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College of Engineering

Department of Computer Science and Engineering

Senior Project Report

Advanced Navigational Endoscopy System: Integrating Real-Time Control and Virtual Reality for Enhanced Gastrointestinal Diagnostics

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This project report is submitted to the Department of Computer Science and Engineering of Qatar University in partial fulfilment of the requirements of the Senior Project course.

Declaration

This report has not been submitted for any other degree at this or any other University. It is solely the work of us except where cited in the text or the Acknowledgements page. It describes work carried out by us for the capstone design project. We are aware of the university's policy on plagiarism and the associated penalties and we declare that this report is the product of our own work.

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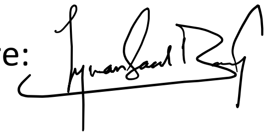
Signature: 

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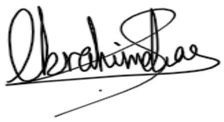
Signature: 

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Abstract

The field of medical diagnostics is witnessing a paradigm shift with the introduction of advanced robotic systems. Our project embodies this shift. The current traditional methods involve the need for professional endoscopists taking long durations to navigate through the Esophagus and the unsatisfactory range of view provided. Our project aims to enhance the precision and safety of gastrointestinal diagnostics. It integrates robotics, machine learning, and medical imaging to innovate endoscopic procedures.

The project's goal is to develop an endoscope with a flexible, navigable tip. This tip is designed for autonomous navigation through the Esophagus to the stomach. Such autonomy is essential to reduce patient discomfort and increase diagnostic accuracy. The tip, equipped with two degrees of freedom, captures live images. These images are relayed in real-time to Microsoft HoloLens VR headset worn by the physician. This setup ensures continuous monitoring and control during the procedure.

A key feature of this project is the use of machine learning for esophageal center detection. This detection guides the endoscope along a safe path. The integration of AI in this context is a notable advancement in medical robotics. It demonstrates the potential of machine learning in medical applications.

The endoscope's tip movements are controlled by Maxon ECX SP13 motors, operated via EPOS4 controllers. The coordination between the AI system and these motors is critical. It ensures precise navigation and alignment of the endoscope within the Esophagus. This coordination is crucial for the safety and effectiveness of the procedure.

This report focuses on the project's initial phase, the proof of concept for the center detection and motor control integration. The testing of this integration, using live video feedback, has shown promising results. These results validate the feasibility of the proposed system and its potential in autonomous medical navigation.

The full implementation of this system has significant implications for medical diagnostics. It not only aims to improve gastrointestinal endoscopies but also sets a precedent for AI and robotics in healthcare. The Advanced Navigational Endoscopy System is a pioneering project. It marks a significant step towards technology-driven, patient-centric medical care.

Acknowledgment

First and foremost, we would like to thank the almighty God for granting us success in our project to the fullest. In the journey of bringing the Advanced Navigational Endoscopy System project to fruition, the support and guidance we received from various individuals and organizations have been invaluable. At the forefront of this assistance was our esteemed supervisor, Prof. Amr Mohamed, whose expertise, and insights have been a guiding light throughout the development of this project. His dedication to our progress, coupled with his willingness to share his profound knowledge, has been instrumental in shaping our approach and refining our methodologies.

We are also immensely grateful to Mr. Abdulrahman Soliman for his general guidance helping us navigate complex challenges with greater confidence. His role in this project has been pivotal in guiding us in particular aspects with our practical implementation.

Our collaboration with the team at Hamad Medical Corporation (HMC) has been another cornerstone of our project's success. We extend our heartfelt thanks to Dr Nikhil Navkar and Ms. Sophia Basha for their cooperation and invaluable contributions. Their expertise in the field has significantly influenced the direction and execution of our project. The equipment and resources provided by HMC have been crucial in enabling us to conduct thorough research and develop a robust proof of concept.

We would be remiss if we did not acknowledge the support of Qatar University in this endeavor. The university's commitment to fostering innovation and research has been evident through the provision of necessary funding and resources. This support has been a key factor in allowing us to pursue our project with the necessary tools and facilities at our disposal.

Lastly, our families deserve our deepest gratitude for their understanding and sacrifices. Their support, patience, and encouragement have been a source of strength and motivation, enabling us to dedicate ourselves fully to the success of this project.

In conclusion, the collaborative effort of each individual and organization mentioned has been fundamental to the success of our project. We are profoundly grateful for their contributions and are honored to have had the opportunity to work alongside such distinguished professionals and institutions.

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1. Introduction and Motivation

1.1. Problem statement

The realm of gastrointestinal endoscopy has long been constrained by the need for skilled endoscopists to manually navigate endoscopic equipment, a process that demands precision, experience, and can vary significantly in efficiency and effectiveness based on the operator's skill. This project addresses the challenge of developing an autonomous navigation system for an upper gastrointestinal endoscope, aimed at streamlining the diagnostic process and reducing the dependency on the endoscopist's manual skills.

The technical challenges of this project are multifaceted and include:

- Developing a machine learning algorithm capable of accurately identifying the center of the Esophagus in real-time, using live video feeds.

- Integrating this algorithm with the mechanical movements of the endoscope, particularly the navigable tip, to ensure smooth and accurate navigation through the Esophagus to the stomach.

- Ensuring seamless communication between the endoscope's navigation system and the Maxon ECX SP13 motors, controlled by EPOS4 controllers, for precise manipulation of the endoscope's tip.

- Establishing a reliable and intuitive interface for the physician, using Microsoft HoloLens VR, to receive live feedback and control the endoscope upon reaching the stomach.

The non-technical challenges include:

- Ensuring the system's usability and acceptance by medical professionals, particularly in adapting to a new method of endoscopic navigation.

- Addressing any regulatory and compliance issues related to the introduction of an autonomous system in a medical procedure.

- Training medical staff to effectively use the new system, including the interpretation of data and manipulation of the endoscope via the VR interface.

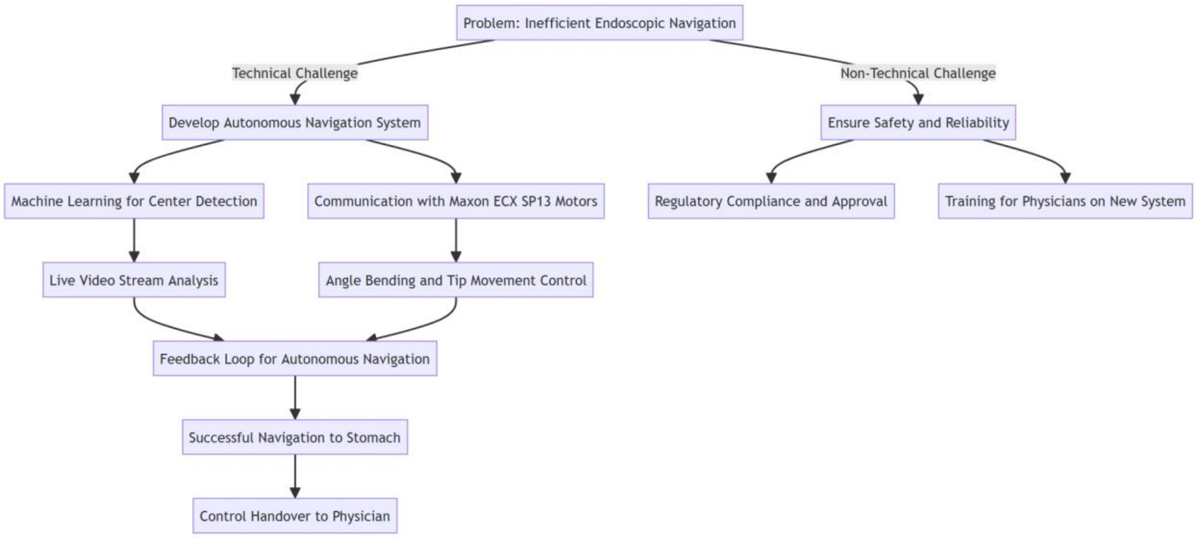


Figure 1: The technical and non-technical challenges

1.2. Project objectives

The objectives of our project are clearly defined to ensure the successful realization of an innovative medical device that enhances the efficiency and effectiveness of gastrointestinal diagnostics. These objectives include:

- Develop an autonomous navigation system for an upper gastrointestinal endoscope that can independently navigate through the Esophagus to the stomach, reducing the need for manual control by an endoscopist.

- Implement a machine learning algorithm for real-time center detection of the Esophagus, ensuring accurate and safe navigation of the endoscope.

- Integrate the autonomous navigation system with Maxon ECX SP13 motors and EPOS4 controllers for precise manipulation of the endoscope's tip.

- Provide the physician with a Microsoft HoloLens VR interface for live feedback and control of the endoscope, enhancing the diagnostic process and allowing for more intuitive interaction with the endoscopic imagery.

- Develop automatic robot-control for the endoscope to intelligently navigate through Esophagus, thereby increasing the efficiency of the diagnostic procedure.

- Ensure that the system is user-friendly, reliable, and meets the stringent safety and regulatory standards required for medical devices.

1.3. Project significance and expected benefits

In the realm of medical procedures, the significance of our project, the "Advanced Navigational Endoscopy System," cannot be overstated. It addresses a pressing issue that affects both patients and healthcare providers worldwide. The problem revolves around the inefficiencies and limitations of traditional upper gastrointestinal endoscopy procedures, which rely heavily on the manual navigation of endoscopes by skilled endoscopists.

As indicated by studies in the field, the global clinical burden of upper gastrointestinal issues is substantial, with a significant portion of the world's population suffering from various conditions that necessitate endoscopic examinations [1]. The primary concern lies in the shortage of specialized endoscopists in many geographical areas, which restricts access to timely and accurate diagnostic procedures. This shortage of expertise can lead to delayed diagnoses, inadequate treatments, and increased healthcare costs.

Our project's significance lies in its potential to revolutionize upper gastrointestinal endoscopy by automating the navigation process. By replacing manual navigation with an autonomous system, we aim to eliminate the need for an endoscopist to be physically present during the procedure. This innovation can greatly enhance access to endoscopic examinations, especially in underserved areas where the shortage of skilled healthcare professionals is most acute. Patients will benefit from faster and more efficient procedures, leading to quicker diagnoses and better treatment outcomes.

The contribution of our work extends beyond the immediate impact on patient care. It represents a significant step forward in the field of medical robotics and autonomous systems. The development of an autonomous endoscopy system with real-time feedback to healthcare providers is an innovation that holds the potential to transform not only upper gastrointestinal endoscopy but also other areas of medical practice. The integration of machine learning algorithms for center detection and the precise control of the endoscope's tip using Maxon ECX SP13 motors and EPOS4 controllers showcase the technical sophistication of our senior design project.

The non-triviality of our project is evident in the fact that existing solutions cannot be trivially extended to address this problem. Traditional endoscopy procedures rely entirely on the expertise of human endoscopists to navigate the endoscope through the complex and delicate anatomy of the upper gastrointestinal tract. Automating this process requires a combination of advanced robotics, image processing, and machine learning techniques, making it a challenging and non-trivial endeavor.

What drew us to this senior project was its potential to make a meaningful impact on healthcare delivery and the collaboration of Hamad Medical Corporation (HMC) at the behest of our supervisor providing us with the necessary equipment, technology and experience required. The opportunity to work on a project that has the potential to improve patient access to vital diagnostic procedures and reduce the burden on healthcare professionals resonated strongly with our career goals. As undergraduate students majoring in computer engineering, this project provided us with a unique opportunity to apply our technical skills and expertise to a pressing healthcare challenge. It also aligns with our university's commitment to interdisciplinary research and innovation.

In summary, our senior project aims to address a significant problem in healthcare by developing an Advanced Navigational Endoscopy System. The potential benefits are far-reaching, encompassing improved patient access to endoscopic examinations, more efficient diagnoses, and advancements in medical robotics. This project has the potential to contribute valuable insights to the academic body of knowledge and represents an innovative approach to a complex medical challenge.

1.4. Analysis of global, economic, environmental, and social impact

Table 1. Expected benefits and impacts of various contexts

Context	Expected benefits and impacts
Public Health, Safety, and Welfare	Improved patient access to endoscopic examinations, leading to faster diagnoses and better treatment outcomes. Reduced risk of complications and adverse events during endoscopy procedures due to precise autonomous navigation.
Global	Potential to address the global shortage of specialized endoscopists, especially in underserved regions. May contribute to reducing the global clinical burden related to upper gastrointestinal issues.
Economic	Enhanced economic competitiveness through the development of advanced medical technologies. The manufacturability of the autonomous endoscopy system may pose challenges in terms of production costs as the complexity of the autonomous endoscopy system and the need for precision components may pose production cost challenges that need to be addressed.
Environmental	Reduced environmental impact compared to traditional endoscopy procedures, as the autonomous system may require fewer resources and generate less waste, such as, eliminating the need for Endoscopists and therefore their transportation CO2 emissions to the Hospital and back.
Societal	Potential to create cultural change in medical practice by introducing automation and robotics into the field of endoscopy. Improved societal well-being through quicker diagnoses and reduced healthcare costs for patients.

1.5. Market Research and Business Viability

Our market research indicates a significant need for an Advanced Navigational Endoscopy System. With unique features, competitive pricing, and a comprehensive plan for market entry, our project has strong business viability potential in the medical equipment industry.

