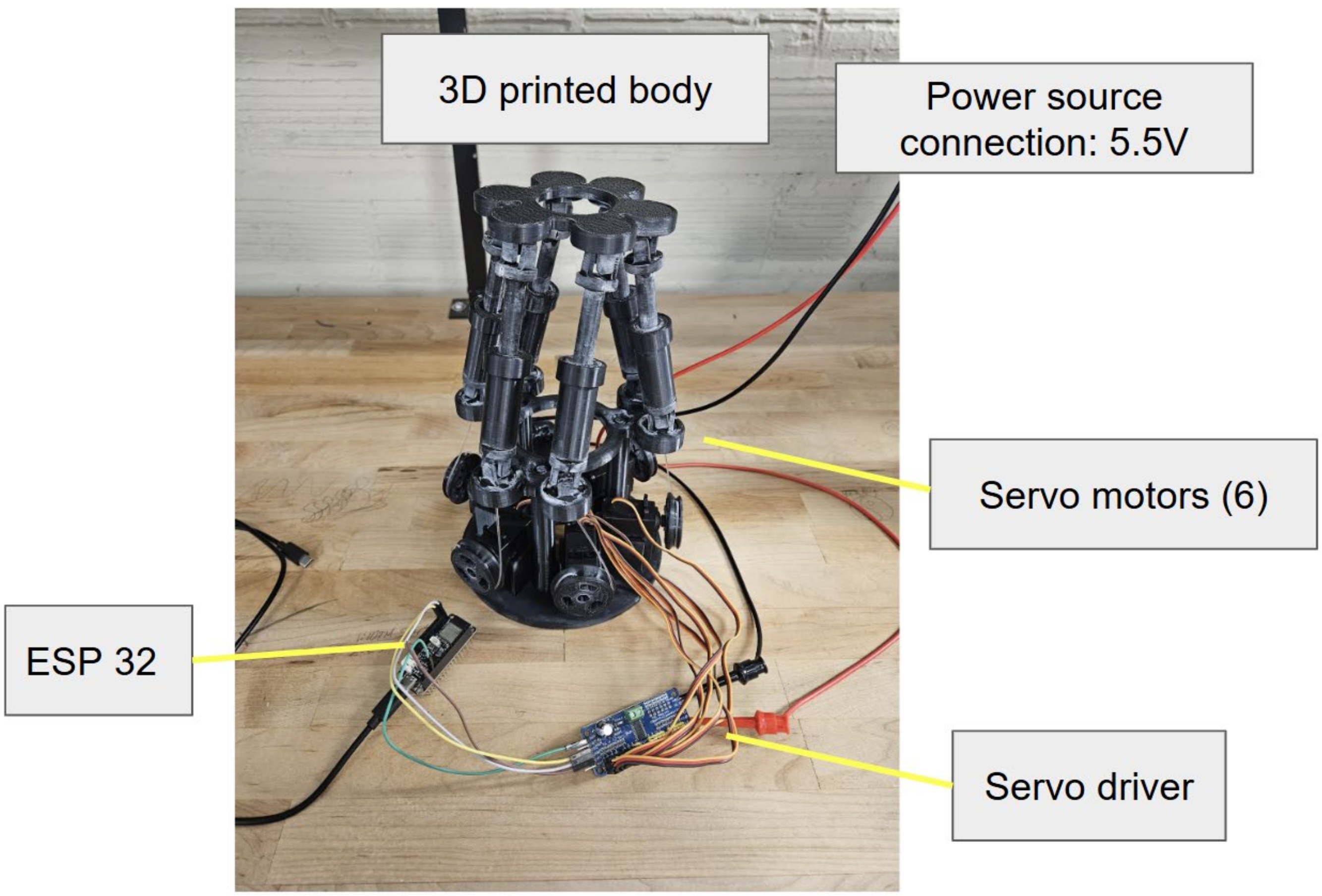
6 DOF Stewart mechanism to retrofit on Endoscopes for minimally invasive Robotic teleoperated surgery



