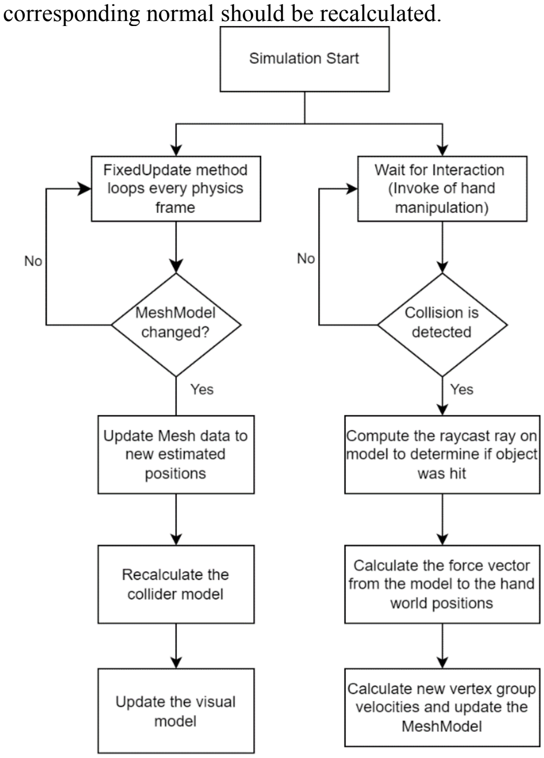

Fig. 4. The proposed Algorithm Flowchart

IV. RESULTS AND DISCUSSION

The proposed approach is developed within Unity using the Meta2 AR headset. Once the simulation starts, the headset is launched and the environment calibration begins. The 3D model appears at the center of the field of view and can be intractable the moment a collision contact point between the projected model and the hand's input is detected (and visualized) in world space.

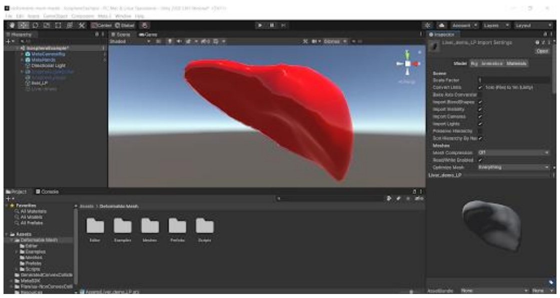

Fig. 5. Biomechanical Model settings.

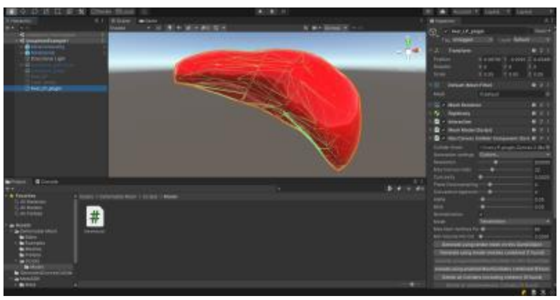

Fig. 6. Generation of the global Convex Collision Model.

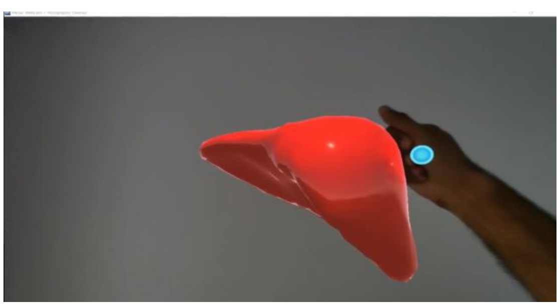

Fig. 7. Simulation of the Biomechanical Model within the Meta2 AR headset.

In the first couple of experiments, the deformation was not smooth due to the latency between the visual touch and the scripted interaction, resulting in undesired deformable behavior. This might be due to inaccurately setting of Springforce parameters and velocity values updates.

During the following tests, the model collider was adjusted to fill the needs with having multiple convex colliders that update faster and more accurately during the simulation runtime. This allowed the interaction with the model volume to be more precise. Furthermore, the estimated group of vertices to deform, given a calculated velocity that attenuates overtime, were executed in the FixedUpdate method, that constantly evaluate a newer displaced position until the velocities values approximately nullify, which marks the end of the deform action that originated from the hand interaction.

V. CONCLUSION

In this paper, a new Augmented Reality (AR) approach is proposed in order to simulate the reconstructed model of the human liver organ. Given a set of the patient's pre-operative CT scan images, the 3D model is reconstructed using the INVESALIUS 3 tool. A new methodology is established to generate and manipulate the biomechanical model. In this regard, the properties of this model are defined, and the algorithms are developed within the Unity environment. The results offered by the proposed approach are convenient, representing an efficient tool to help doctors during open hepatic surgery. The current state of affairs in this research field and the works so far seem very promising and may serve as an impulse for abundant discussions in research and medical field. Nevertheless, the accuracy of the simulation depends on the number and density of mesh colliders representing the surface of the biomechanical model. Thus, the future works will be focused mainly on the development of improved algorithms to manipulate the generated biomechanical model.

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