1.5.1. Market Need and Size

The market need for our project is driven by several factors. Firstly, there is a growing demand for efficient and precise medical procedures, particularly in the field of gastrointestinal diagnostics. Upper gastrointestinal issues, such as esophageal and stomach disorders, are prevalent worldwide, and timely and accurate diagnoses are crucial for effective treatment. Additionally, the shortage of specialized endoscopists in many regions has created a need for autonomous systems that can assist in performing these procedures.

The market size for autonomous endoscopy systems is substantial, given the global prevalence of upper gastrointestinal issues. According to research conducted by Grand View Research, the global endoscopy market was valued at approximately USD 31.9 billion in 2020 and is expected to grow at a compound annual growth rate (CAGR) of 8.4% from 2021 to 2028[1]. This growth is attributed to an aging population, increased healthcare expenditure, and advancements in endoscopy technologies. Our product addresses a specific segment of this market by providing an autonomous solution for upper gastrointestinal endoscopy.

1.5.2. Target Customers and Demographics

Our target customers include healthcare institutions, hospitals, and medical clinics that perform upper gastrointestinal endoscopy procedures. Additionally, medical professionals specializing in gastroenterology and general surgery are key users of our system. The demographic profile of our target customers varies but generally includes healthcare providers such as HMC and professionals with expertise in endoscopy procedures [2] [3].

1.5.3. Competition and Unique Features

In the competitive landscape, globally there are existing endoscopy systems, both manual and semi-autonomous, offered by established medical equipment manufacturers. However, as per our research there is no local competitor that provides traditional endoscopy systems, let alone the autonomous ones. Moreover, our project distinguishes itself through its unique features and capabilities. Unlike traditional systems, our product offers:

- Full autonomy in navigation: Our system can autonomously navigate the upper gastrointestinal tract, reducing the need for manual control and specialized endoscopists.
- Live feedback to physicians: The system provides real-time video feedback to the physician via a Microsoft HoloLens VR headset, enhancing their situational awareness and control.
- Integration of machine learning: Machine learning algorithms are employed for center detection and precise navigation, ensuring accuracy and safety.
- Improved patient experience: The autonomous navigation reduces procedure time and minimizes discomfort for patients, leading to a more positive experience.

1.5.4. Pricing Strategy

Determining the appropriate pricing strategy for our product is essential for its market viability. The pricing of medical equipment typically takes into account factors such as manufacturing costs, research and development expenses, competition, and market demand. Given the complexity and advanced technology involved in our project, it is expected to be positioned as a high-end medical device.

The pricing will be competitive within the market segment of advanced endoscopy systems, taking into consideration the value it offers in terms of enhanced patient care, reduced procedure time, and improved physician control and feedback. However, specific pricing details will be further refined based on a comprehensive cost analysis and market assessment to ensure competitiveness and profitability.

Following are the different approaches that includes value-based pricing and cost-based pricing, supported by market and competitive analysis:

Cost-Based Pricing: Given the high R&D costs and the advanced technology involved in our project, it's important to fully account for these when setting your price. This ensures that you cover all your costs and achieve a profitable margin. Analyze all costs involved in manufacturing, development, and regulatory compliance to set a baseline price that ensures profitability while remaining competitive [4].

Value-Based Pricing: Focus on the specific benefits that your system offers over traditional endoscopy systems. This includes enhanced patient care, reduced procedure times, and improved physician control and feedback. Evaluate how these improvements can translate into cost savings for healthcare providers or better outcomes for patients, which can justify a premium price. As per insights from industry experts, incorporating value-based pricing involves understanding the full value story of our medical device and aligning it with healthcare economic data to illustrate its benefits clearly [5].

Competitive Analysis: Study pricing strategies of existing endoscopy systems, particularly those that incorporate advanced technologies such as robotics or enhanced imaging capabilities. Understand the pricing structure and market positioning of these competitors to better inform our own pricing strategy. This could involve looking at premium pricing tactics if your system offers significant technological advancements over current market offerings [6] [7].

Negotiated and Bundled Pricing: For institutions making larger purchases or committing to long-term contracts, consider negotiated pricing strategies. Bundling our system with other services or products could also provide attractive options for hospitals and clinics, allowing them to derive more value from a single purchase [8] [9].

By adopting a comprehensive pricing strategy that considers both the economic value our product delivers, and the costs associated with its development and delivery, we can set a price that is both competitive and profitable. The goal is to not only cover costs but also to capitalize on the unique benefits your innovative system provides.

1.5.5. Bringing the Product to Market

Bringing our product to the market will involve several key steps, including:

- Regulatory approvals: Ensuring that the product complies with all relevant medical device regulations and obtaining necessary approvals from regulatory bodies.
- Manufacturing and quality control: Setting up manufacturing processes to produce the Advanced Navigational Endoscopy System efficiently and with high quality.
- Marketing and distribution: Developing marketing strategies to promote the product to healthcare institutions and professionals. Establishing distribution channels to reach target customers effectively.
- Training and support: Providing training programs for healthcare professionals on the use of the system and offering ongoing technical support.
- Business partnerships: Exploring partnerships with healthcare organizations and institutions to facilitate product adoption and implementation.

1.6. Justification of the problem as a complex engineering problem

The development of the Advanced Navigational Endoscopy System is a prime example of a complex engineering problem, as defined by the IEEE standards. This project encapsulates a myriad of technical challenges, necessitating the integration of multiple disciplines and technologies to devise a solution that is both innovative and functional in the real-world medical setting. The complexity of this project is not only in its technical aspects but also in its potential impact on healthcare delivery, patient care, and medical practice.

Multiple Components or Subsystems

The architecture of our project is inherently complex, comprising multiple components or subsystems that must function cohesively. These include:

1. Machine Learning Algorithm: At the heart of the system is a sophisticated machine learning algorithm designed for real-time identification of the Esophagus' center. This algorithm must process live video feeds efficiently and accurately, a task that involves advanced image processing.

2. Mechanical Navigation System, Motor Control and Feedback Systems: The integration of the machine learning algorithm with the mechanical components of the endoscope, particularly the navigable tip, Maxon ECX SP13 motors controlled by EPOS4 controllers, is crucial. This subsystem involves precision mechanics to ensure smooth and accurate navigation through the Esophagus.

3. Virtual Reality Interface: The Microsoft HoloLens VR interface for physicians is another critical component. It must provide intuitive and real-time feedback, necessitating expertise in human-computer interaction, software development, and virtual reality technologies.

Multidisciplinary Nature

The project's multidisciplinary nature is evident in the diverse range of expertise and knowledge areas it encompasses:

1. Medical and Biological Sciences: Understanding the anatomy and physiology of the gastrointestinal tract is essential for designing a system that navigates this complex environment safely.

2. Robotics and Mechanical Engineering: The development of the autonomous navigation mechanism for the endoscope involves robotics, mechanical design, and control systems engineering.

3. Computer Science and Machine Learning: The project heavily relies on advanced algorithms for image processing and machine learning for real-time decision-making and navigation.

4. Electrical and Electronic Engineering: The implementation of the control systems for the motors, as well as the integration of sensors and feedback mechanisms, require in-depth electrical and electronic engineering knowledge.

5. Software Engineering and User Interface Design: Developing software for system control, data processing, and the VR interface involves software engineering and user interface design skills.

6. Ethical and Regulatory Considerations: Navigating the ethical and regulatory landscape of medical device development is also a critical aspect, requiring knowledge of healthcare regulations, patient safety standards, and ethical considerations in medical technology [10].

Addressing Real-World Challenges

The real-world application of the Advanced Navigational Endoscopy System involves addressing several challenges:

1. Safety and Reliability: Ensuring the safety and reliability of the system in a medical setting is paramount. This involves rigorous testing, validation, and adherence to medical safety standards.

2. User Acceptance and Training: The system must be designed with the end-user in mind, ensuring ease of use and acceptance by medical professionals. This involves not only intuitive design but also comprehensive training programs.

3. Interdisciplinary Collaboration: The project requires effective collaboration across various disciplines, bringing together experts in medicine, engineering, computer science, and more to ensure a holistic and well-rounded approach to the problem.

4. Innovation and Non-triviality: The project goes beyond extending existing solutions. It requires innovative thinking and novel approaches to overcome the unique challenges of autonomous navigation in a delicate and variable environment like the upper gastrointestinal tract.

In conclusion, our project exemplifies a complex engineering problem. It involves integrating multiple components and subsystems, requires a multidisciplinary approach, and addresses significant real-world challenges in the medical field. The successful development of this system will not only represent a technological triumph but also a significant advancement in medical diagnostics and patient care.

2. Background and related work

2.1. Background

Upper Endoscopy:

Upper endoscopy, or esophagogastroduodenoscopy (EGD), is a crucial medical procedure that enables the investigation and diagnosis of conditions affecting the upper gastrointestinal tract, which includes the esophagus, stomach, and duodenum. Figure 2 shows the implementation of the procedure of Endoscopy. This technique is vital for identifying organic diseases, inflammatory conditions, and malignancies, such as gastric and esophageal cancers [11].

Endoscopic Therapeutic Robot Systems (ETRS):

ETRS represents a significant advancement in medical procedures, integrating robotic systems, artificial intelligence (AI), and advanced imaging techniques to improve the precision and capabilities of traditional endoscopy. The ideal robotic endoscope combines affordability, versatility, precise control, comfort for the endoscopist, and smart functionality through integrated AI [12].

Robotic Arms in Medicine:

Robotic arms in medicine are highly precise tools that extend the capabilities of human surgeons and physicians. In endoscopic procedures, robotic arms offer enhanced precision and stability, which are crucial for delicate maneuvers and intricate surgical tasks. These systems can reduce human error and improve the outcomes of procedures by providing steadier instrument handling and better control.

Virtual Reality (VR) in Medicine:

Virtual Reality (VR) is increasingly being used in medical settings for training, planning, and conducting surgeries. In endoscopy, VR can simulate procedures for training purposes, allowing practitioners to gain experience in a risk-free environment. Additionally, VR can be used in real-time during procedures to provide a more immersive view of the patient's internal structures, enhancing the precision of endoscopic surgeries.

Machine Learning in Medical Navigation:

Machine learning models are transforming medical navigation by enhancing the accuracy of diagnostics and the efficiency of treatments. In endoscopic procedures, ML can analyze vast amounts of imaging data to identify patterns that might not be visible to the human eye, predict patient outcomes, and recommend precise intervention strategies. These capabilities make ML an invaluable tool in improving the safety and effectiveness of medical procedures.

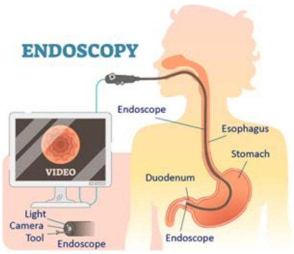


Figure 2: upper gastrointestinal tract endoscopy procedure [6]

2.2. Related work

In this section, we conduct a comprehensive review of existing Endoscopic Therapeutic Robot Systems (ETRS) to highlight their advancements in autonomous navigation and machine learning integration. Moreover, we discuss the different navigational methodology used in traversing the gastrointestinal tract, distinguishing between approaches that incorporate AI technologies and those that rely on traditional, non-AI based techniques. Finally, we aim to explicitly identify the research gap or areas requiring further investigation within the ETR’s discussed. This contextualization will serve as the foundation for our project, highlighting the significance of our work in addressing specific challenges and contributing to the current state of the field.

Starting in 1996, Khan et al. [13] designed a vision-based navigation system that employs low-level computer vision techniques for the guidance of an ETRS used in colonoscopy. The system leverages the extraction of two distinct types of navigational cues from colon images: dark regions and curved contours. Dark regions, characterized by areas of reduced intensity, primarily occur in the lower portion of the image, and serve as essential landmarks. The presence of curved contours indicates the occlusions caused by the inner colon muscles and aids in spatial mapping. To facilitate the integration of these visual features and enable efficient navigation, a hierarchical search space and environment representation, known as the QL-tree, is developed. The QL-tree comprises multiple interconnected quadtrees spanning all levels of the hierarchy.

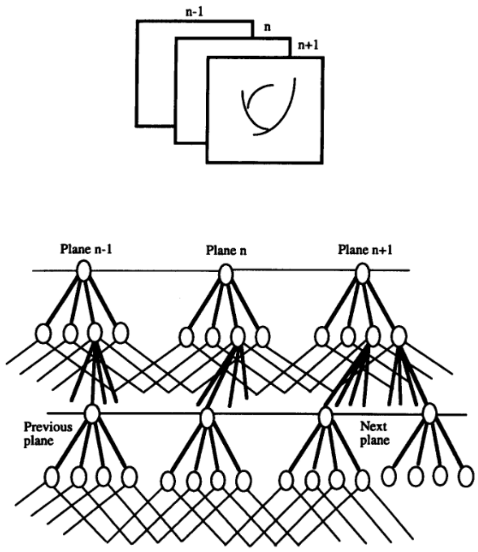


Figure 3: A section of QL-tree representation [13]

In their paper titled "Safety-aware robotic steering of a flexible endoscope for nasotracheal intubation," Deng et al. [14] propose a control framework, known as the Robotic Nasotracheal Intubation System (RNIS), for automated navigation of a flexible endoscope. The system utilizes visual feedback from endoscopic images to detect the lumen center. This is achieved through a fusion of image intensity and optical flow measurements. The image intensity analysis extracts anatomical features, while the optical flow method estimates scene motion and localizes the lumen center. By effectively combining these measurements using a weighted fusion strategy, the system achieves robust detection of the lumen center. The detected lumen center is then used as guidance for the orientation controller, which adjusts the endoscope tip's orientation to accurately track the center during the navigation process.

