Contributions to the visualization process and manipulation of pseudo-holographic images

Teză de doctorat – Rezumat

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The thesis contributes to the development of new medical visualization systems that are based on the latest generation of input and output devices, by introducing new algorithms, models and software components. The presented solutions allow the users to have a gesture based interaction with the rendered three-dimensional models that can be alternatively visualized using a pseudo-holographic display. The thesis provides a comprehensive analysis of the current software and hardware technologies that are most commonly used in 3D pseudo-holographic imaging, which facilitates the starting of new projects by any research groups with interests in this field. Due to the limitations imposed by the browser-oriented architecture of the developed applications, a new segmentation algorithm was developed and implemented that allows for faster execution times. The resulting software tools where tested with the help of publicly available real 3D medical image sets and 3D molecular models, that allowed to validate the results based on the proposed methodology and test scenarios developed for specific target groups (students in medicine and chemistry).

The introduction of PACS (Picture Archiving and Communication Systems) [1] and the DICOM (Digital Imaging and Communications in Medicine) standard [2] has the purpose to improve the medical imaging technologies and to increase the level of interoperability between different institutions and medical equipment (provided by various manufacturers). The major challenge the users are facing when installing the associated applications of the provided equipment is the dependence on other proprietary software components or operating systems. These problems are eliminated with the help of the newly introduced web based solutions [3], which are allowing the visualization of the images extracted from the DICOM files inside a browser window.

Accessing the images by conventional input devices (e.g. mouse or keyboard) during medical interventions, represents a major risk factor in operating rooms. Several systems that are based on gesture recognition have been proposed in [4], [5], and [6] that could help overcome such undesired complications. These solutions allow the interaction with the patients' images without any physical contact and are helping to keep the operating environment sterilized.

The image data in the patients' DICOM files are stored as a group of 2D parallel slices representing the scanned anatomical area and can be used for 3D volume rendering in the case of MPR (multi-planar reconstruction) [7]. The resulting 3D images can be alternately visualized by a larger group of users on a pseudo-holographic display (without wearing any kind of special 3D glasses) enhancing the collaboration between specialists from different medical fields [8].

The main objective of the thesis is to consolidate theoretically and practically the field of the applications for medical image analysis using the latest generation of gesture tracking devices and 3D pseudo-holographic displays in a modular and personalized manner for specific user groups. The challenges faced at the technological level came from the novelty of both software and hardware components used for development and defining new metrics and parameters that will sustain the proposed solutions. In order to achieve these tasks the following specific activities where defined:

- A comprehensive analysis of the current software and hardware technologies used for pseudo-holographic imaging.
- Development of a new segmentation algorithm that is fast enough to be applied in a browser-based medical visualization system.
- Implementing an interactive client-side colorization algorithm for the purpose of isolating the studied anatomical details by highlighting the regions of interest in the rendered medical images.
- Modeling and extending the functionalities of a web oriented 3D molecular viewer suitable for biomedical research, by adding gesture tracking for enhanced user experience.
- Evaluation of the developed software tools on target users using publicly available real medical image sets and 3D molecular models in order to validate the results based on specific test cases.

The thesis consists of the following chapters that describe the technological state-of-the-art, the methods used to develop the applications, the results and the conclusions with further development opportunities:

- Chapter 1 provides the introduction into the research topic.
- Chapter 2 is a technological overview of the new generation of input devices, brain-computer interfaces and pseudo-holographic display technologies that are suitable to build the next generation of natural user interfaces.
- Chapter 3 describes the open source software modules used during the research with emphasis on their role in the development process from JavaScript based Augmented Reality towards an open source client-side DICOM viewer that allows gesture-based interaction in a web browser.
- Chapter 4 presents the architecture, advantages, the problems and the solutions for the development of a web-oriented DICOM viewer based on the software technologies described in chapter 3.
- Chapter 5 details the open source libraries used, for the development of extended functionalities for a 3D molecular viewer by adding gesture-based control of the rendered chemical models.
- Chapter 6 presents the evaluation procedure and results of the applications described in chapter 4 and 5.
- Chapter 7 presents the conclusions of the thesis and describes future directions for the research community.

