COMP390 Honours Year Project

Detailed Proposal

Computer Vision and AR for Endovascular Intervention

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Statement of Ethical Compliance

Data Category: A

Participant Category: 0

I confirm that I have read the ethical guidelines and will follow them during this project. Further details can be found in the relevant sections of this proposal.

Contents

1 Project Description

In recent years, 3D visualization methods like virtual reality (VR), augmented reality (AR), and mixed reality (MR) have garnered significant attention and traction.[1]Our project, CathSim, combines machine learning with AR/VR [2, 3] to create an open-source simulator for autonomous cannulation in endovascular operations. Current training methods for these robots are lengthy and fraught with safety concerns, especially during interactions between the catheter and the aorta.[4] Existing simulators are mostly proprietary and overlook autonomous aspects. [5] CathSim offers a high-fidelity model of the catheter and aorta, integrating an advanced endovascular robot. It provides real-time force sensing and has shown, through preliminary tests, to effectively mimic real-world robot behaviours.[4] Furthermore, we aim to deploy CathSim on VR devices like HoloLens[6] or Meta Quest[7], enhancing its accessibility and utility for medical professionals.

2 Aims & Requirements

2.1 Aims

1. To conceptualize and establish a high-fidelity, open-source simulator, named CathSim, tailored for the nuances of autonomous cannulation in endovascular operations.
2. To integrate advanced machine learning algorithms with CathSim, ensuring efficient training and accurate simulations of autonomous endovascular navigation.
3. To harness AR/VR technology to provide an immersive simulation experience, specifically targeting platforms like HoloLens or Meta Quest 3, thus elevating the educational and research potential of CathSim.
4. To amplify the realism of CathSim through real-time force sensing between the catheter and the aorta, ensuring safer and more representative simulations.

2.2 Requirements

1. The software should be fully open-source, enabling global developers and researchers to access, modify, and contribute to its codebase.
2. Implement mechanisms to sense and showcase real-time interactions between the catheter and the aorta.
3. High performance:
   -The software must ensure smooth simulations with high real-time frame rates to deliver a realistic user experience.

   -Machine learning models integrated into CathSim should have shortened training durations without compromising accuracy.
4. Easy for Implement and improve:
   -It should be compatible with, and easily deployable on, AR/VR devices, particularly platforms like Meta Oculus Quest Series.

   -The platform should support the implementation and testing of various machine learning algorithms, especially those focusing on reinforcement learning for endovascular tasks.

   -The software architecture should be modular, allowing for future enhancements, additions, or integration of new features or algorithms.
5. Safety and Incident Management:
   - The software shall incorporate error handling to manage unexpected scenarios during simulations, ensuring stability and consistency of the training environment.

   - Safety protocols need to be implemented within the software to prevent any misrepresentation of medical procedures that could lead to misuse or harm.

   - Regular security audits and updates are required to protect against vulnerabilities and to maintain the integrity of the simulation data.

   - Documentation must include best practices for safety and guidelines for responding to safety incidents within the simulation environment.

3 Key Literature & Background Reading

The literature review and background research for this project has focussed on pinpointing fitness models (mainly reinforcement learning) with the aim of speeding up training and improving performance. Emphasis was also placed on understanding the interaction of forces between the catheter and the aorta during endovascular manipulation. Attention is also given to the feasibility and implementation of this simulator in VR and AR systems, such as HoloLens .

One of the most prominent revelations in the literature is the effectiveness of deep reinforcement learning in complex medical navigation tasks, such as guidewire navigation in coronary artery models[8]. This approach not only demonstrates the potential to improve the efficiency and accuracy of autonomous intravascular navigation, but is also based on a decision-based policy gradient that can work in a continuous operating space. Notably, for many tasks, the algorithm has been shown to learn the strategy from scratch: directly from the raw pixel input [9].

In-depth studies have found that semi-supervised deep neural network models provide insight in estimating interaction forces, particularly during robotic surgical interventions [10]. Moreover, in robot-assisted minimally invasive surgical scenarios, the use of unsupervised strategies to estimate interaction forces has been shown to improve the accuracy of force estimation. This approach not only improves the accuracy of force measurements, but also outperforms existing state-of-the-art methods [11]. These models offer a promising avenue for improving the accuracy of force measurements between catheters and the aorta. Accurate force sensing is critical because it helps to significantly reduce the risk of potential injury during surgery, thereby improving the overall safety and reliability of the procedure[12].

