

3D Stereo-lithographic models placed in Virtual Reality to assist in pre-operative planning

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ABSTRACT

Congenital heart disease¹ is the most common congenital abnormality affecting 8 per 1000 children. Children with univentricular circulation undergo three staged procedures, the last of which is a Fontan procedure. In some children, the anatomical arrangement makes completion of the Fontan procedure highly complicated, and in some cases not possible, which may imply a serious morbidity or mortality for the child. Currently, echocardiography (ECG), cardiac magnetic resonance imaging (MRI) and computed tomography are used to define the preoperative cardiac anatomy. Five 3Dprinted hearts are already developed for Crumlin Hospital to assess the utility of preoperative 3D printing in assessment of patient suitability for Fontan procedure. The project described in this paper involves the development of 3D stereolithographic models of complex cardiac defects and place them in a VR headset for a medical team to be able to rehearse the surgical procedure.

CCS CONCEPTS

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• **Software and its engineering** → Virtual worlds training simulations • *Computing methodologies* → 3D imaging

KEYWORDS

Virtual Reality, Augmented Reality, 3D modelling

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1 INTRODUCTION

According to the Irish Heart Foundation, every year about 500 to 600 babies are born in Ireland with a congenital heart defect. Although scientists have been researching for many years to find its causes, which lead to finding some factors that explain its development such as viral infection, German measles, heredity or conditions that interfere with multiple organs (e.g. Downs' syndrome), for the majority of the cases the causes are still unknown. Children with a congenital heart defect will have to endure at least one surgery, if not a sequence of surgeries, to increase their chance of living a relatively normal life. At this stage in their life, even a small surgery by itself is life threatening. For this reason, it is extremely important to do preoperative planning to prevent no unexpected problems during surgery.

The development and advances in medical image registration facilitate the diagnosis and/or the monitoring of heart diseases or defects but this alone is not enough. For years, 3D modelling has increasingly become the focus of many research papers, journals and articles due to its broad applicability in different areas of medicine. It has proven to be

extremely important not only as a tool for diagnosis, therapy and planning of invasive procedures, but also for educational purpose.

The quality of the images obtained using different modalities such as magnetic resonance imaging (MRI), computed tomography (CT) and echocardiography provide enough information to achieve a model that presents the heart structure in detail. This facilitates the understanding of heart disease or defect without the need of taking the patient with a complex structural problem [1] into a “discovery” surgery and prevents discovering another problem in the patient’s heart during a procedure, which may cost the patient’s life. Especially when dealing with children’s hearts, it makes all the difference if all information about the structure of the defect can be acquired before the procedure. Once the heart model is created, it can also be 3D printed, as the resulting generated file can be imported into the 3D printer. In some cases, having the solid model with detailed internal structure of the heart may also help to reduce the length of the procedure and increase the chances of success. This can be achieved because the surgeon can select the correct equipment to be used during the procedure prior to the surgery [2].

When relating 3D models with education, some research has been carried out about the use of an immersive environment or Virtual Reality (VR) as an educational tool. Nyamse [3] presented the use of an immersive environment as a novel way of teaching undergraduate medicine students about heart anatomy, however, this approach can be used to learn about anatomy of any organ in the human body. The advantage of using this method is that the model can be used by many students, whereas, following the traditional method, which uses cadaveric material, once a group of student have finished the dissection of the parts, it cannot be reused. This method has also proven to motivate the students to learn actively as they can interact with the model and focus on a determinate area of the heart.

The models placed into Virtual Reality can be used not only as educational tools but also to support preoperative planning, as presented by Itagaki [4] and Valverde et al. [5]. In both cases, patient specific models were generated prior to performing the surgery to make decisions about the appropriate technique to be used in the procedure.

This paper is organized as follows: Section 2 - provides an overview of related work and a brief explanation of the main algorithms used for the generation of the 3D model; Section 3 - presents the implementation of the project; Section 4 - model and software evaluation and section 5 - overall conclusion of the work undertaken.

2 BACKGROUND RESEARCH

The understanding of the anatomical structure of the human body has been a priority in medicine since its beginning. This knowledge was mainly transmitted through 2D images in books or notes and dissection of cadavers.