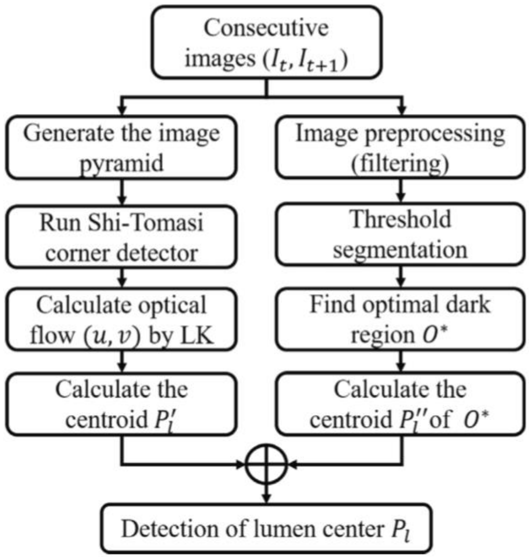


Figure 4: The computational process of lumen center detection [14]

Yang et al. [15] designed an advanced navigation algorithm that leverages monocular vision to automate the endoscope and enhance its maneuverability. The navigation pipeline consists of several key steps. Firstly, a data-driven depth estimation technique is employed to reconstruct a real-time approximate tissue surface, providing the system with spatial awareness. This is achieved by training a Convolutional Neural Network (CNN) to estimate pixel-wise depth maps from endoscopic images. Subsequently, digital topology techniques are applied to extract the spatial shape of the lumen by analyzing the skeleton of the tissue. To ensure smooth and efficient navigation, the skeleton is modified to obtain a smooth pathway that guides the endoscope through the luminal structure. Geometric information derived from the pathway is then utilized in an adaptive control strategy, enabling the endoscope to autonomously steer and advance with optimized speed.

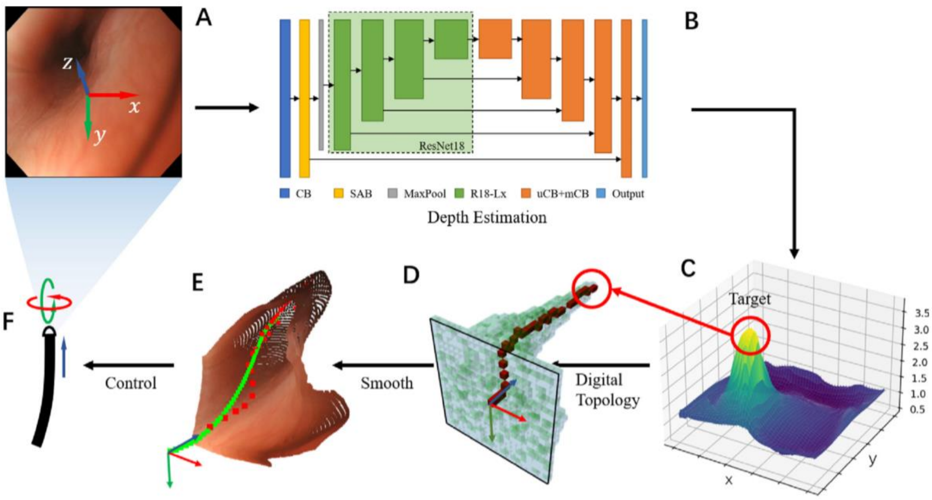


Figure 5: An overview of the pipeline of spatial awareness

Horie et al. [16] introduces an innovative approach for esophageal cancer detection by integrating artificial intelligence (AI) with endoscopy. The system utilizes convolutional neural networks (CNNs), a type of deep learning model specifically designed for image analysis. The CNN analyses endoscopic images by passing them through successive layers with convolutional filters that capture local patterns and features associated with esophageal cancer. Through training on a large dataset comprising 8,428 esophageal cancer images obtained from 384 patients, the CNN learns to recognize complex visual patterns indicative of cancerous lesions, achieving high sensitivity (98%) in detecting cancer cases, including small lesions below 10 mm. It also demonstrates the ability to differentiate between superficial and advanced cancer stages with 98% accuracy. The computational efficiency of the system allows for quick analysis of test images, making it a promising tool for early detection of esophageal cancer and potentially improving patient outcomes. The authors emphasize that further training could enhance the system's diagnostic accuracy, leading to early detection and improved prognoses for patients with esophageal cancer.

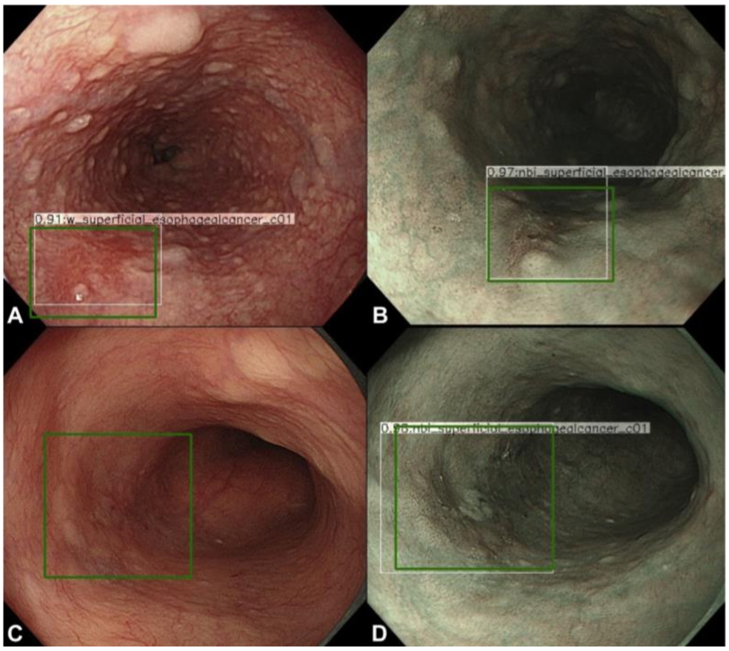


Figure 6: Examples of AI diagnosed images [16].

Mingqiang et al. [17] used image contour data to autonomously navigate the endoscope camera through the colon tract in colonoscopy procedure. This methodology involved three main steps, starting with image preprocessing for contour extraction it includes steps such as: greying, gaussian filtering, CLAHE and other image processing techniques

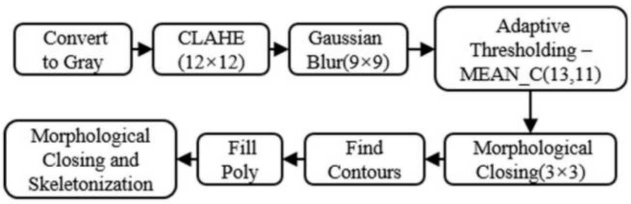


Figure 7: Image pre-processing steps for detecting contours and extracting them [17].

The second step requires for the contours to be clear, the main goal is to compute the steering value E. When the endoscopic view shows an increase in the closed contour this makes the curvature radius of the intestine increasing allowing the endoscope to maintain a faster speed. However, when there is a turn the number of closed contours decreases, and open contour increases hence making the speed of the endoscope lower. And start turning by factor E

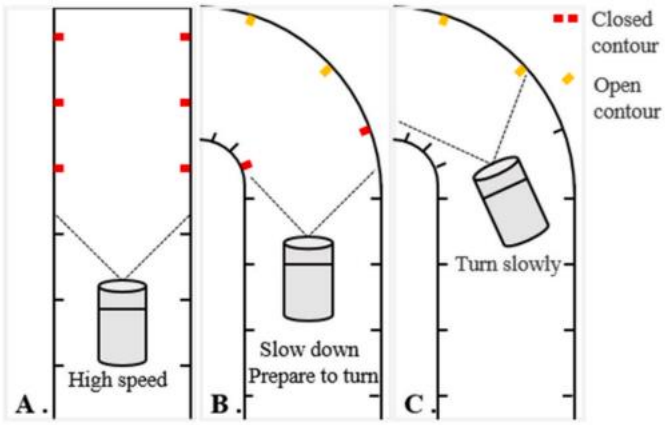


Figure 8: Three scenarios can be encountered [18].

The final step is when the contours are not clear this happens due to oversteering and understeering. A triple control method will be used during this case. This method is simply analyzing the latest data and it must achieve a relative correct control. When the number of consecutive frames cannot extract a clear contour, the physician takes control of the endoscopy camera.

Gruijthuijsen et al. [18] used the autonomous instrument tracking, this method used computer vision (CV) and deep learning (DL) techniques to track the laparoscopic instruments. This paper uses a novel tooltip localization system for autonomous tracking of the instruments. The following are explanation are the overview of this method used.

1- Tool tip localization: A mixture of DL and CV techniques are used to localize the tooltip. This method relies on tool segmentation, then extracting of 2D entry points and tips. This tooltip localization method can detect the tips of the medical instruments from the frames that are captured. According to the paper this localization method was able to detect tips in 84.46% of the frames.

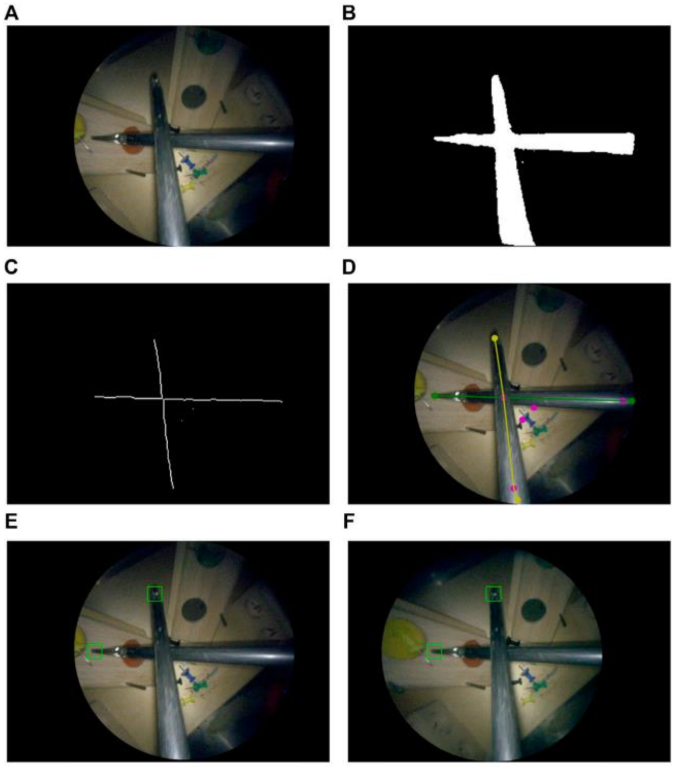


Figure 9: Instrument localization steps [18].

2- Visual Servoing: Visual servoing is a technique that uses visual feedback to control the motion of the robotic entity. The visual servoing used in this research paper combines the positional based visual servoing (PBVS) and Image based visual servoing (IBVS) which is for 3D based images. Allowing the endoscope to support remote center of motion and endoscope bending.

By integrating the tooltip localization technique and the combination of PBVS + IBVS, the system enables autonomous localizing the position of the endoscope camera. Moreover, the co-manipulation fallback is supported in this approach, which allows an easy switching functionality from robotic control to surgeons control.

Table 2. Comparison of related work and proposed solution

Name	Intended Use	AI Integration	MR Integration	Co-manipulation
Vision based navigation system [11]	Colonoscopy	N/A	N/A	Yes, requires human input for precise control
Robotic Endotracheal Intubation System (RNIS) [12]	Nasotracheal intubation procedures	N/A	N/A	Not needed, high level of autonomy is used

Lumen adapted navigation-based system [15]	Navigate along the luminal structure	Yes, Employs spatial awareness network for depth estimation	N/A	Not needed, operates independently
N/A [22]	Detect esophageal cancer	Yes, uses Single shot multibox detector (SSD)	N/A	N/A
Using image contour data to navigate [13]	Colonoscopy	N/A	N/A	Yes, only with continuously unclear contours
Autonomous instrument tracking (AIT) [14]	Minimal invasive surgery	Yes	N/A	Yes, surgeon can take over functional tasks
Advanced Navigational Endoscopy System **(Our Solution)**	Upper Gastrointestinal Endoscopy	Yes, utilizes yolov8 model	Yes, HoloLens is used to control insertion and retraction.	Yes, when the center cannot be detected in multiple consecutive frames

3. Requirements analysis

3.2. Functional requirements

We defined the functional requirements in Table 3 to ensure smooth functioning of our project for each aspect of the project.

Table 3. Functional Requirements

Functional Requirements	Description
Autonomous Navigation	The system requires a machine learning based navigation mechanism that enables the endoscope to autonomously travel from the mouth to the stomach. This involves continuous detection of the center path within the Esophagus and adjusting its trajectory to avoid obstacles. During this stage, the Physician must not have any navigation controls.
Robotic Arm Control	A robotic arm is needed to insert and retract the endoscope. It must synchronize with the endoscope's navigation system to ensure smooth and safe passage through the Esophagus.
Real-Time Imaging and Lighting	The endoscope must be equipped with a camera and lighting at its bendable tip. This setup is crucial for providing

	real-time visual feedback as the endoscope navigates through the Esophagus and into the stomach.
VR Interface for Physician Control	Upon reaching the stomach, the system should offer a VR interface (e.g., HoloLens) to the physician. This interface will display a live feed from the endoscope and allow the physician to control the endoscope's tip/camera movement on reaching the stomach.
Feedback and Control Transfer	The system must be capable of transferring control of the endoscope from its autonomous navigation mode to the physician. This transfer should be seamless, allowing the physician to take over for detailed examination and diagnosis inside the stomach.
User-Friendly Interface for Physicians	The interface for the physicians should be intuitive, allowing them to easily control the endoscope's movements and camera angles by simple gestures or movements, such as turning their head while using the VR headset.