In addition to the exploration of models and algorithms, the literature review highlighted the integral role of simulation environments in medical training and the development of autonomous systems.Platforms such as the MuJoCo Physics Engine are lauded for their ability to orchestrate complex simulations, especially in virtual spaces where high-fidelity interaction is critical [13].The integration with Unity, further amplifies its capabilities. The combined strengths of MuJoCo and Unity form a comprehensive platform, melding the robust physics simulation of MuJoCo The combined strengths of MuJoCo and Unity form a comprehensive platform, melding the robust physics simulation of MuJoCo with Unity's proficiency in real-time rendering and interaction. This seamless fusion offers an optimal environment for intricate simulations pertinent to autonomous systems.[14, 13]In addition, the emergence of magnetic resonance-safe endovascular robotic platforms and the development of endovascular catheterised robotic systems equipped with magnetically-controlled haptic force feedback demonstrate the direction of the industry towards perceptible force sensing and hyper-realistic feedback in training scenarios.[15, 5]

The expansion into augmented reality (AR) for surgical applications has also been a significant point of interest in recent literature. The feasibility and benefits of using Microsoft HoloLens for holographic augmented reality in endovascular surgery have been explored, with findings supporting the device's potential for clinical application[16]. Similarly, studies on wearable AR navigation systems for surgical telementoring based on Microsoft HoloLens indicate that such technology could revolutionize surgical education and remote guidance[17]. The efficiency of marker tracking for surgical navigation using both mono and stereo vision in Microsoft HoloLens underscores the device's applicability to the medical field[18]. Additionally, the Microsoft HoloLens 2 has been analyzed extensively for its use in medical and healthcare contexts, showing promising prospects for future advancements[19]. Lastly, a systematic review of the HoloLens in medicine has categorized its applications and outcomes, further highlighting the device's versatility and utility in medical settings[20].

4 Development & Implementation Summary

4.1 Development Environment & Languages

1. Python:

   It was chosen as a language for developing machine learning models because it is recognised as a powerful language in the field of machine learning and has a variety of libraries suitable for complex algorithmic tasks.

2. Unity Engine & C#[21, 14]

   Unity provides an advanced interface for building comprehensive simulations and interactive user experiences. By using C# in Unity, which is known for its efficiency and scalability, we can develop complex simulation behaviours, and interactive elements, and integrate a variety of assets, and Unity's asset store and large community resources will be invaluable for improving visual fidelity and interaction quality.

3. Mujoco[13]

   As a high-quality physics engine, MuJoCo will be an integral part of our development process. Its accurate modelling of the laws of physics will allow us to create realistic simulations of catheter and aortic interactions, a key feature of our project, and the synergy between MuJoCo's physical simulation capabilities and Unity's graphical strengths will result in a highly realistic and responsive environment.

4.2 Implementation &Workflow Summary

1. Model Training:

   The development phase will begin with the construction of machine learning models centred on reinforcement learning techniques suitable for the autonomous navigation of intravascular robots. This phase will be characterised by exploring various algorithms and architectures to determine the most efficient performance.

2. Simulator & Unity Design:

   The Unity design phase will focus on building a virtual environment that reflects the complexity of endovascular surgery. Work will include the development of high-resolution 3D models, realistic textures, and dynamic animations that interact with user input and simulation results.

3. User Interface (UI) Design:

   The user interface will be developed with a focus on clarity and interactivity to ensure that the user can easily navigate the simulator and interpret the data displayed, enabling the user to manipulate variables and directly observe the effects on the simulation in real-time.

4. Deployment to VR/AR Devices & Optimization:

   The deployment phase will include rigorous testing on VR/AR devices such as HoloLens or Meta Quest 3 to ensure that the simulator runs at high performance and low latency. Optimisation will include fine-tuning the simulator's frame rate, resolution and interaction fidelity.