The purpose of the **2nd chapter** is to provide an overview of the latest technological innovations that any researcher needs to consider when faced with building a state-of-the-art user interface. The presented hardware modules are grouped in three main categories: input devices based on gesture recognition, brain-computer interfaces and some of the novel 3D display technologies. The author of the thesis also presents some solutions to those who need to have a tactile feedback that could be provided by the haptic devices described in this chapter.

Amongst the identified gesture tracking devices, the LEAP Motion controller is very accurate in detecting individual fingers at a very high detection rate, which is surpassed only by the Google's Soli project that offers an even smaller device suitable for wearable interfaces. The alternative gesture tracking technologies for mobile devices, such as the SideSwipe and SoundWave technologies can provide a more convenient solution in some cases.

While the MYO armband's development purpose is to detect various gestures by interpreting electrical signals at the muscular level, it is also suitable to control a prosthetic limb thus becoming also a brain-computer interface. The main advantage of MYO over the OHMG is that it doesn't require an invasive surgery, making it less prone to clinical injuries during operation. However the OHMG is recommended for achieving a better signal.

The EPOC headset offers a non-invasive alternative to the BrainGate technology where the microelectrode array needs to be surgically implanted to the patients in order to receive the electrical signals directly from the brain. While these two technologies are reading signals, the FES is used to stimulate the muscles in order to avoid muscular atrophy and help the patients to have a more active lifestyle.

Stereoscopic displays provide the stereopsis (the 3D depth perception) with the help of various 3D glasses. While this technology provides a single perspective, the autostereoscopic displays are capable to provide several different perspectives to multiple users without the use of any kind of special additional equipment. Some of the enhanced versions of autostereoscopic displays are providing also 3D volumetric data that takes the form of individual voxels or hogels depending on the image element's positioning. In some special cases the surrounding air (or thin water vapors) can be also used as projection surface (e.g. Heliodisplay).

With the purpose of providing a tactile feedback for the blind persons several Braille terminals where developed that are using a pattern of rounded pins to simulate visual feedback. This technology has been further developed into haptic devices (e.g. Geomagic Touch) to assure tactile feedback that is not available otherwise during the visualization of 3D content.

Based on the researchers specific needs these technologies can be used separately or combined in order to provide a more elaborate view of the studied 3D models and to configure specific user interaction scenarios.

One of the major contributions of chapter 2 is the inclusion of a comparative study that groups the presented devices by category, explains their main characteristics and recommended use for further development, helping the research community to quickly identify the optimal solutions required for a specific project.

Chapter 3 proposes several software architectures to support the daily work of medical professionals, facilitate the learning process for medical students and may be generalized to other domains, as bioinformatics or chemistry.

The 3rd chapter also describes a set of open source software technologies used during various phases of the research by the author of the thesis. The aim and the major contribution brought by the applications developed based on these libraries is to demonstrate that researchers can achieve viable software alternatives that do not depend on specific pre-installed operating systems or proprietary software components. This is considered to be an important aspect that can affect the budget and the visibility of many research projects as discussed in [9] and [10].

During the research several approaches to build a browser-based medical visualization system were proposed, designed, implemented and tested that are detailed in the thesis:

- In a first (more theoretical) approach presented by the author in [11] and [12], a support system has been proposed to diagnose patients during trauma recovery using standards like WebRTC (Web Real-Time Communication) and open source libraries like JSARToolKit (JavaScript Augmented Reality Toolkit), ThreeJS and NanoDICOM. The idea behind this application was to use the patients DICOM images to create a 3D model that can be superimposed over the studied anatomical area of the body and use WebRTC to share the augmented image with a remote web browser. By virtually attaching the 3D model to the real-time image of the patient, the model can rotate the same way as, for example, the subject rotates his leg, providing a digitally refined view to the physician. The main advantage during diagnosis or patient monitoring is that other colleagues could see the same image from a browser in another place without installing additional software components on the local operating system.
- The second step was to use and implement the results of the theoretical module adapting the system to gesture tracking devices and to visualize the rendered 3D model on a pseudo-holographic display providing a natural user interface. The Leap Motion controller was used for interacting with the application by hand gestures and a custom-made autostereoscopic display for visualizing the pseudo-holographic images. The results were presented by the author in [13] and [14].
- In a third option, that demonstrates the generalization possibilities of the proposed models and solutions these were used for building a virtual laboratory for biomedical and chemistry students. The system was adapted to a browser-based 3D molecular viewer. In this case GLmol (a molecular viewer written in JavaScript) was extended by adding gesture tracking code using LeapJS and ThreeLeapControls as an interface between the two modules that allow the interaction with the rendered 3D molecular data. The results were published by the author in [15].

Chapter 3 also presents a comparison of the software technologies used during the research, their characteristics and recommended use for various research projects that will be presented in the following.

The NanoDICOM toolkit allows the extraction of relevant imagistic data from the DICOM files but it needs to be installed on the server side increasing the execution times of the application since the extracted data needs to be sent back to the browser for visualization. A better alternative is provided by CornerstoneJS (written in JavaScript) that runs inside a web browser and has also an image loader component that allows the manipulation of the extracted images. Both solutions can harvest the features of WebRTC that allows direct communication between two peers (browsers) without installing additional plug-ins or third-party software components, thus decreasing the application costs and simplifying its architecture.

While JSARToolKit needs a physical marker to be attached to a real world object that needs to be tracked across the video frames, ThreeLeapControls can provide a similar functionality without a marker by linking the hands position extracted with LeapJS to the rendered 3D virtual object (using ThreeJS) inside a 3D scene provided by WebGL on a HTML5 canvas element.

The use of the LeapJS library totally eliminates any extra calibration steps that are usually needed in other environments where multiple cameras are used to extract 3D depth related information coming from multiple users of the application. This is a major improvement because multiple users can interact with the application at the same time without having to undergo a separate training phase that is needed in older applications to differentiate between the shapes of the hands of each particular individual.

The 3rd chapter concludes with a comparative study, the presented open source libraries and APIs providing a valuable resource for every development team faced with the challenge to build a browser-based medical imaging application. These software solutions have a large applicability in other areas where gesture-based interaction facilitates the interaction with complex 3D models as further demonstrated in the thesis.

Chapter 4 of the thesis describes the development of a browser-based DICOM viewer that provides gesture-based interaction with the rendered 3D model of the studied anatomical area without using any additional browser extensions or third-party plug-ins. Even if there are plenty of open source libraries available this is still not a trivial task because of the limitations regarding the execution time of the scripts on the client-side of a web-oriented software application. The author of the thesis had to provide a simplified segmentation algorithm [12] that is capable to extract the pixel data from the DICOM files in a timely manner, before the browser stops the script execution.

The application named simply JSDV (JavaScript DICOM Viewer) is based on the open source libraries described in chapter 3. In order to extract the imaging information from the DICOM files the author used the CornerstoneJS library. The resulting JSDV application has the following additional functionalities:

- image segmentation with a variable threshold;
- colorization;
- saving of individual slices on the local file system in PNG format;
- multiplanar 3D reconstruction based on the saved slices;
- loading of a set of slices saved from a previous session;
- interaction with the displayed 3D model either by the mouse or with a LEAP Motion controller.

Chapter 4 of the thesis demonstrates that the users can interact with the displayed 3D images using simple gestures providing an enhanced user experience during image interpretation. The application can be easily adapted for use in conjunction with a pseudo-holographic device by rendering the 3D image in a modal window (available in Bootstrap). The browser-based approach allows the deployment of the code on any operating system without the need to install a virtual machine or any third-party browser extensions.

The advantages of the simplified segmentation algorithm developed by the author of the thesis are derived from the fact that it has to check only for a single neighboring pixel resulting in increased script execution times, a key factor that needs to be considered during the development of any browser-based application. Even if this approach may result in a rough contour of the obtained edges, as the author described it in the current chapter, this shortcoming might be surpassed by using a variable threshold as it is implemented in the application.