Table 4. Use cases

Use Cases	Description
Autonomous Endoscope Insertion	The system autonomously inserts the endoscope into the patient's mouth, navigating through the Esophagus to the stomach. This process involves real-time detection and avoidance of obstacles, ensuring safe passage.
Real-Time Imaging and Data Streaming	As the endoscope navigates, it continuously transmits real-time video and data back to the physician. This includes high-quality imaging and lighting adjustments for clear visibility inside the Esophagus and stomach.
Physician Interaction with VR Interface	Upon reaching the stomach, the physician interacts with the VR interface to receive live feed and control the endoscope. This includes manipulating the camera angle for thorough examination.
Transfer of Control from Autonomous to Manual	The system seamlessly transfers control from its autonomous navigation mode in Esophagus to handing over manual control in the Stomach for wide view by the physician. This transition is crucial for the detailed diagnostic phase inside the stomach.
Physician-Controlled Detailed Examination	The physician conducts a detailed examination of the stomach, controlling the endoscope's movements and camera via the VR interface. This phase allows for precise diagnosis and investigation.

Retraction and Safe Removal of Endoscope	Post-examination, the system retracts the endoscope safely from the stomach, through the Esophagus, and out of the patient's mouth, either autonomously or under physician control.

3.3. Design constraints

Table 5. Design constraints

Constraint	Type (Technical/ Socio-Economical)	Relevance to the Project	Evaluation Plan	Success Criteria
Video Capturing	Technical	The design should provide at least 30 to 45 frames per second to avoid any lag detected by the physicians during the operation.	The design should be tested on an end device.	The nearer the frame count is to 30 frames per second, the more optimal it is.
Quality of streamed video to the HoloLens	Technical	The frames taken by the camera should be streamed in an acceptable resolution for the physicians to see on the HoloLens and for the model to be trained on. It should not be lower than 720p.	Various endoscopes with varying camera qualities will be evaluated.	The best fit camera with endoscope to all applicable constraints will be chosen.
Real-time Navigation and Control	Technical	The system must navigate in real-time with minimal latency to avoid lag and ensure accurate and safe maneuvering through the Esophagus.	Testing latency and responsiveness under various conditions.	The architecture should not exceed 250ms latency. The processing of the frames by the central entity should not exceed 33ms to accommodate for the 30fps streaming rate.

Centre detection	Technical	The model should provide an accurate result that meet the requirements by 95%.	Testing the ML model with test images to check if the model detects the center.	The accuracy should be at least 95%.
Data Privacy and Security	Socio-Economical	Protecting patient data and ensuring compliance with data protection regulations.	Ensuring that rules and regulations are implemented by the client who will be using our system.	Adherence to IEEE, ACM, and local Ministry of Public Health standards.
Cost-Effectiveness	Socio-Economical	The system should be financially viable for widespread use in medical facilities.	Cost analysis and comparison with existing solutions.	Costs remain within a competitive range for similar medical devices.

3.4. Design standards

Table 6. Engineering Standards used in the project

Standard	Relevance to the project
ISO 13485:2016	This standard relates to the quality management systems for medical devices. It ensures that the endoscopic system is designed and manufactured to consistently meet applicable regulatory and customer requirements.
IEC 60601-1	Pertains to the basic safety and essential performance of medical electrical equipment. It is crucial for ensuring the endoscopic system is safe for patient interaction and operation in a medical environment.
IEEE 802.11 (Wi-Fi)	For wireless communication standards, ensuring reliable and secure data transmission between the endoscope and the HoloLens.
USB 3.0	For high-speed data transfer between the endoscope camera and the processing unit, ensuring real-time image and data transmission.

3.5. Professional Code of Ethics

Social Issues and Responsibilities

- **Accessibility and Non-Discrimination**: The technology should be accessible to all patients regardless of socio-economic status, race, gender, or religion, aligning with principles of equity in healthcare as practiced by our collaborator HMC.

- **Transparency and Patient Consent**: Patients should be fully informed about the procedure, the technology used, and any associated risks, ensuring informed consent.

Ethical Considerations and Stakeholder Interests

- **Beneficence and Nonmaleficence**: The primary goal is to benefit the patient by providing a more accurate and less invasive diagnostic tool while ensuring no harm is caused.
- **Professional Integrity and Accountability**: The development team must maintain high standards of integrity, acknowledging and correcting errors, and being transparent about the system's capabilities and limitations.

Selected ACM and IEEE Code of Ethics

- **IEEE 1.2**: "Avoid real or perceived conflicts of interest whenever possible, and disclose them to affected parties when they do exist." This is relevant in ensuring that the development and deployment of the system are free from conflicts of interest, particularly in terms of financial gains or research biases.
- **IEEE 1.5:** "Seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data."
- **IEEE I-7**: " Stakeholders and users should accept our terms and services which include avoiding injuring others and their property and protecting the privacy of others.
- **IEEE II-7:** Stakeholders and users should not use our product or service to discriminate any part of the community according to their race, religion, etc.
- **IEEE 7.8**: "Treat fairly all persons regardless of such factors as race, religion, gender, disability, age, or national origin." This aligns with the project's commitment to accessibility and non-discrimination.
- **ACM 1.2**: "Avoid harm." In the context of this project, this involves ensuring that the technology does not cause physical harm to patients and that data security measures are robust to prevent harm through data breaches.
- **ACM 1.6:** "Respect privacy of the people and their properties and collect/train data after confirmations."
- **ACM 2.3:** "Usage of product/services should be under the local and international laws and regulations."

Table 7. Engineering Code of Ethics and Professional Practice

Sec. No	Code	Usage and practice addressing an identified issue
IEEE 1.2	Avoid conflicts of interest	Ensuring the project's objectives are aligned with patient welfare and not influenced by external commercial interests.
IEEE I-5	Seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data.	Positive and negative feedback as well as suggestions are welcomed for further improvements to our developed system.
IEEE 7.8	Treat all persons fairly	Developing and deploying the system in a manner that is accessible and equitable to all patient demographics.
IEEE I-7	Users should accept our terms and services which include avoiding injuring others and their property	Patients are asked to accept our terms and services in order for the system to work efficiently and for the success of the operation.

	and protecting the privacy of others.	
IEEE II-7	Users should not use our product or service to discriminate any part of the community according to their race, religion, etc.	It is illegal to prevent or delay anyone from using our system because of their race, religion, or gender
ACM 1.2	Avoid harm	Implementing rigorous testing and safety protocols to ensure the technology is safe for patient use.
ACM 1.6	Respect privacy of the people and their properties and collect/train data after confirmations.	The data collected through the Endoscope camera shall only be used in assisting the diagnosis.
ACM 2.3	Usage of product/services should be under the local and international laws and regulations.	Before using our system, users need to get official approvals from Ministry of Public Health and any other related governmental entity

3.6. Assumptions

For smooth functioning of our system, we assume the following points to have been met:

- **Availability of Equipment and Materials:** Successful implementation of the system assumes that all required hardware and software are readily available. This includes the robotic arm, endoscopic devices, and any ancillary materials needed for procedures. Ensuring availability is crucial to avoid delays in deployment and operation.
- **Stable and Reliable Computer System:** The system depends on the computational power and reliability of the computers used to control the robotic arm and process data from the HoloLens. Stability in this context means the systems are robust against crashes and capable of handling real-time data without lag, ensuring smooth operation during medical procedures.
- **User Training and Acceptance:** For the technology to be effective, users (surgeons, technicians) must be adequately trained on how to operate the new system and must accept its usage as part of standard medical procedures. User acceptance is critical to the successful adoption and optimal use of the technology.
- **Maintenance and Support:** Regular maintenance and readily available support are assumed to ensure that the system functions correctly over time. This includes scheduled check-ups, updates to software, and quick-response troubleshooting to address any issues that may arise during operations.
- **Power Supply:** The assumption here is that a consistent and uninterrupted power supply is available to support the operation of all components throughout their usage. This is essential to prevent disruptions during medical procedures, which could pose risks to patient safety.
- **IMU information is built-in on the HoloLens:** It is assumed that the Inertial Measurement Unit (IMU) necessary for tracking movements in space is integrated into the HoloLens. This integration is critical for accurate spatial navigation and alignment in augmented reality applications used during endoscopic procedures.

- **The Esophagus tissue data used to train the machine learning model has no significant disorder to allow increased accuracy for the center detection:** For the machine learning models to accurately predict and analyze the center of the esophagus during procedures, they must be trained on high-quality data. This assumption means that the data used is representative of typical esophageal conditions, without abnormalities that could skew the model's accuracy.

4. Project Plan

4.1. Project milestones

Table 8. Milestones of the project – SDP I

Milestone	Description	Deliverables
Project inception, conceptualization, literature review and related work	Discuss and understand the project, its requirements, and components. Then, research on related past work.	Complete the relevant sections of the report
Investigating the required hardware	Visit HMC (project collaborators) and investigate the hardware availability	Readiness of hardware and timed access to it at HMC
Gain necessary knowledge to work on the hardware	Learn how to deal with and implement the hardware – its relevant interfaces, programming languages and other supported configurations	Initial system implementation
Proof of Concept	Implement the Proof of Concept to demonstrate the feasibility of the project.	Complete the PoC sections in the report
Initial version of the Interim Report	Complete all the required sections in the report for the first part of the project (SDP I).	Initial version of the report
Report review and final version of the Interim report	Review all the report contents with the supervisor for the content, grammatical and lexical errors to make the necessary corrections for the final version the interim report	Final version of the report
Presentation	Create a presentation and a video demonstration for the project to motivate the audience for our project	PowerPoint presentation and video demonstration

Table 9. Milestones of the project - SDP II

Milestone	Description	Deliverables
Individual sub-system development	Develop each sub-system highlighted in the project and test it.	Document the development and testing by completing the relevant sections of the report
System integration	Visit HMC and integrate the entire system and test it.	Document the integration and testing of the overall system by

		completing the relevant sections of the report
Initial version of the Final Report	Complete all the required sections in the report for the entire project.	Initial version of the report
Report review and final version of the Final report	Review all the report contents with the supervisor for the content, grammatical and lexical errors to make the necessary corrections for the final version the interim report	Final version of the report
Presentation	Create a presentation, poster and a video demonstration for the project to motivate the audience for our project	PowerPoint presentation, poster and video demonstration

4.2. Project timeline

While most team members worked in every part of the project, we assigned a team member to be primarily responsible and overlook a particular task wherein they had to corroborate with other team members for that particular task.

Table 10A. SDP-I Timeline

Milestone	Tasks	Description	Start Date	End Date	Assigned to
Project Conceptualization	Complete report section 1	Formulate the idea of the project to explain the problem statement, objectives, and significance. Assess the impact and market research while justifying the problem as a complex Engineering problem	03/09/2023	09/09/2023	Baig
Literature Review	Background and related work	Research existing work related to the project and compare our design to similar products available in the market	10/09/2023	23/09/2023	Aloush Ibrahim

Preparing access to the required hardware	Collaborating with HMC	Communicating with the HMC team to provide appropriate gate passes to access the relevant hardware required for the project	10/09/2023	26/11/2023 (Last visit to HMC for SDP1)	Aloush Baig
Machine learning model	Develop the ML model	Develop the ML model for the endoscopic tip to be able to navigate through the center of the Esophagus	20/09/2023	10/11/2023	Hilou Ibrahim
Mapping range navigation	Map the endoscopic tip movement onto the motors	Map the endoscopic tip range and degrees of freedom onto the motors with the EPOS4 controllers	01/10/2023	17/11/2023	Hilou Ibrahim
Proof of Concept (PoC)	Implementation of the Proof of Concept	Proves the feasibility of our design idea	10/11/2023	23/11/2023	All
Interim Report (First version)	Submit the first version of Interim report	Fill in all the required sections for the interim report and finalize the submission	10/11/2023	25/11/2023	Baig
Interim Report (Final version)	Make necessary changes and submit the final version of the report	Make all the changes suggested by the supervisor with respect to the content, lexicology and syntax and finalize the submission of the final version of the Interim report	10/11/2023	2/12/2023	Baig

Presentation	Create a PowerPoint presentation	The presentation explains the motivation and implementation of our project	20/11/2023	25/11/2023	Baig
Demonstration	Create a demo video	Create a video demonstrating the proof of concept of our project	20/11/2023	1/12/2023	All

Table 11B. SDP-II Timeline

Milestone	Tasks	Description	Start Date	End Date	Assigned to
HoloLens Interfacing	Get the IMU sensor readings based on user's head movements and map it to insert/retract the endoscope from Esophagus		04/02/2024	22/02/2024	Aloush & Ibrahim
Robotic Arm Interfacing	Control the robotic arm movements through Wi-Fi as a sub-system playing a role in insertion/retraction		22/02/2024	07/03/2024	Hilou & Ibrahim
Unity Simulation	Simulate the entire system onto unity		04/02/2024	01/03/2024	Ibrahim & Baig
3D Model Design	Design and print a 3D model resembling the actual human Esophagus to test the system on		10/03/2024	04/04/2024	Hilou
System Testing	Performing system unit testing and entire system testing		16/04/2024	20/04/2024	All
Final Report (First version)	Submit the first version of Interim report	Fill in all the required sections for the interim report and finalize the submission	10/11/2023	25/11/2023	Baig & Ibrahim
Final Report (Final version)	Make necessary changes and submit	Make all the changes	23/04/2024	30/04/2024	Baig

	the final version of the report	suggested by the supervisor with respect to the content, lexicology and syntax and finalize the submission of the final version of the Interim report			
Presentation & Poster	Create a PowerPoint presentation	The presentation explains the motivation and implementation of our project	23/04/2024	30/04/2024	Baig
Video Demonstration	Make pitching and demonstration videos	Pitching video briefly gives and idea of our project while the demonstration video	23/04/2024	30/04/2024	Aloush
All final deliverables	Report, Peer review, Presentation, Pitching video, Demonstration Video	All the deliverables demonstrating our work throughout the SDP	1/05/2024	11/05/2024	Baig

4.3. Anticipated risks

Table 12. Risks

Risk event	Approach to minimizing the effect on project success
Unavailability of a 3D Esophagus model with defined interior of the Esophagus	Use an alternative plastic ripples pipe mimicking similar features to an interior of the Esophagus
Inaccessibility of the equipment	Accessing the equipment (Endoscope, robotic arm, etc.) could be a hassle as they are provided by our collaborators, HMC, and accessing HMC premises requires gate passes which take immense time to get approved and have to be regenerated for every visit. To overcome this, we plan to work other parts of the project in the meantime.