5 Data Sources

This section outlines the data sources utilized for the current project, namely the MuJoCo physics engine and the HoloLens 2 Emulator archive. Both tools are implemented to provide simulation environments relevant to the project's goals.

1. MuJoCo Physics Engine[13]:

   MuJoCo is a physics engine geared towards the detailed and efficient simulation of complex systems with robotics, biomechanics, and animation applications. The engine generates simulation data, including numerical representations of physical interactions. This information is non-personal and procedural in nature, ensuring that there is no inclusion of personal or sensitive data. Access to MuJoCo is granted under a specific software license that dictates the terms of use, and all simulations carried out are in compliance with those terms.

2. HoloLens 2 Emulator Archive[6]:

   The HoloLens 2 Emulator facilitates the testing and debugging of mixed-reality applications in a virtualized environment. It is used to replicate the behaviour of applications within a simulated HoloLens 2 device. Data retrieved from the emulator pertains to spatial mappings, user interactions, and performance metrics. The data is generated for project purposes, with no personal identifiers involved. Usage of the emulator falls under the Microsoft Software License Terms, which guide the management and use of the data collected.

6 Testing & Evaluation

The evaluation process for the project will be carefully designed to test all key aspects of the simulation environment. Testing will include rigorous validation of the accuracy of the machine learning model through repeated trial runs to ensure that the algorithms perform consistently and predictively across different scenarios. The accuracy and realism of the force feedback mechanisms will be assessed by comparing simulation results with empirical data from actual endovascular procedures. The frame rate of the simulator will also be monitored to maintain a smooth and immersive experience, especially when operating in VR. This will include evaluating the graphical performance and computational efficiency of the system under different load conditions.

7 Project Ethics & Human Participants

I have read and abide by the University's ethical guidelines[22]. The project did not involve direct interaction with human participants during the design, implementation or evaluation phases. An extensive review of the project scope and methodology confirmed that no personal data was collected, analysed or used. In addition, all activities were within the scope of activities permitted by our ethical guidelines. It was verified with the project supervisor that no customised activities required separate ethical approval. Therefore, there are no other ethical issues involved in this project.

8 BCS Project Criteria

1. An ability to apply practical and analytical skills gained during the degree programme:

   The project will apply practical programming knowledge and skills acquired during my study at the university, specifically in Python, C#, and C++. These languages are pivotal in developing and implementing the functionalities of the model design and the Unity engine development. Additionally, modules covering computer vision and artificial intelligence will be particularly relevant, as they provide the theoretical foundation for the project's technical aspects. The integration of these subjects into the development process will showcase the analytical capability to address and solve complex, multidisciplinary challenges within the project scope.

2. Innovation and/or creativity:

   The innovative core of this project focuses on enhancing the CathSim simulator with intuitive AR/VR interfaces. The goal is to merge complex autonomous cannulation procedures with a user-friendly experience, enabling users to interact with and understand the simulation with ease through advanced visualization techniques.

3. Synthesis of information, ideas and practices to provide a quality solution together with an evaluation of that solution:

   The project incorporates principles from Virtual Reality and Augmented Reality (VR/AR), applications in the healthcare domain, and computer science disciplines such as computer vision, artificial intelligence and software development. The convergence of knowledge from different domains provides an innovative approach to simulation and mixed reality applications in healthcare. The convergence of these different fields aims to improve the fidelity and effectiveness of healthcare simulations, thus potentially contributing to medical training and treatment visualisation.

4. That your project meets a real need in a wider context:

   This project focuses on the critical medical procedure of Autonomic Endovascular Catheter Insertion, utilising VR/AR technology to improve its safety and efficiency. As the medical field evolves, the demand for precise and minimally invasive techniques is increasing, especially for catheter insertion - a procedure that is critical to many diagnoses and treatments. By providing an innovative simulation interface for training and instruction, the project aims to improve the skills of healthcare professionals and potentially enable remote catheterisation services. The insights and advances brought about by the project could lead to safer, more effective procedures and ultimately improved patient outcomes. This coincides with a broader need for continuous improvement in medical technology and procedures, ensuring the relevance and potential impact of the project in the healthcare sector.