The new segmentation algorithm is not limited only to static images and might be used in other areas where the fast extracting of specific features from images might be essential (e.g. surveillance, automotive and aerospace industries). The execution speed of an application that analyzes video frames rather than specific images would grow considerably since instead of verifying up to eight additional pixels to establish if a specific pixel belongs to the ROI, the current algorithm has to check for a single one.

Other open source applications such as OsiriX [16] or VolView [17] are also available for visualization of the patient's DICOM files, however these applications depend on a previously installed operating system that in some situations might limit their portability (e.g.

OsiriX runs only on Mac OS X) and impose other financial restrictions(e.g. due to the operating system's proprietary license). Neither one of them is implementing gesture-based interaction nor provides an interface suitable for visualization on a pseudo-holographic device.

The JSDV application has been tested during the research by a large ammount of volunteers and the results were presented by the author in chapter 6 of the thesis.

Chapter 5 of the thesis underlines the versatility offered by any open source oriented application architecture. In order to demonstrate this, the author of the thesis extended the GLmol web application by adding extra functionalities for the user interaction mechanism and presented it in [15]. The newly implemented gesture-based manipulation features are possible due to the openly available LeapJS library that can be interfaced with GLmol using ThreeLeapControls. This way the application works both with a classical mouse and with a LEAP Motion Controller if available, making it easier to the users to manipulate the displayed 3D molecular structures.

GLmol is a client-side 3D molecular viewer, which facilitates the visualization of chemical structures stored in openly available databases (e.g. RCSB PDB, PubChem) under various file formats. GLmol has a dual open-source license of LGPL3 and MIT license. The rendered 3D chemical models can be directly embedded inside web pages resulting in a more interactive experience that is very suitable for virtual laboratories.

After the 3D chemical structure is rendered by the GLmol application the user can rotate, pan and scale it with a 2D mouse. As shown by the author of the thesis in chapter 5 this interaction method can be improved by adding gesture-tracking functionalities to the application. The advantage of adding these extensions to GLmol is that the application will enable the user interaction both with a classical mouse and a LEAP Motion device, facilitating the manipulation of the rendered 3D molecular structures that also can be visualized on a pseudo-holographic device.

As chapter 5 demonstrates the previously described software technologies are a suitable solution to developers in any other areas where the users need to interact with complex 3D models. Similar areas might include architecture, aeronautical engineering, computer simulators.

The original contributions of the author of the thesis as described in the current chapter is the adaptation of the GLmol application to gesture-based interaction that adds a new dimension to the user interface.

As the last part of the research, in **chapter 6**, both JSDV and GLmol LEAP have been tested on specific user groups. The author of the thesis started with separate test plans for each application. These test plans included the usability test objectives, methodology (equipments, participants' characteristics, and procedures), usability tasks description, usability metrics and usability goals as it should be organized according to [18]. For the test plans the author of the thesis used a template [19] provided by Usability.gov a site that is managed by the Digital Communications Division in the U.S. Department of Health and Human Services' (HHS) Office of the Assistant Secretary for Public Affairs. These templates serve as a blueprint for a test plan, are available in the public domain and have been adapted by the author of the thesis for both applications since they have a general character. Each test plan had 7 annexes that included the following:

- Annex 1 - a consent form that each participant completed before the actual testing where they confirmed that the participation is voluntary and that they agreed to participate in the test. For this annex the author of the thesis adapted the template provided by Usability.gov [20] for each application;