However, due to shortages of cadaveric material and ethical problems in this practice, some institutions are seeking for an alternative approach to impart this knowledge to their students and motivate their interest in learning. There are many articles, journals and conference papers related to 3D modelling that are being used in medical research to provide a better understanding of different body structures and to create a training tool for new surgeons to learn procedures before perform them on live patients.

Sorensen et al [6] created a 3D model using magnetic resonance imaging (MRI) data. They made use of two contour approaches to obtain the edges, which formed the boundary of the heart; the Balloons approach was used to roughly obtain the boundary and the result from that model was used to initialize the Snake approach, which refined the contour. To achieve a smooth surface, the Minimal Weight Triangulation was used but a punishment was applied to triangles if all its vertices were found in the same contour. After creating the model, it was placed into an immersive environment (Holobench – Tan, Germany) with shutter glasses (Crystal Eyes, SteroGraphics, California, USA) and a tracking device (head sensor and pencil-shaped tracking devices with buttons) called Polhemus Fastrak (Polhemus, Vermont, USA). At that time, computerized tomography (CT) was being introduced.

Nyamse et al [3] presented the use of an immersive environment as a tool to provide a novel way of teaching undergraduate medicine students about heart anatomy. It was also shown that the virtual reality can be used to increase patients’ understanding of their condition or awareness about risk factors. They opted for a more simplistic interface that could be adjusted according to the audience, for example, if the virtual model is being used by medicine students there should be more options and more information.

Costello et al. [7] presented a small trial of the utilization of 3D printing as a tool for simulation-based education for premedical and medical students. It focused on the congenital heart diseases (CHD) and ventricular septal defects (VSDs). Utilizing the 3D printing technology, they printed samples from the most common VSDs (infundibular, membranous, inlet, muscular and atrioventricular). The data utilized for the modelling was from de-identified magnetic resonance imaging (MRI), which was provided by the Children’s National Health System.

Ringenberg et al. [8] presented the use of coarsely-sliced short-axis images to create a patient-specific cardiac 3D image. The data used as reference was a high-resolution diffusion tensor MRI (DTMRI) from hearts of ex vivo male canine subjects. They used canine hearts due to the difficulty of obtaining ex vivo human hearts, as in the majority of cases, ex vivo human hearts are used for transplants, and therefore rarely available.

Schlichting et al. [9] presented the 3D modelling of the pericardium using images from CT scan with sections of 1.2

mm. These images consisted of 147 sequential sections from diaphragm to common carotid division. The CT Viewer was used only to anonymize and select the images that would be used in the next step of the modelling. After selecting the images, the Blender software was used to delimit the outer surface of the heart and its large vessels. The approach taken by the researchers was to manually detect the external edges of the myocardium and then using a feature of Blender to project points from one slice to the next one - this feature also adjusts the number of points passed to the next slice to generate the boundaries. Another feature of Blender, Solidify Modifier, was then used to adjust the blood vessels wall thickness.

Pavarino et al. [10] provided the development of a solid 3D model of a heart using data obtained in echocardiography. The researchers used the Finite Element Method, which consists of the use of geometric shapes to break down an object into smaller parts to be able to obtain more accurate 3D representation of the object, to generate the mesh. One of the most commonly used algorithms from this method is the Delaunay algorithm, due to its efficiency.

Itagaki [4] presented in this article the 3D modelling and printing of a full-size hollow lumen of an artery and a solid luminal model to assist the pre-operative planning of multiple asymptomatic splenic artery aneurysms. The data used was provided by a CT scan with slice thickness of 1.5mm. To create the surface model, the axial images from the CT angiographic scan were loaded into Osirix and a basic threshold segmentation algorithm was applied. Having the STL generated, this file was then imported into Blender to manually correct errors in the mesh (duplicated vertices, non-manifold edges). For the hollow model, the researcher expanded the external boundaries of the solid model and subtracted the volume of the hollow model using the solidify feature of Blender. Having both files, internet based 3D printer companies were used to print the models, the solid model using nylon and the hollow model using transparent resin to enable visualisation during the planning of the surgery procedure.