Poor computer specifications to implement the Machine Learning model	The machine learning model implementation could take a very long time (like 30 hours) with regular computer specifications available. Access to a powerful computer available with QU CSE department is needed to be able to minimize the effect of project progress. The group is trying to get access to a powerful server with GPU to speed up the training task.
Equipment delivery	Our progress would at times remain on hold due to delivery times of items ordered that are needed immediately. To overcome this, we anticipate the required equipment and try to place the orders early on.

5. Solution design

5.1. Solution overview

Our proposed solution is a groundbreaking endoscopic system, designed to enhance the precision and effectiveness of medical procedures. At its heart, the system integrates a robotic arm with an advanced endoscope, equipped with a high-resolution camera. This integration allows for meticulous navigation and detailed visualization within the human body, particularly focusing on the Esophagus. The system is further augmented by a sophisticated machine learning model (Yolo v8), which aids in the precise autonomous maneuvering of the endoscope tip through the center of the Esophagus, ensuring safety and accuracy in procedures.

To complement this technology, we incorporate the use of a Microsoft HoloLens VR headset, offering medical professionals an immersive and intuitive view of the internal structures they are navigating. This aspect of the design not only enhances the user experience but also contributes to the accuracy and efficiency of medical procedures. The entire system is designed with a keen focus on reliability, including a dependable power supply and a comprehensive maintenance plan, ensuring consistent performance and longevity. In essence, our solution represents a fusion of cutting-edge technology and practical functionality, aiming to revolutionize the field of endoscopy by making it safer, more precise, and more user-friendly.

5.2. High level Architecture

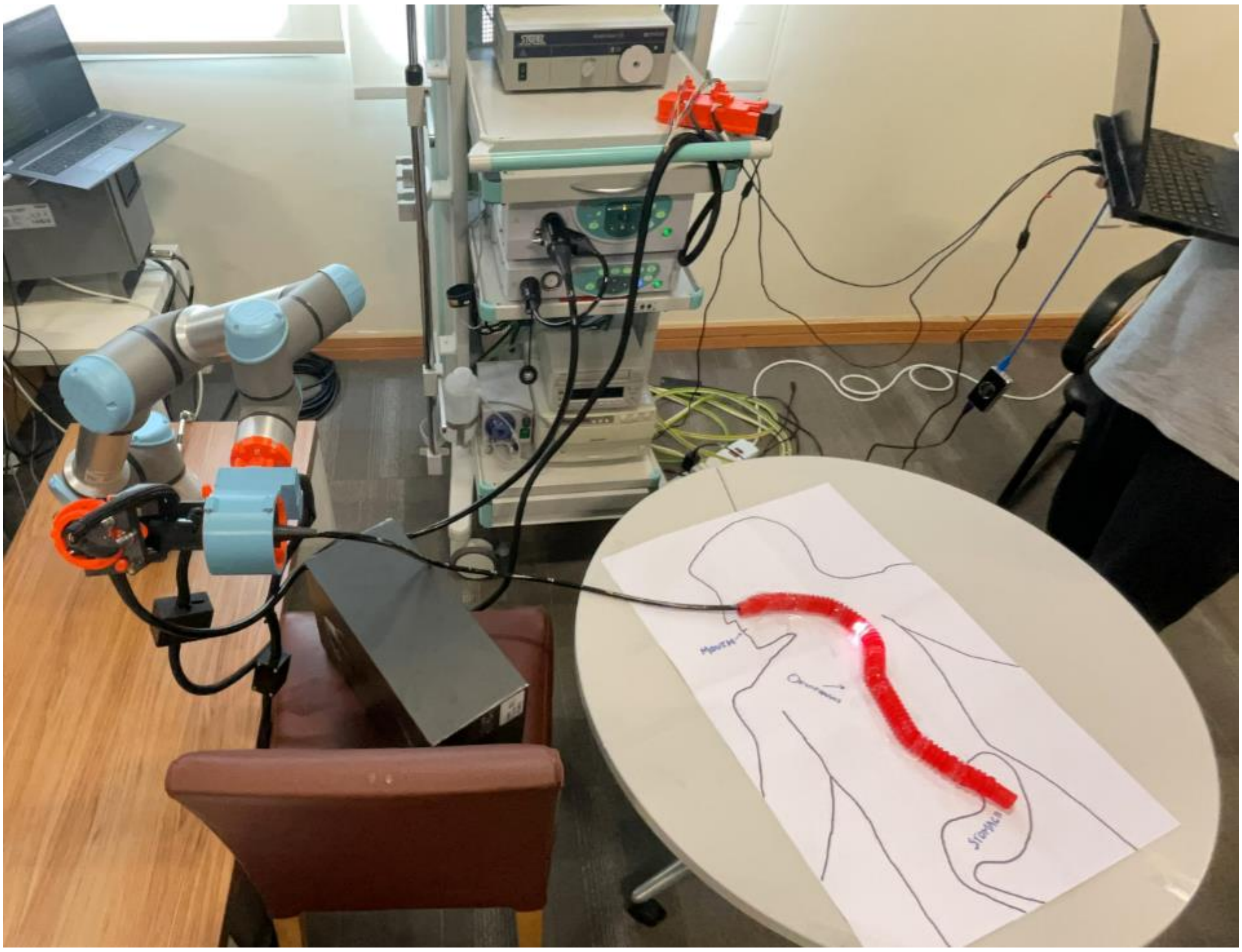


Figure 10. High Level Architecture

The system involves several components: a robotic arm, an endoscope, a machine learning module, motor controllers, a VR (virtual reality) system, and the doctor who oversees the procedure.

- The Robotic Arm initiates the process by inserting the endoscope.

- The Endoscope is responsible for transmitting a live video stream and has reached the stomach, which triggers a signal to stop navigation.

- The Machine Learning Module performs critical functions such as detecting the center of the esophagus and calculating the required angle for navigation to ensure the endoscope navigates through the esophagus effectively.

- The Motor Controller (EP054) adjusts the tip angle of the endoscope based on the machine learning module's calculations.

- There is a specific motor mentioned, Maxon ECX SP13, which likely refers to a type of motor used in the endoscope for precision movements.

- The VR System (HoloLens) displays the live image stream that the endoscope captures.

- Finally, the Doctor is the end user who is provided with the live image from the VR system to observe during its navigation in the Esophagus and then be able to control the endoscopic procedure.

The figure 11 shows the connections in a high-level representation of the system's operation, highlighting the interaction between hardware components and the software or machine learning elements, with the doctor providing oversight and control. It is indicative of a sophisticated medical procedure that integrates advanced technologies like robotic automation, machine learning for navigation and image analysis, and immersive VR for real-time monitoring.

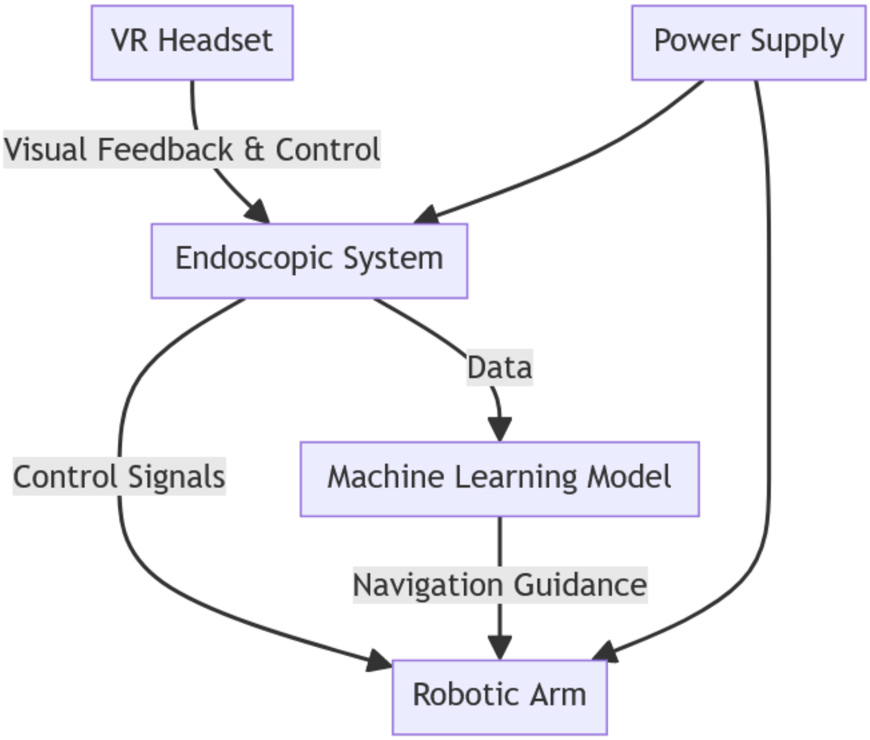


Figure 11: Block diagram

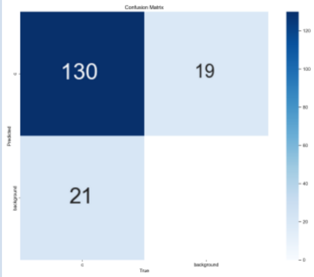
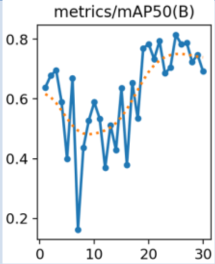
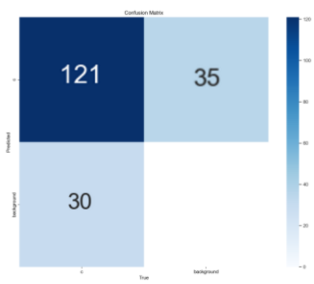
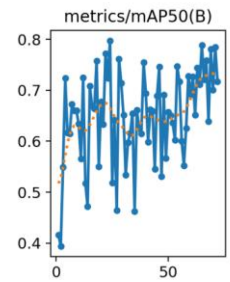
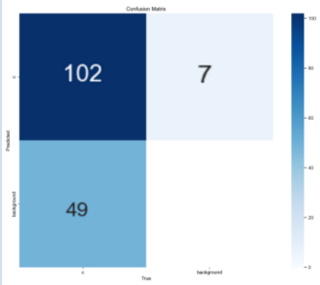
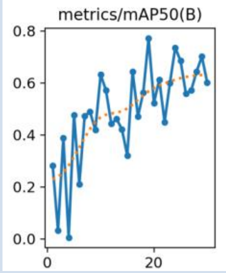
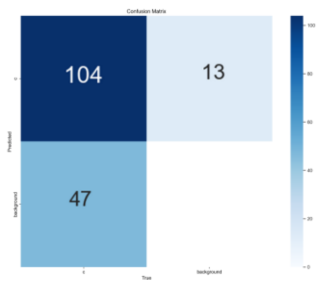
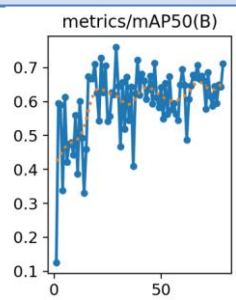
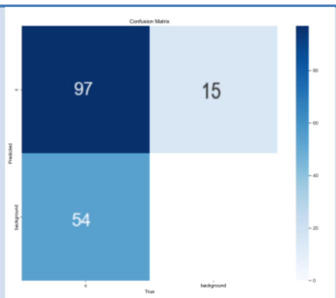
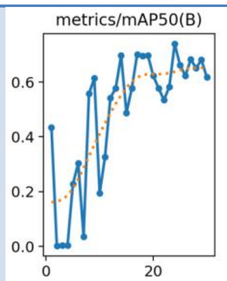
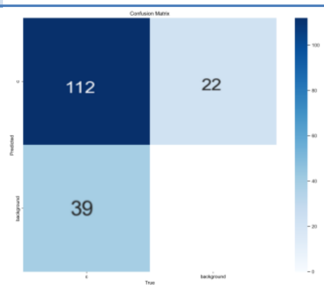
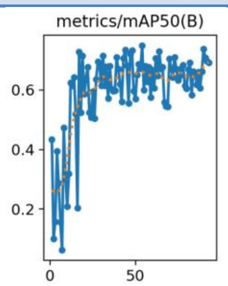
5.3. Design alternatives

5.3.1. Machine Learning Model

In this project we have trained our model using YOLO v8 in different sizes and complexities

Table 13. Model comparison of YoloV8

Model	Size	F1 score	Epochs	Confusion Matrix	Results (mAP)

Yolov8n	Nano	0.865	30		
Yolov8n	Nano	0.794	150		
Yolov8s	Small	0.784	30		
Yolov8s	Small	0.7761	150		
Yolov8m	Medium	0.7578	30		
Yolov8m	Medium	0.7860	150		

5.3.2. Robotic Arm

With regards to the robotic arm, we could either design our own robotic arm which is very specific to the needs of our project or use a readily available, widely used robotic arm in the market. Since building our own is out of scope of our project and requires its own testing and given the time constraints and equipment availability constraints, we decided to proceed with the robotic arm that was available to us, UR5e. One alternative design that we did develop as a prototype to demonstrate for the project was 3D printed using Blender software.