- Annex 2 - a pre-test demographic and background information questionnaire regarding age, gender, professional status, previous experience with the equipment and software used for testing;
- Annex 3 - a table containing the task scenarios (task description, what is required to perform by the user, succesful completion criteria and a maximum time for completion) used by the test moderator during the testing;
- Annex 4 - a time on task table used by the moderator to record the time for completion of each task completed by the participants;
- Annex 5 - a five-point Likert scale usability questionnaire inspired by the questions from the Software Usability Measurement Inventory (SUMI) [21] questionnaire adapted separately to each tested application. This qestionnaine provides answers regarding specific quantitative metrics for each application;
- Annex 6 - a five-point Likert scale 2D mouse assessment of comfort questionnaire based on the ISO 9241-9 [22] and the presentation of the standard from [23]. This questionnaire provides answers regarding some subjective metrics regarding the ease of use of the mouse by the users related to the applications.
- Annex 7 - a five-point Likert scale Leap Motion device assessment of comfort questionnaire also based on the ISO 9241-9 and presentation mentioned above. This questionnaire provides answers regarding some subjective metrics regarding the ease of use of the LEAP Motion device by the users.

For both applications the author of the thesis used a custom-built pseudo-holographic 3D display which allowed the user to have a more vivid representation of the displayed 3D model resulting in a better understanding of the studied images.

The testing followed the same patterns for both JSDV and GLmol LEAP applications. The author of the thesis divided in both cases the entire population into smaller sample groups for comparison.

In both cases the results showed that the natural user interface was well received and helped the participants to obtain better results even when they were using a novel gesture-tracking device like the LEAP Motion.

The results for testing the GLmol LEAP application were also encouraging and provided a viable option for future virtual laboratories when multimodal interaction can act as a key component to disseminate chemistry related knowledge.

The main contributions identified by the author of the thesis in **chapter 7** are the following:

- A comparative study of the latest hardware technologies available for future use by various reserch groups in the development of some novel multimodal user interfaces.
- A comprehensive analysis of the curent software technologies used during diverse phases of the research. The presented open source libraries and APIs are constituting a valuable tool for every researcher faced with the development of viable software alternatives (as demonstrated by the thesis) that do not depend on specific pre-installed operating systems or proprietary software components.
- The implementation of the studied hardware and software modules, resulting in the development of a client-side DICOM viewer. This browser-based medical imaging application provides both a regular 2D user interface and a novel 3D interface that allows the users to interact with the rendered 3D models based on patients' DICOM files with the help of diverse hand gestures.

- The development of a new segmentation algorithm with a variable threshold that improves the execution speed and significantly reduces the noise (that is usually present in the edges) resulting in an adjustable smooth contour of the extracted images.
- The implementation of an interactive client-side colorization algorithm that has been used for highlighting specific tissue types inside the rendered 2D images that provided a base for the multiplanar 3D reconstruction of the studied anatomical area of the patient.
- Updating the ThreeLeapControls JavaScript library to the latest functionalities provided by the current LeapJS v 0.6.4 and ThreeJS rev. 79. The new version detects the number of individual fingers that are extended and provides gesture-based interaction with the rendered 3D models inside both JSDV and GLmol LEAP applications.
- Adapting a client-side 3D molecular viewer to gesture-based interaction. The new version named by the author of the thesis GLmol LEAP allows the users to interact with the rendered 3D chemical structures in its standard way (with a 2D mouse) and with the help of a LEAP Motion device if available providing extended multimodal user interaction capabilities.
- Proposing a proper methodolgy and testing of the JSDV aplication with the help of specific user groups. The author of the thesis used publicly available DICOM files for the evaluation of the newly developed 3D medical visualization system. The results were analized in chapter 6 in order to provide insights from the user performance and user satifaction point of view. The forms used during testing and the gathered raw data are available in the Annex 1 of the thesis.
- The evaluation of the extended GLmol application (GLmol LEAP) has been done also with the help of specific user groups by using publicly available 3D macromolecular models. The assessed usability metrics provided answers regarding user performance and satisfaction levels. The testing results are exposed and analized in chapter 6 of the thesis. The forms used during evaluation and the colected raw data are available in the Annex 2 of the thesis.

As the author conludes in chapter 7 the thesis results add formal and practical knowledge in terms of methodology, algorithms, implementation, and evaluation regarding the various hardware and software technologies that are representing a key component in the development of applications that are used to manipulate pseudo-holographic images using gestures. The complexity of the subject implies further work that might be based on the authors curent findings.

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