Valverde et al. [5] described the process of using 3D cardiac model for pre-operative planning for children. Similarly to many other papers, the focus was the resulting model being used to choose the best approach for the surgery. What made this article interesting is the software used for the creation of the 3D model. Ayra is a software developed to generate finite element meshes (using the marching cube algorithm) or rapid prototyping (STL file). The 2D data collected from CT, MRI or PET (DICOM file) can be imported directly to the program to create the desired file (mesh or STL). This software can also be used to plan or simulate surgery procedures, where the object being analysed can be moved or rotated to change the angle.

There are many algorithms used for the generation of the mesh in the literature related to 3D modelling such as Minimal

Weight Triangulation, Variational Implicit Surfaces, Delaunay and Marching Cubes. Some research has been done on the combination of the Voronoi diagram and Delaunay algorithm to create a smoother surface [11]. Using this method, skinny triangles were avoided, generating a more accurate surface. Although this method presented good results, Marching Cubes is still the most common algorithm used for surface generation due to its robustness and simplicity.

The Marching Cube algorithm takes a divide-and-conquer approach. It consists of generating small cubes covering the whole object to be segmented and checking all the vertices of each cube to determine if one or more of them are inside or outside the object. Once the verification of the vertices of a cube is done, the result is matched to a lookup table containing all the possible cases to generate the surface. Originally, the Marching Cubes algorithm has a lookup table containing 2^8 possible cases, however, if operations such as rotation and mirroring are taking into account, the number of unique cases reduce to 15. Another important point that needs to be mentioned is about the cube size, the smaller the cube, the more detail can be captured by the algorithm, but the more computationally expensive it is.

A lot of research has been carried out to improve Marching Cubes. For example, Raman et al (2008) extended the lookup table to 3^8 based on tree possible labels (“+”, “-”, “=”) and Feltell et al [12] added a level set method to correct deformities resulting from Marching Cubes and the use of two lookup tables, one the same as the Marching Cube, and the other recording information about how vertices should be linked together.

3 IMPLEMENTATION

For the implementation phase of the project, the Unity Professional version was the main software used to integrate all the required components. The implementation process was divided into four stages: Stage 1: Augmented Reality (AR) into Unity; Stage 2: Virtual Reality (VR) into Unity; Stage 3: Model interaction using Razer Hydra Controller in Unity; Stage 4: Integration of the components.

3.1 AR into Unity

The integration of AR into Unity was achieved by the use of ARToolKit. Once the plugin was imported into Unity, a folder containing sample scenes, resources, materials and scripts was added to the project. These scripts are provided to create and initialize the AR, set the origin, perform pattern recognition, track the marker and the object in AR, get positioning of the real-world camera and a few other functions. The 3D model is scaled and rotated to fit into the scene or to appear in the real-world camera stream. Configurations need to be done prior to running the scene, such as choosing the pattern to match the one that was printed on paper, and checking if all the children of the “Marker Scene” are placed into the “AR background” layer in

Unity. Only the real-world camera shows the objects placed into the “AR background”. The result of this process can be seen in Figure 1, where the model appears on the top of the printed marker placed on the table.

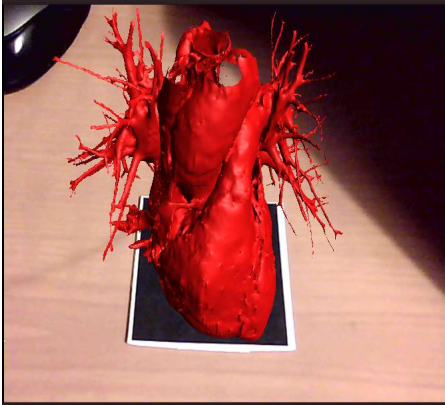


Figure 1: Heart model placed into AR using ARToolkit plugin for Unity

When loading the 3D model into Unity, it was noted that, due to the size of the mesh, it was automatically divided into 15 parts. This happened for the reason that Unity restricts mesh sizes to a maximum size of 65535 vertices. For the AR and VR this does not create any problems, however, for the implementation of stage 3, it can be an issue. This problem was addressed in stage 3, because the model still needed to be divided into selectable parts.