5. An ability to self-manage a significant piece of work:

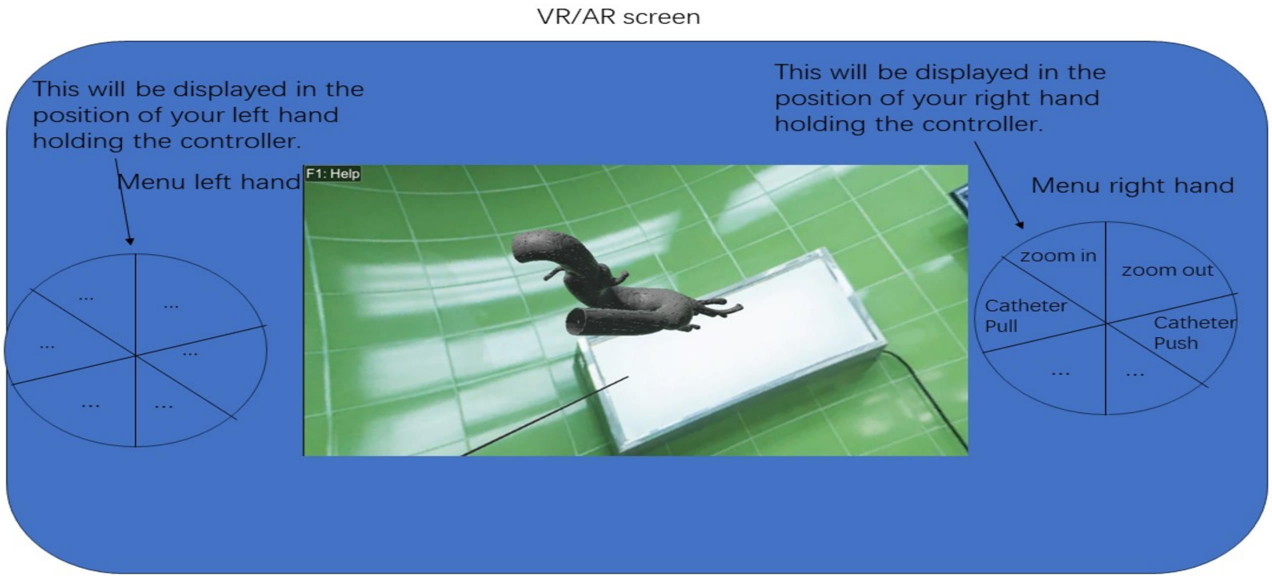
   It is anticipated that the project will require a sustained commitment of 10 hours per week throughout the academic year. This commitment emphasises the need for self-motivation and careful organisation to ensure successful completion of the project. Given the complexity and importance of developing an autonomous endovascular catheter system, the time commitment is reasonable and necessary. Responsibility for the effective management of this workload rests solely with the individual, with clear timelines and regular milestones to track progress and maintain focus on project goals.