Table 14. Alternative Designs of Robotic Arm

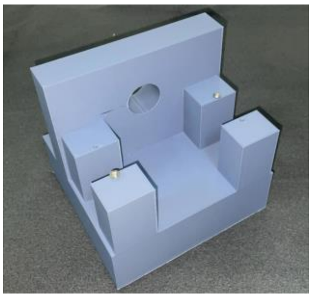
Robotic Arm Design	Details
	Readily available and tested robotic arm widely used in the medical field for various implementations that will be used to insert and retract the endoscope into the Esophagus.
	A custom 3D printed prototype to replicate the implementation of a robotic arm. The wheels along with the support resting on a motor synchronously carry out the function of insertion and retraction of the endoscope into the Esophagus.

5.4. Hardware/software used

Table 15. Needed HW/SW

HW/SW details	Image	Platform	Avg Cost	Justifications & Specifications
Microsoft HoloLens VR headset		Microsoft Windows	3500 USD	The best in the market since it comes built in with Inertial measurement unit (IMU) that contains 4 sensors - Accelerometer, gyroscope, and magnetometer, that'd help in mapping the IMU movements for Physician VR navigation of

				Endoscopic tip in the stomach.
Robotic Arm Universal Robots UR5e		-	32105 USD	Lightweight (5kg) in comparison to other robotic arms with joint navigation capabilities making it a good choice for medical use.
Esophagus Replica		-	2 USD	Best model replica of an Esophagus available.
Endoscope with navigable tip and camera EC-590WM4		-	3275 USD	Available with navigable tip that can be controlled from the rear using the motors controlled by a microcontroller are perfect in size.
EPOS4 Controllers		-	590 USD	Compact design with prior use in medical field makes it an ideal choice
Maxon ECX SP13 motors		-	350 USD (x2)	Super-fast, configurable brushless DC motors allowing required latency make it a good choice.

Raspberry Pi Pico Microcontroller		-	6 USD	
Fujinon System Processor 4400		-	1300 USD	Best supplier in the market providing that can handle the live communications needed for an endoscope with good latency make it an ideal choice.
Fujinon Lightsource 4400		-	1300 USD	Best supplier in the market providing specifications such as light, camera live feed, etc. make it a good available choice in the industry.
3D printed model			15 USD	The best customized design could be obtained by designing it and printing it to imitate a robotic arm.

5.5. Hardware design

In our project, the hardware design is a critical component that ensures the seamless integration of various technologies to achieve the desired functionality. This section will delve into the design aspects of the major hardware subsystems, discussing the technological approaches, trade-offs, and justifications for the selected approaches.

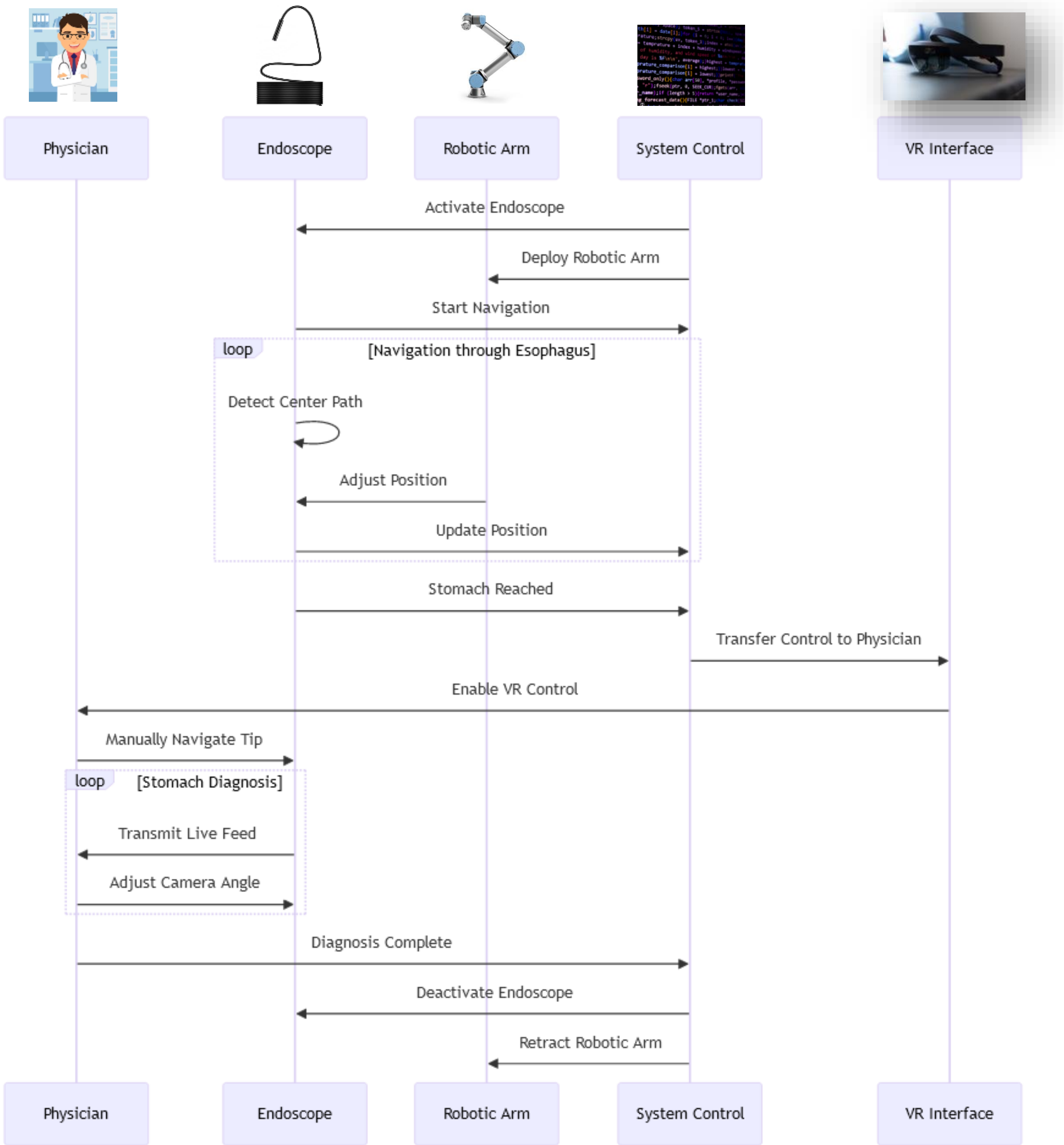


Figure 12 Signal Logic Diagram

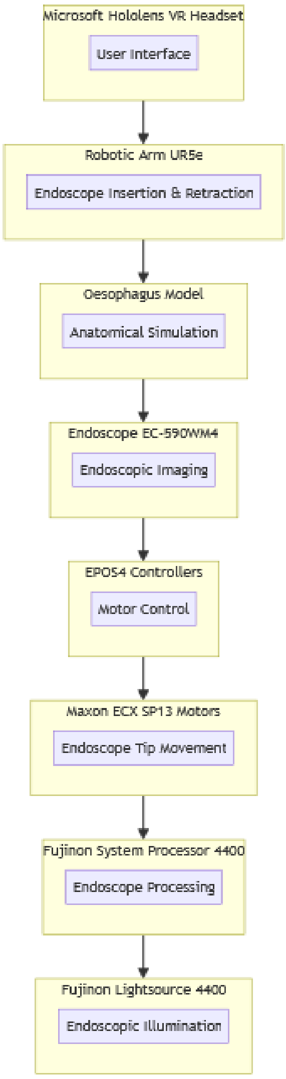


Figure 13 Connectivity diagram for modular hardware

Microsoft HoloLens VR Headset

Theory: The Microsoft HoloLens VR headset is utilized for the physician's interface, providing an immersive and interactive 3D visualization of the endoscopic procedure. This augmented reality (AR) technology overlays digital information onto the real world, enhancing the physician's perception and decision-making during the procedure.

Trade-offs: The choice of AR over traditional 2D screens offers enhanced depth perception and spatial awareness, crucial for delicate medical procedures. However, this comes with increased complexity in data processing and the need for a more sophisticated user interface.

Justification: The HoloLens was selected for its advanced AR capabilities, ease of integration with medical imaging systems, and its ability to provide real-time, hands-free information to the physician, thereby enhancing the precision and safety of the endoscopic procedure.

Robotic Arm Universal Robots UR5e

Theory: The UR5e robotic arm is employed for the precise insertion and retraction of the endoscope. Its design allows for smooth, controlled movements, essential for navigating the sensitive gastrointestinal tract.

Trade-offs: While the UR5e offers exceptional precision and reliability, it is a more costly option compared to simpler robotic systems. Its size and complexity also require careful integration into the medical environment.

Justification: The UR5e was chosen for its high precision, ease of programming, and robustness, making it ideal for medical applications where accuracy and reliability are paramount.

Endoscope with Navigable Tip and Camera EC-590WM4

Theory: This endoscope model is equipped with a navigable tip and camera, providing high-resolution images from inside the gastrointestinal tract. The navigable tip enhances maneuverability, allowing for thorough examination of the tract.

Trade-offs: The advanced features of this endoscope model come at a higher cost and complexity compared to standard models. However, the enhanced capabilities justify the investment.

Justification: The EC-590WM4 was selected for its superior image quality, navigability, and compatibility with the robotic arm and control systems, ensuring comprehensive and detailed gastrointestinal examinations.

EPOS4 Controllers and Maxon ECX SP13 Motors

Theory: The EPOS4 controllers and Maxon ECX SP13 motors are integral for controlling the movements of the endoscope tip. These components provide the necessary precision and responsiveness for the up, down, right, and left movements of the endoscope tip.

Trade-offs: The selection of these high-end components ensures optimal performance but at a higher cost. The complexity of the system also requires skilled personnel for maintenance and operation.

Justification: These components were chosen for their reliability, precision, and compatibility with medical-grade equipment, ensuring the endoscope can be maneuverer safely and accurately within the gastrointestinal tract.

Fujinon System Processor 4400 and Lightsource 4400

Theory: The Fujinon System Processor 4400 and Lightsource 4400 are essential for processing the endoscopic images and providing the necessary illumination. These components ensure that the images captured by the endoscope are clear and well-lit, crucial for accurate diagnosis.

Trade-offs: The choice of these specific Fujinon models ensures high-quality image processing and illumination but may involve higher costs and specific maintenance requirements.

Justification: The Fujinon System Processor 4400 and Lightsource 4400 were selected for their high performance, reliability, and compatibility with the EC-590WM4 endoscope, ensuring optimal visualization during the endoscopic procedures.

5.6. Software design

The software aspect in our code focuses on the machine learning model for the detection of the center of the Esophagus by the camera in the endoscope tip which then communicates this to the EPOS4 controller to allow the realignment of the tip appropriately to be able to proceed forward.

The software design is structured in a modular and sequential manner. This approach is particularly beneficial for debugging and iterative development, allowing for isolated testing and modification of individual components without the need to execute the entire codebase.

The process begins with the importation of necessary libraries, including OpenCV for frame capture and YOLOv8 for object detection, indicating the application's reliance on image processing and advanced object detection capabilities. The inclusion of Excel libraries, primarily for debugging purposes, suggests a methodical approach to tracking and analyzing the program's execution.

Following the initial setup, the code includes a cell with methods to control the EPOS (Electronic Power Output System), crucial for interfacing with hardware components. Ensuring the connection of the EPOS units is vital, as it verifies the operational status of the physical components in the system.

The GPU check is a preliminary step to ensure the availability of computational resources, especially important given the use of a sophisticated model like YOLOv8. The selection of a specific trained model for use indicates a customized approach, tailoring the software to specific requirements or datasets.

Activating the Excel sheet for debugging purposes demonstrates a pragmatic approach to monitoring the software's performance and outputs, indicative of a development process that values real-time feedback and data logging. This would further help us testing and evaluating our model.

The core functionality resides in a comprehensive method that encompasses several operations, including analyzing the model's output for detected objects, focusing on the largest box, and calculating spatial coordinates or movements (xAngle and yAngle). The system's dynamic response to real-time inputs is evident in the conditional actions based on these angles, particularly the command sent to EPOS.

The main cell captures frames from the camera and feeds them to the model, creating a feedback loop where visual input directly influences hardware actions. This setup is characteristic of systems requiring real-time interaction with the environment.

In summary, the software design is characterized by its modular structure, with each cell performing distinct functions that collectively contribute to the system's overall operation. The integration of image processing, object detection, hardware control, and real-time feedback mechanisms highlights a sophisticated and purpose-built software architecture.