3.2 VR into Unity

To be able to run VR from a computer, the Oculus SDK needed to be installed and configured. If the demo scene in the Oculus Configuration Utility window can be run, the computer is ready and the Oculus Utilities plugin can be imported into Unity. Similarly to ARToolkit, a folder is generated containing sample scenes, prefabs and scripts. The prefabs available are really useful when starting development for the Oculus because they provide a basic configuration for player controller, camera and boundary tracking. Having the set up ready, a new scene was created in the project to create the virtual environment, but without the camera object. Before placing the model into the scene, a room was created using primitive shapes and the component mesh colliders were added to all the walls of the room. The model was then imported into the scene and placed in a desired position. Using the prefab for game controller, it only needs to be placed into the scene and it is ready to run. During the implementation of the VR using the DK1, many challenges were faced due to known bugs and plugins incompatibility

with this version of the Oculus Rift. Some plugins are having issues even with DK2 with the fixing patch coming in their next version.

3.3 Model Interaction

The integration of the Razer Hydra Controller into Unity is achieved by importing the Sixsense plugin in Unity. Once all the necessary files are imported, a folder containing examples, prefabs and scripts is added into the project and it can be used to provide interaction with the model. However, for the completion of this part, the model needed to be divided into parts that can be selected by the razer hydra controller. To reduce the number of vertices of the mesh, instead of using sampling or mesh simplification, the method selected was the Quadric Edge Collapse Decimation. This method provides options to preserve the boundaries of the mesh and topology, and also to obtain the best optimal position of the simplified vertices. As the accuracy of the mesh was not the focus for the remaining of the project, the initial target number of faces selected were 250,000. This value is almost half of the number in the original mesh (485,494).

The next step was dividing the mesh into sections that could be selected using the Razer Hydra Controller. Three software were tested to try to obtain a more realistic division of the model of the heart, namely Blender, Netfabb and Autodesk Meshmixer. Blender (open source) and Netfabb (free version) were able to only perform plane cuts, which cuts the model only into straight lines in any direction. The best result was obtained using Autodesk Meshmixer. Meshmixer is open source software for 3D printing which is available for Windows, OS X and Linux. It provides features such as re-meshing the model, creating face groups, performing plane cuts and smoothing, to name a few. Once the mesh was loaded into Meshmixer, the first step was to re-mesh the model to generate a better triangulation and facilitate the selection of the parts as shown in Figure 2.

Having the model divided into parts, the next step was to load the parts into a Unity scene. As there were 5 parts, an empty game object needed to be created to add the parts as children of this parent object. When the parts are added as children, it automatically assembles the original shape of the heart due to the positions they were saved in Meshmixer.

For the integration of the razer hydra controller, a new scene with a room was created and the hands prefab from Sixsense was added to the scene. To add the model into the scene, as it was divided into parts, an empty game object was then created to hold all the parts of the heart. When adding the mesh collider for each part, another limitation of Unity was found. Mesh collider can only be added to object with less than 255 polygons. Some parts of the divided mesh had more than this limit, therefore it was necessary to add more than one collider in those parts and manually edit them to cover the entire region. It is also necessary to create a script to change the colour of the area when collision occurs which can be

added to any game object in the scene. In this case, it was added to the right hand. At this point, it was possible to select specific parts of the heart using the razer hydra controller in Unity.

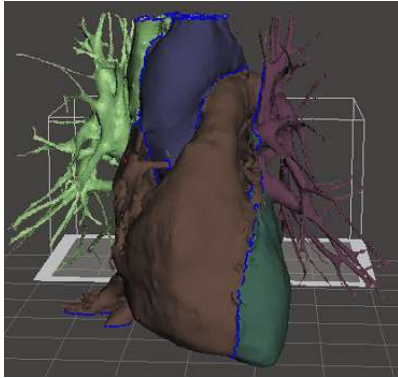


Figure 2: Meshmixer view of the heart model grouped into areas

3.4 Integration of the components

Having finished the implementation of the individual parts, the next phase was to integrate all the stages into one final project. The first step was to integrate the ARToolKit and the Oculus Rift (DK1). As mentioned previously, DK1 does not have positioning tracking. The idea was to use the USB camera position from ARToolKit to move the player in VR. This should be possible by obtaining the transformation matrix of the USB camera and using those values to change the position of the user. This should be achieved by sticking the USB camera in the Oculus Rift DK1. For the development of this phase, the license key for Unity Professional was necessary and it was provided on February 29th. Only then it was possible to start the integration of AR and VR.