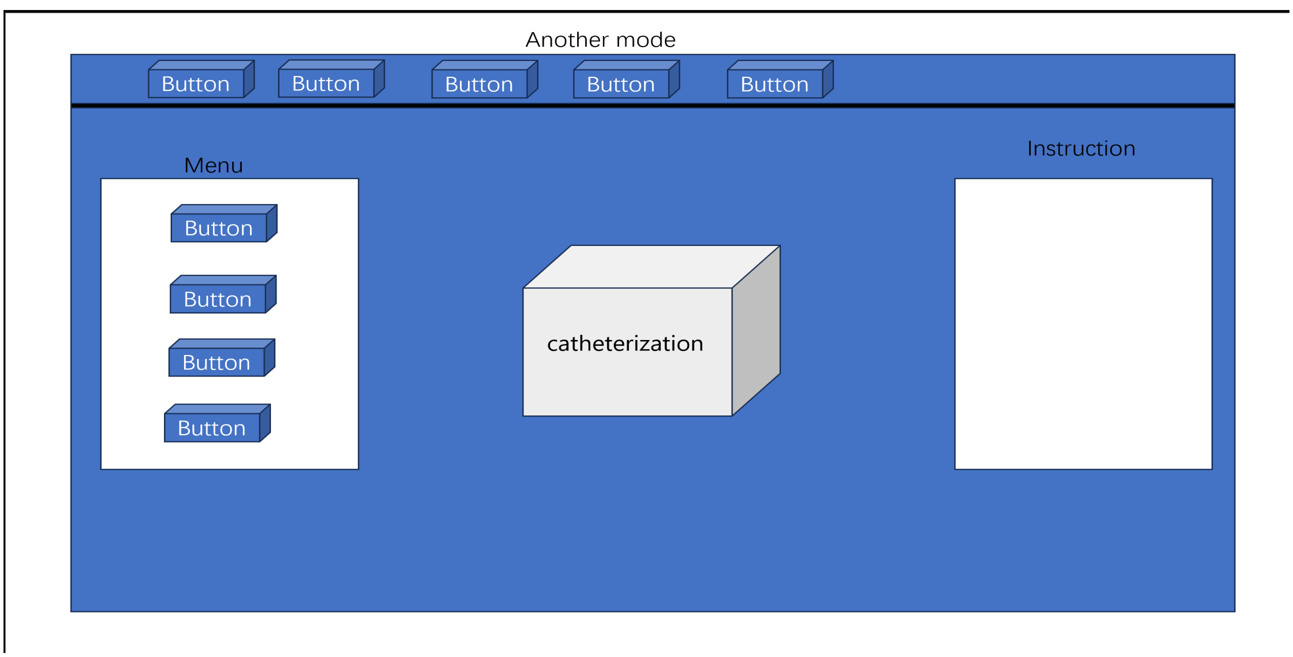
6. Critical self-evaluation of the process:

   In the conclusion and self-reflection section of the thesis, a comprehensive assessment of the individual's performance throughout the project will be undertaken. This will include a critical appraisal of the methodology adopted, the challenges faced, the problem-solving strategies adopted and the overall management of the project life cycle. Reflection on successes and areas for further development will provide a balanced perspective of the project's implementation and help to identify valuable learning experiences and areas for future professional growth.

9 UI/UX Mockup

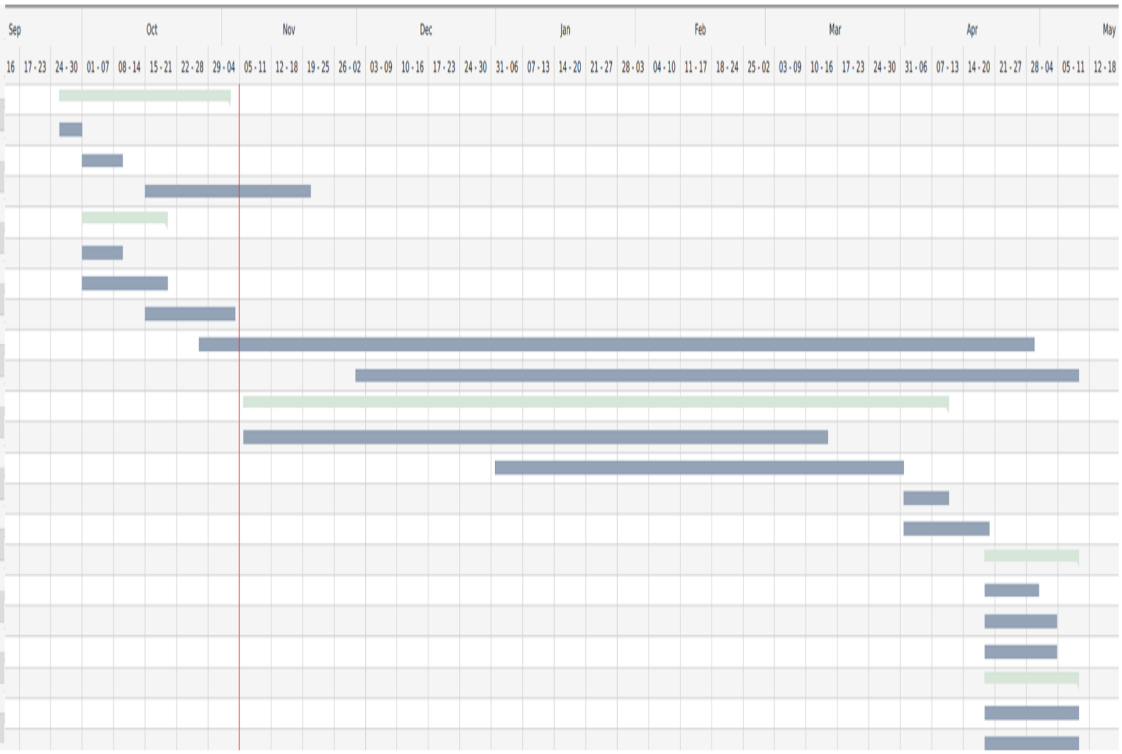
The preliminary wireframes attached to this paper represent the envisioned interface for an autonomous intravascular catheter insertion VR/AR application. These preliminary designs are intended to provide a conceptual view of the layout and interactive elements that make up the user interface.
***The screen displayed in a VR, or AR headset may be very different from what is shown in a flat schematic. Menu details will be added later in the project process.