Here is a flowchart illustrating the software design process:

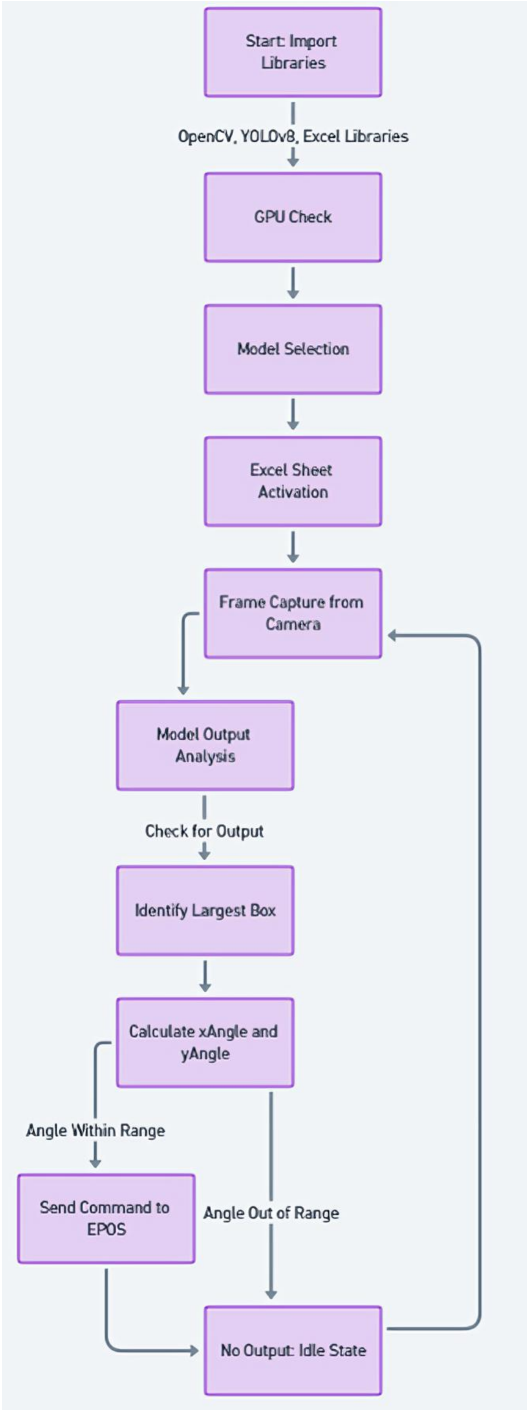


Figure 14 Software design process and implementation

5.7. New-gained knowledge

While developing the 'Advanced Navigational Endoscopy System,' our team has acquired a wealth of new knowledge and skills, particularly in the realms of hardware and software design. This subsection highlights the significant areas of new-gained knowledge, the methods used to acquire these skills, and the resources that facilitated our learning.

Advanced Endoscopic Technology: Working with the EC-590WM4 endoscope introduced us to the latest advancements in endoscopic technology. We learned about the design and functionality of high-resolution endoscopic cameras, navigable tips, and the integration of these components with external control systems. Medical equipment forums, product manuals, and collaboration with medical professionals provided us with a deep understanding of these technologies.

Motor Control and Electronic Power Systems: The project required us to gain expertise in motor control, specifically using the EPOS4 controllers and Maxon ECX SP13 motors. We explored the principles of electronic power systems, motor dynamics, and control theory. Online tutorials, datasheets, and user manuals from Maxon and EPOS were crucial resources. Additionally, we engaged in hands-on experimentation to understand the practical aspects of motor control in our system.

Software Design for Real-Time Image Processing: The software component of our project involved developing a machine learning model for real-time image processing. We learned about object detection algorithms, particularly YOLOv8, and their implementation in medical imaging. Online machine learning courses, forums like Stack Overflow, and documentation from OpenCV and YOLOv8 were key learning resources. We also gained practical experience by coding and testing the software with real-time data.

Problem-Solving and Innovation: Throughout the design process, we encountered various challenges that required innovative solutions. We learned to navigate technical forums, engage with expert communities, and consult academic research to find workarounds and alternative approaches. This not only enhanced our problem-solving skills but also broadened our perspective on design thinking and innovation.

In summary, the design phase of our project was a rich learning experience, encompassing a range of disciplines robotics to software development and machine learning. The combination of theoretical research, practical experimentation, and community engagement played a major role in acquiring these new skills and knowledge, which were integral to the successful design of our solution.

6. Implementation

We worked on implementing the basic hardware of the project, the endoscope navigation system, and testing it using the windows interface. Furthermore, we interfaced the robotic arm and the HoloLens VR with the Endoscope.

6.1. Hardware Setup and Wiring

Our hardware implementation involved setting up the endoscope with its navigable tip and camera (EC-590WM4), integrating it with the robotic arm (Universal Robots UR5e), and connecting these components to the control systems (EPOS4 Controllers and Maxon ECX SP13 motors). The Fujinon

System Processor 4400 and Lightsource 4400 were set up to process and illuminate Esophagus pathway.

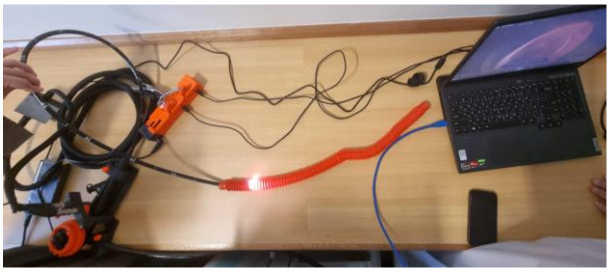


Figure 15: Wired Image - endoscope processor and Lightsource (left)

Figure 16: Robotic arm demonstrating insertion and retraction movements (middle)

Figure 167: Wired image - Endoscope connected to laptop interface while going in the Esophagus model (right)

6.2. Software and frameworks

The software implementation involved developing a machine learning model for real-time image processing and navigation. We utilized OpenCV for frame capture and YOLOv8 for object detection. The software was designed to interface seamlessly with the hardware components, particularly for controlling the movements of the endoscope tip based on the image data captured.

6.3.Novel aspects of Implementation

One of the novel aspects of our implementation was the integration of augmented reality (AR) technology, using the Microsoft HoloLens VR headset, for an enhanced visualization of the endoscopic procedure. This innovative approach provided the physician with a more intuitive and interactive way to view and interpret the endoscopic images, compared to traditional 2D screens. The implementation of this AR/VR technology will be done in SDP2 phase as we progress in our project.

Another innovative aspect was the use of a sophisticated machine learning model for real-time navigation of the endoscope. This model was trained to accurately identify and track the center of the Esophagus, facilitating precise and automated navigation of the endoscope.

6.4.Challenges and Solutions

During the implementation phase, we encountered several challenges. One of the primary challenges was ensuring the compatibility and seamless integration of the various hardware components such as adjusting the angular mapping onto the Maxon motors depending on the range of navigation of the endoscopic tip. This was addressed through rigorous testing and iterative adjustments to the hardware setup.

Another challenge was the development of the machine learning model for real-time image processing. The initial versions of the model were not as accurate as required, leading to suboptimal navigation of the endoscope. We addressed this by refining the training dataset and optimizing the model parameters, which significantly improved the accuracy and reliability of the navigation system.

Another challenge we encountered was implementing the simulation which we couldn't proceed with due to not having enough system requirements to run the opencv++. Despite consultation from technical experts, we reached a dead-end and decided to not pursue the simulation any further.

In conclusion, the implementation phase of our project was a complex but a rewarding process. It involved careful planning, integration of diverse technologies, and innovative problem-solving. The successful setup of the hardware and software components, along with the testing and refinement of the system, laid a solid foundation for the further development and eventual deployment of our project.

6.5.New-gained knowledge

The implementation phase of our project was not only a journey of bringing our design to life but also a significant learning experience. This phase enriched our team with new knowledge and skills, spanning across various platforms, frameworks, and techniques. Here, we highlight the key areas of new-gained knowledge and the methods employed to acquire and utilize these skills.

Advanced Machine Learning for Image Processing

- **Learning Method:** Implementing the YOLOv8 model for real-time image processing required us to enhance our machine learning skills. We undertook online courses on advanced machine learning and deep learning, focusing on real-time object detection and image processing.
- **Resource Type:** Online courses from platforms like Coursera and edX provided to us by our university, along with open-source communities and GitHub repositories, provided the necessary resources.

Robotic Control and Navigation

- **Learning Method:** The control of the Universal Robots UR5e robotic arm and the navigation of the endoscope demanded a deep understanding of robotic control systems. Our team used the knowledge we learnt in our previous and current courses overtime during our course of study at Qatar University.
- **Resource Type:** Manufacturer-provided manuals, simulation software, and robotics forums were key resources.

Software-Hardware Integration

- **Learning Method:** Integrating the software with the various hardware components, such as the EPOS4 Controllers and Maxon ECX SP13 motors, required practical skills in hardware-software interfacing. This was achieved through trial-and-error experimentation, guided by technical documentation and support from hardware manufacturers.
- **Resource Type:** Technical manuals, online support communities, and direct consultations with technical experts (HMC team).

Debugging and Problem-Solving in a Complex System

- **Learning Method:** Debugging a complex system with multiple interacting components was a challenge that improved our problem-solving skills. We relied on a systematic approach, breaking down the system into smaller modules and addressing issues individually.
- **Resource Type:** Guidance by our supervisor and collaboration with peers in the field were crucial in this learning process.

Collaboration and Project Management Tools

- **Learning Method:** Effective team collaboration was essential for the success of our project. We learned to use project management and collaboration tools like Asana and GitHub more efficiently, which enhanced our project coordination and communication.
- **Resource Type:** Online tutorials and guides for these tools, along with practice and team discussions, were the main methods of learning.

In summary, the implementation phase was a rich learning experience that expanded our technical expertise and problem-solving abilities. The knowledge and skills acquired during this phase were not only crucial for the success of our current project but will also be invaluable in our future endeavors in the field of medical technology and robotics.

7. Testing and Evaluation

7.1 Sub-system testing

Our system consists of three important sub-systems that were designed and worked upon in the course of this project. The three sub-system parts testing are:

1) Insertion and Retraction of the Endoscope

For the insertion and retraction, we gathered the IMU readings from the HoloLens headset based on the movements of the user and communicated them to the robotic arm wherein tilting the head forward meant insertion, tilting the head backward meant retraction and keeping the head up straight meant no movement of the endoscope (no insertion or retraction). These readings were mapped as 1, -1, and 0 respectively based on which the insertion, retraction, no movement operations took place accordingly.

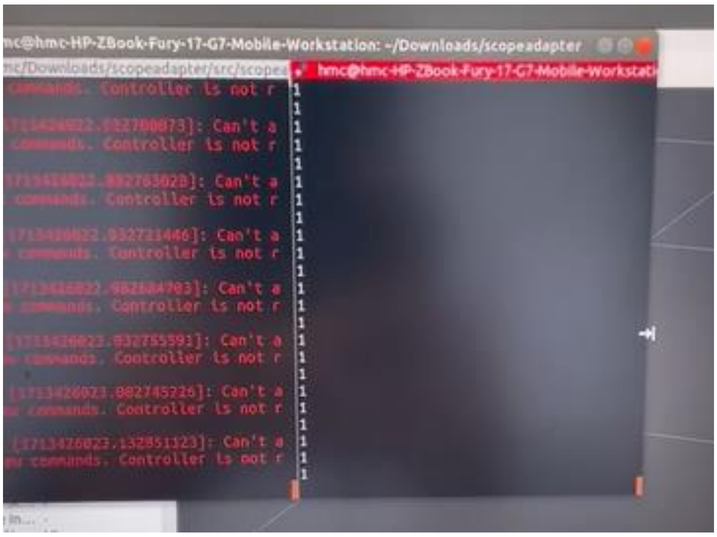
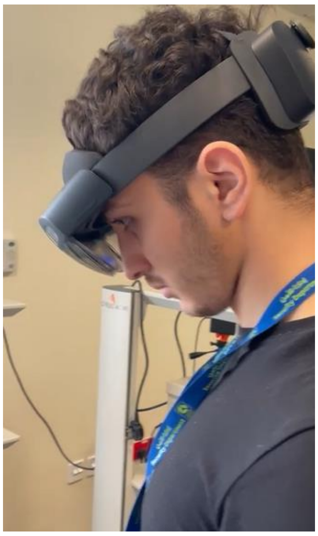
 

Figure 17 & 18: Insertion operation taking place when user's head is tilted forward

Figure 19: Robotic arm undergoing the insertion operation

2) Endoscope-camera detection of the center of Esophagus model

The images of the interior of the plastic pipe representing the model of the Esophagus were used to train the machine learning model to be able to detect the center of the Esophagus. This was carried out with the objective for the Endoscope-tip to be able to curve and self-navigate its way through the Esophagus. The experiments conducted initially provided 86% accuracy, which is way below the desired accuracy. Overtime, improvement of the model by increasing the training dataset increased the accuracy to 92%. However, with repeated training and perfection of the model over the course of SDP-II, the center-detection model now gives no errors deeming it to be almost 100% accurate.