To complete this phase, two scripts were created, one to obtain the list of the cameras connected to the desktop and transform the feedback from the camera into a WebCamTexture and the other to obtain the positions of the marker and the camera. When trying to use this WebCamTexture as a background in Unity, it was not possible. It was decided then to create a wall, using a primitive shape, and add the created texture to it. This method worked but the model appeared displaced in the VR. If more time was provided, this problem could be solved. Unfortunately, after many attempts of integrating the VR with the Razer Hydra controller, it was found that there is a drive incompatibility between them. One or the other can interact in Unity, not both.

4 EVALUATION

4.1 Model Evaluation

Building a 3D model of a critical organ such as the heart requires sufficient knowledge of the human anatomy and organ tissue composition. Another important skill that is needed is the ability to read a CT scan and to understand the meaning of the grey-scale on the CT scan. The heart is composed of soft tissues that are not easily differentiated in the grey-scale images from the surrounding tissues.

Having a short time to produce a 3D model of a complex organ and acquiring that base knowledge did not produce an accurate model. The model created is probably lacking some parts that should have been included and including some parts that should have been omitted. This was caused by the manual selection and cleaning of the mesh performed in InVesalius and MeshLab. One with enough knowledge or with the support of an expert on differentiating those subtle differences in grey-scale in the CT scan would be able to obtain a more accurate 3D model.

Another reason for not having an entirely accurate model is the limitations of the software used for the integration of the model into VR; Unity places a restriction on the maximum number of vertices. To allow specific selection of parts of the model, using the razer hydra controller, the number of vertices of the model had to be drastically reduced, as mentioned in section 4.4.3. As result, fewer details were preserved on the model.

4.2 Software Evaluation

4.2.1 InVesalius

Advantages: Open source; User-friendly interface; Provides an option for manual selection and removal of areas from the mask; Provides a simple user guide for using the software.

Disadvantages: Lacks information online for help such as tutorials and forums; Some of the features explained in the user guide are not actually available in the software and the user guide is only available in Portuguese; Occasionally crashes when generating the surface.

4.2.2 MeshLab

Advantages: Open source; User-friendly interface, can be used intuitively; Provides a wide range of algorithms that can be applied to the model. Some of the algorithms show information about the paper from where it was sourced; There is plenty of information available online in the form of documentation, tutorials and forums.

Disadvantages: Does not allow undo operation; Some of the algorithms cause the software to crash, depending on the size of the mesh; Although the version installed was 64-bit, it kept giving an error message saying that the filter only works with a 64-bit version due to memory allocation.

4.2.3 Meshmixer

Advantages: Open source; User-friendly interface and can be used intuitively; Provides a good selection of options for re-

meshing, removing parts of the mesh, closing holes, smoothing, grouping faces, sculpting and a few more; Provides preview of an operation before applying it to a mesh; There is plenty of information available online in the form of documentation, tutorials and forums.

Disadvantages: Quite slow as the preview operation cannot be turned off; Does not generate meshes, just fixes pre-existing ones.

5 DISCUSSION

Patient specific 3D printed models to assist in preoperative planning have shown to be very effective reducing risks during procedures. Placing the model into Virtual Reality, as well as providing the model faster, normally 3D printing of an organ such as the heart takes approximately 8 to 10 hours, allows the model to be reusable. When providing a more precise way of interacting with the model placed in VR, it can also allow the procedure to be simulated.

The project aimed to test the feasibility of using Unity as a tool to perform the integration of AR, VR and motion capture. It was found that, at the actual state of this game engine, there are still a number of restrictions that are imposed for integration. However, with a longer time frame, it may be possible to find workarounds to reduce the impact of some of the restrictions or even remove some of them.

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