10 Project Plan

Title	Start Time	End Time
Project Planning	09/26/2023	11/02/2023
Initial discussion with supervisor	09/26/2023	10/01/2023
Defining project aims and requirement	10/01/2023	10/10/2023
Defining the timeline	10/15/2023	11/20/2023
Literature Review & Background Researc	10/01/2023	10/20/2023
Literature review on Cathsim	10/01/2023	10/10/2023
Literature review on AR/VR developme	10/01/2023	10/20/2023
Detailed Proposal	10/15/2023	11/04/2023
Continue learning Unity engine	10/27/2023	04/30/2024
Project Dissertation	12/01/2023	05/10/2024
Design of ML and AR/VR Models	11/06/2023	04/11/2024
Design machine learning algorithms	11/06/2023	03/15/2024
Develop AR/VR simulations	01/01/2024	04/01/2024
Testing and refinement	04/01/2024	04/11/2024
Project Video	04/01/2024	04/19/2024
Deployment	04/19/2024	05/10/2024
Deploy the system on VR/AR devices	04/19/2024	05/01/2024
Finish documentation	04/19/2024	05/05/2024
Final system testing and bug fixes	04/19/2024	05/05/2024
Evaluation and Reporting	04/19/2024	05/10/2024
Prepare final dissertation	04/19/2024	05/10/2024
Evaluate the project against objecti	04/19/2024	05/10/2024



11 Risks & Contingency Plans

Risk:	Contingencies:	Likelihood :	Impact :
ML Model Inaccuracy	Implement iterative training phases, enhance model with more training data, apply model fine-tuning, cross-validation for model robustness.	Medium	High
Inaccurate Force Feedback Simulation	Constantly refine the haptic feedback model based on real-world surgery data and expert input.	Medium	High
Low Simulator Frame Rates	Optimize code for performance, invest in high-quality hardware, and perform load testing.	High	High
Data Privacy Breaches	Encrypt sensitive data and adhere to best practices in cybersecurity. Conduct regular security audits and ensure compliance with data protection laws.	Low	Very High
Integration with Medical Hardware	Create a robust API and a set of integration protocols to ease the process.	Medium	High
VR/AR Motion Sickness	Include customizable settings for users to adjust their experience.	Low	Medium
Incompatibility with New VR Systems	Design the simulator with modularity in mind to adapt to new systems.	Medium	Medium
Inadequate User Training	Offer a detailed training program, including online tutorials, and hands-on workshops. Provide continuous support.	High	High
Simulator Overload During Emergency Scenarios	Optimize simulator code and hardware to handle high-load situations. Implement stress-testing to ensure stability.	Very Low	Very High
Patient Emergency Scenarios (e.g., Blood Vessel Rupture)	Implement detailed emergency modules in the simulator that can trigger and guide through crisis management protocols. Train users on emergency procedures through simulated crisis events.	Very Low	Very High
Ethical Implications of AI Decision-making	Establish an ethics board; integrate ethical guidelines in AI training and decision processes.	Medium	Very High

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