Figure 18: Plastic pipe used to model the esophagus

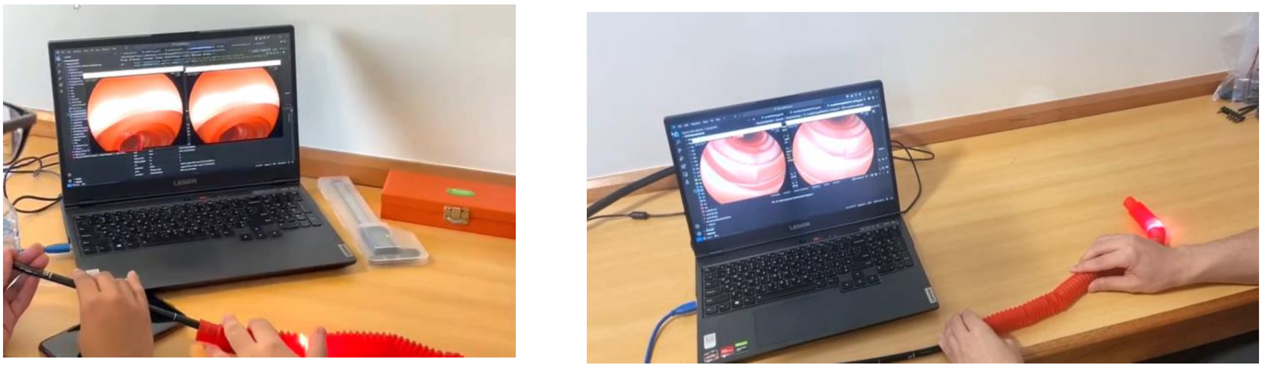


Figure 19: Testing the ML model for center-detection

3) Mapping the Endoscope tip movement onto the Maxon motors

After receiving feedback from the camera of the Endoscope as to where the center of Esophagus is, the angular movement required for the tip to move needs to be conveyed to the motors that control the tip. The field of view for the Endoscope tip is 140° (from -70° to 70°). Given this information, we used the absolute angles and derived a linear equation to map it from 0 to 1 along the x-axis and the y-axis. We assumed 0 to be -70° and 1 to be 70° wherein the center of the image would be 0.5 (corresponding to 0°). Now upon the feedback of from the Endoscope camera on the as shown in figure 21, appropriate angular mapping would be applied to the Maxon motors that would determine the direction of the Endoscope's navigable tip.

Figure 20: EPOS motors controlling the tip of the endoscope

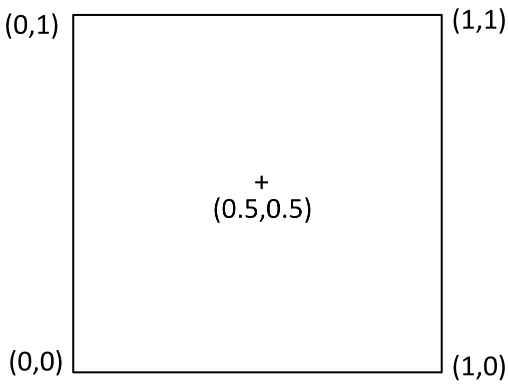


Figure 21: Image coordinates

Our testing phase has been delayed due to HMC access limitations since our equipment is placed there. As a result, the testing phase of the report will be updated in the final draft submission.

7.2 Complete System testing

Once the sub-systems testing proved to be successful, we integrated the entire system together and ran the system. The test results indicate that our prototype largely meets the functional requirements and design constraints. The successful integration of advanced technologies like VR, robotic control, and real-time image processing, coupled with the system's cost-effectiveness and adherence to data security standards, underscore its potential in revolutionizing gastrointestinal endoscopy.

Table 15. Design Constraints Met/Not met

Constraint	Relevance to the Project	Evaluation Plan	Success Criteria	Met? (Explanation)
Video Capturing	The design should provide at least 30 to 45 frames per second to avoid any	The design should be tested on an end device.	The nearer the frame count is to 30 frames per	Yes (33 fps with no lag)

	lag detected by the physicians during the operation.		second, the more optimal it is.	
Quality of streamed video to the HoloLens	The frames taken by the camera should be streamed in an acceptable resolution for the physicians to see on the HoloLens and for the model to be trained on. It should not be lower than 720p.	Various endoscopes with varying camera qualities will be evaluated.	The best fit camera with endoscope to all applicable constraints will be chosen.	Yes (720p, 30.3 fps)
Real-time Navigation and Control	The system must navigate in real-time with minimal latency to avoid lag and ensure accurate and safe maneuvering through the Esophagus.	Testing latency and responsiveness under various conditions.	The architecture should not exceed 250ms latency. The processing of the frames by the central entity should not exceed 33ms to accommodate for the 30fps streaming rate.	No (The robotic arm is experiencing a lag after the user's head-tilt movement)
Centre detection	The model should provide an accurate result that meet the requirements by 95%.	Testing the ML model with test images to check if the model detects the center.	The accuracy should be at least 95%.	Yes (100% accuracy)
Data Privacy and Security	Protecting patient data and ensuring compliance with data protection regulations.	Ensuring that rules and regulations are implemented by the client who will be using our system.	Adherence to IEEE, ACM, and local Ministry of Public Health standards.	Yes (Based on Qatari rules and regulations, these criteria are assumed to be met)
Cost-Effectiveness	The system should be financially viable for widespread use in medical facilities.	Cost analysis and comparison with existing solutions.	Costs remain within a competitive range for similar medical devices.	Yes

This section, a critical part of our project, not only validates our design but also lays the groundwork for future enhancements, ensuring that our solution remains at the forefront of medical technology innovation.

8. Analysis of the impact of the engineered solution

Context	Specific contribution through our project	Level of impact (High, Medium, Low)
Public health, Safety, and Welfare	The enhancement of timely treatments that has met defined design criteria considering the local and international regulations contributes deeply	High
Global	Accessible and efficient Endoscopic procedures can improve healthcare outcomes globally, especially in regions with limited access to Endoscopists	High
Societal	Advanced Endoscopy technology can give more quick diagnoses, reducing patient anxiety and discomfort during procedures	High
Environmental	Can lead to sustainable healthcare practices overtime as efficiency improves	Low
Economic	The Endoscopy technology can reduce potential healthcare costs with prolonged hospital stays of the patient	Medium

9. Conclusion

Our project has successfully met its objectives as defined throughout the report as each aspect has been tested with a criterion and all but one of them have passed successfully. Overall, we have achieved a high degree of achievement in completion of our project. Our solution's primary strength is the elimination of involvement of an Endoscopist which will aid healthcare sectors as there's a huge lacking Endoscopists around the globe. Furthermore, our product will reduce the time taken for the procedure to take place. To further enhance our project, we had decided to create a simulation using Unity which couldn't progress much due to system constraints. Furthermore, the lag between the IMU reading of the HoloLens and mobilization of the robotic arm is something that could be attributed to too many devices being connected through the same common interface. Overall, our product is novel in terms of its implementation using the HoloLens as a user interface that communicated with the machine learning model and the robotic arm to navigate through the upper Esophagus.

10. Future Work

Our project can further be developed to address many key works. A few such examples could be:

1) Latency between the HoloLens and robotic arm: Currently, there's a minor lag between the generating of IMU values and the reaction of the robotic arm. This could be due to the use of Wi-Fi as a mode of connection between the two. Our time constraints did not allow for further exploration in this aspect, but other modes of connection, such as wired, or Bluetooth, etc. could be tested to improve the latency and reach a agreeable value.

2) Detection of tumors in Esophagus: The machine learning model responsible for navigation through the Esophagus could be coupled with another machine learning model that could detect tumor, or other medical discrepancies, in the Esophagus while passing through. It could further diagnose the same in the stomach.

3) Replicating for other healthcare uses: Such navigation techniques could be replicated for diagnosis through the lower Esophagus too. A miniaturized model could also be used to diagnose any similar issue through the other natural openings within a human body (nose, ears, genetalia) as the need arises.

11. Student Reflections

AIMAN SAAD BAIG

The journey through our project has been a profound learning experience for me, shaping my professional and personal growth in numerous ways. This project has been a melting pot of various disciplines, blending robotics, software engineering, and medical technology, which underscored the importance of interdisciplinary collaboration. It taught me the significance of viewing problems through multiple lenses and harnessing diverse skill sets for innovative solutions.

My technical acumen, particularly in machine learning and image processing, has notably advanced through this project. Implementing and optimizing the YOLOv8 model for real-time object detection provided me with practical insights. These skills transcend the confines of this project and are highly relevant in the broader technological landscape.

Interpersonally, the project honed my communication and leadership skills. The necessity for clear and effective communication was paramount, especially when discussing complex technical details with team members from varied backgrounds. My role often involved leading discussions, coordinating tasks, report updates, and ensuring team alignment with our project goals, which enhanced my leadership abilities.

On a personal level, the project taught me to adapt to change and manage pressure effectively. The dynamic nature of our work, coupled with stringent deadlines, necessitated a high degree of flexibility and resilience. Especially when coordinating with HMC and the team members and certain things do not happen on time – this made me develop the practice of having an alternate plan ready to work on in the meanwhile. I also learned the importance of professional and ethical conduct, especially given the healthcare implications of our project.

Reflecting on the project, I recognize the need for early and thorough testing in future endeavors as this aspect was largely ignored by us so far since the model gave us pretty good results. However, I realize it is important to test and evaluate in order to have enhanced performance. A greater emphasis on testing in the initial stages would allow for the identification and resolution of potential issues more efficiently. Additionally, I aim to improve my time management skills to mitigate the risks associated with last-minute rushes and potential oversights.

This project has instilled in me a new approach to problem-solving and teamwork. I have learned the value of persistence in overcoming challenges and the importance of collaborative problem-solving. The experience has reinforced that effective teamwork, clear communication, and a willingness to learn from each other are crucial for the success of any endeavor. These lessons will be invaluable in my professional life, equipping me to be a more competent engineer and an effective team player.

In summary, the Senior Design Project has been a significant milestone in my academic and professional journey as it taught me how seamlessly many units can come together to form an overall system. The skills and insights gained are invaluable, and I am confident they will greatly contribute to my future endeavors in the field of technology and engineering.

MOHAMED IBRAHIM

The senior design project is the most important project for an undergraduate student, as it combines most of the technical and non-technical skills learnt throughout the major. The most important non-technical skills were effective time management and teamwork. These foundational skills were imperative for the successful completion of our project centered around the autonomous movement of an endoscopic camera tip.

On the technical side, the project provided a valuable opportunity to delve into the world of Machine Learning. Designing a model, by creating a custom dataset and implementing its outputs to maneuver real-world devices represented a pivotal milestone. To be specific, the utilization of the YOLOv8 model to process the frames on our computer and subsequently applying its output to MAXON EPOS4 positional controller was an important technical achievement. Specifically, mapping model outputs to motor movements was one of the complex parts, as the precision of the mapping is a crucial step.

Furthermore, the significance of the high-performance computing resources played an important role. Learning to harness the capabilities of the RTX4090 GPU through the team viewer was needed. The drastic reduction in training time, from an hour per 4 epochs on our local machine to completing 30 to 150 epochs in no-time.

Moving onwards, the invaluable lessons learned from the project will undoubtedly shape my future career and also the collaboration with Hamad Medical Corporation (HMC) was beneficial, for the future. The qualities learned will undoubtedly contribute significantly to my growth and effectiveness in future endeavors. Overall, it was a great experience combining all the components together and making them work was quite interesting and something new for me.

MOHAMED HILOU

he project affected my growth, and it was the real start of my professional career journey. It converted our idea into a realistic solution that could be used in the medical field to ease physicians work in the field. Also, it reinforced my passion for engineering and affirmed that my academic pursuits had real-world implications.

As for the technical skills, creating a machine learning model and integrating it into our endoscope system was both challenging and rewarding. We trained our model using our own captured data to predict an optimal navigational path. The real time process of the machine learning model demonstrated the power of ML in healthcare technology.

Moreover, having the ability to create models and 3D print them had a significant impact on our project. It managed to bring life to our own designed solution for controlling the insertion of the endoscope and implementing it in our designed system.

In summary, the SDP had a significant impact on me. The skills I learned to achieve this project are valuable, and they will contribute to my future as a computer engineer.

ALBARAA ALOUSH

My journey through the development of this project has been an unparalleled venture into the intersection of medical technology and robotics, offering me insights far beyond the conventional curriculum. This project was not just about applying what I had learned; it was about redefining and expanding my understanding of what it means to be an engineer in the rapidly evolving field of medical technology.

Delving into the realm of autonomous endoscopic systems, I found myself grappling with complex concepts and innovative technologies that were new to me. The challenge of integrating sophisticated algorithms for precise control and navigation of the endoscopic device tested my technical skills and pushed me to venture beyond my comfort zone. It was a process of continuous learning and adaptation, where theoretical knowledge met practical application.

One of the most significant aspects of this project was its real-world impact. Knowing that our work could potentially revolutionize gastrointestinal diagnostics brought a sense of purpose and responsibility to my role. It instilled in me a deep appreciation for the potential of engineering solutions to improve healthcare outcomes and patient experiences. This realization has profoundly shaped my perspective on the role of engineering in society.

Collaboration was another pivotal aspect of this experience. Working alongside peers from diverse specializations, I learned the importance of multifaceted collaboration and the synergy that arises from combining different areas of expertise. This experience has honed my collaborative skills and taught me the value of diverse perspectives in solving complex problems.

Additionally, the project highlighted the importance of risk mitigation. Facing numerous challenges, from technical setbacks to coordination issues with external partners like HMC, I learned the art of resilience. These experiences taught me that setbacks are not roadblocks but stepping stones to greater understanding and success.

In retrospect, this project has been more than an academic requirement; it has been a journey of personal and professional growth. It has equipped me with a unique set of skills, a new way of thinking, and a renewed passion for innovation in medical technology. As I move forward in my career, I carry with me not just the technical knowledge, but the experiences, lessons, and perspectives gained from this groundbreaking project.

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