Graphical Abstract

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1. Executive Summary

EndoPilot is a robotic end-effector developed to enhance control, precision, and stability in endoscopic procedures by integrating a miniaturized Stewart platform at the distal tip of a flexible endoscope. This design provides full 6-DOF (degrees of freedom) control within the constrained environment of the gastrointestinal (GI) tract. Motivated by surgeon interviews and a clear market opportunity, our team developed a proof-of-concept combining gesture-based human-in-the-loop teleoperation, iterative prototyping, and an analytical kinematic model to validate performance. The device was evaluated against commercial tools, and the Stewart platform consistently outperformed alternatives in terms of precision and maneuverability. Through hands-on fabrication, simulation, and customer development, we explored the full product development lifecycle, from need-finding and concept evaluation to prototyping and business modeling. EndoPilot demonstrates the potential for surgical robotics to offer low-cost, modular innovation that integrates seamlessly into existing clinical workflows.

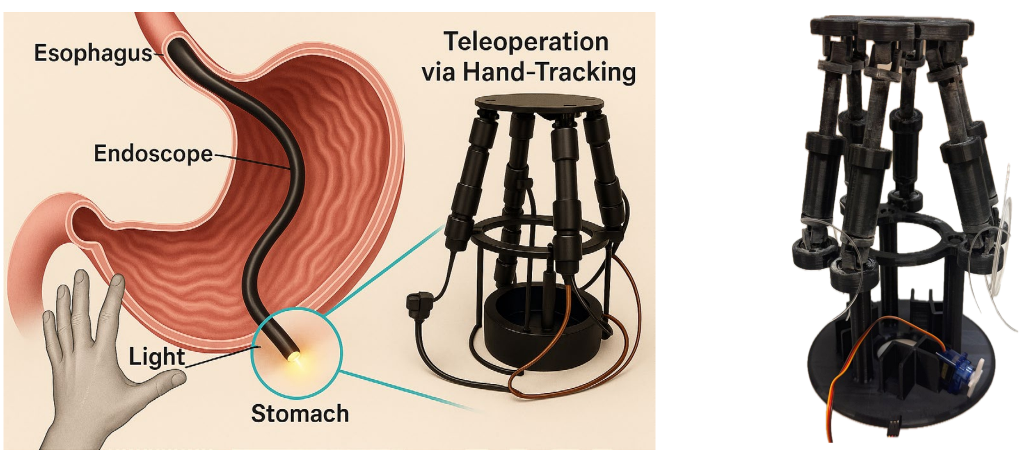

Fig 1: Left: Illustration of miniaturized Stewart platform used for teleoperation Right: Final Product

2. Objective

The objective of this project was to design a system for an endoscopic robot. Our motivation was to use a stabilizing Stewart platform to support an endoscope and enable users to easily change surgical tools within the robotic frame. Our design is a scaled-up prototype of this concept, focusing on the Stewart mechanism. Our 6 DOF robotic platform consists of six MG6994 motors connected to a PCA6985 servo driver. The driver is connected to an ESP32 Feather V2, which serially communicates with a PC. The robot is capable of adjusting the length of its linkage arms through a cable-driven mechanism. Our ESP32 is programmed through ESP IDF, receiving data from a Python program. The motion commands are given in the form of x, y, z, roll, pitch, and yaw, and computed as linkage arm lengths, which ultimately translate to motor signals. Our system executes a feedback loop that receives inputs, performs calculations, updates motors to maneuver the robot, and sends data to be visualized on the GUI. The GUI is hosted by Python.

3. Product Development Description

3.1 Business Opportunity

Endoscopic procedures often suffer from limited dexterity, hand tremors, and control fatigue. From initial interviews with surgeons and clinical advisors, we found consistent pain points: poor articulation, slow maneuverability, and high surgeon fatigue during long procedures.

- Market validation: The endoscopy devices market is valued at $61 billion (2024) and growing at a 3.79% CAGR. Over 191 million procedures were performed in 2024, with projections reaching 207 million by 2030.
- User insights: End-users (surgeons, endoscopists) demand smoother control in tight anatomical spaces with minimal setup overhead.

- BMC realization: Working through our Business Model Canvas emphasized the importance of training, clinical partnerships, and post-sales support.

Our value proposition centers on 6-DOF robotic precision, reduced hand tremors, shorter procedure times, and modular design to retrofit existing scopes.

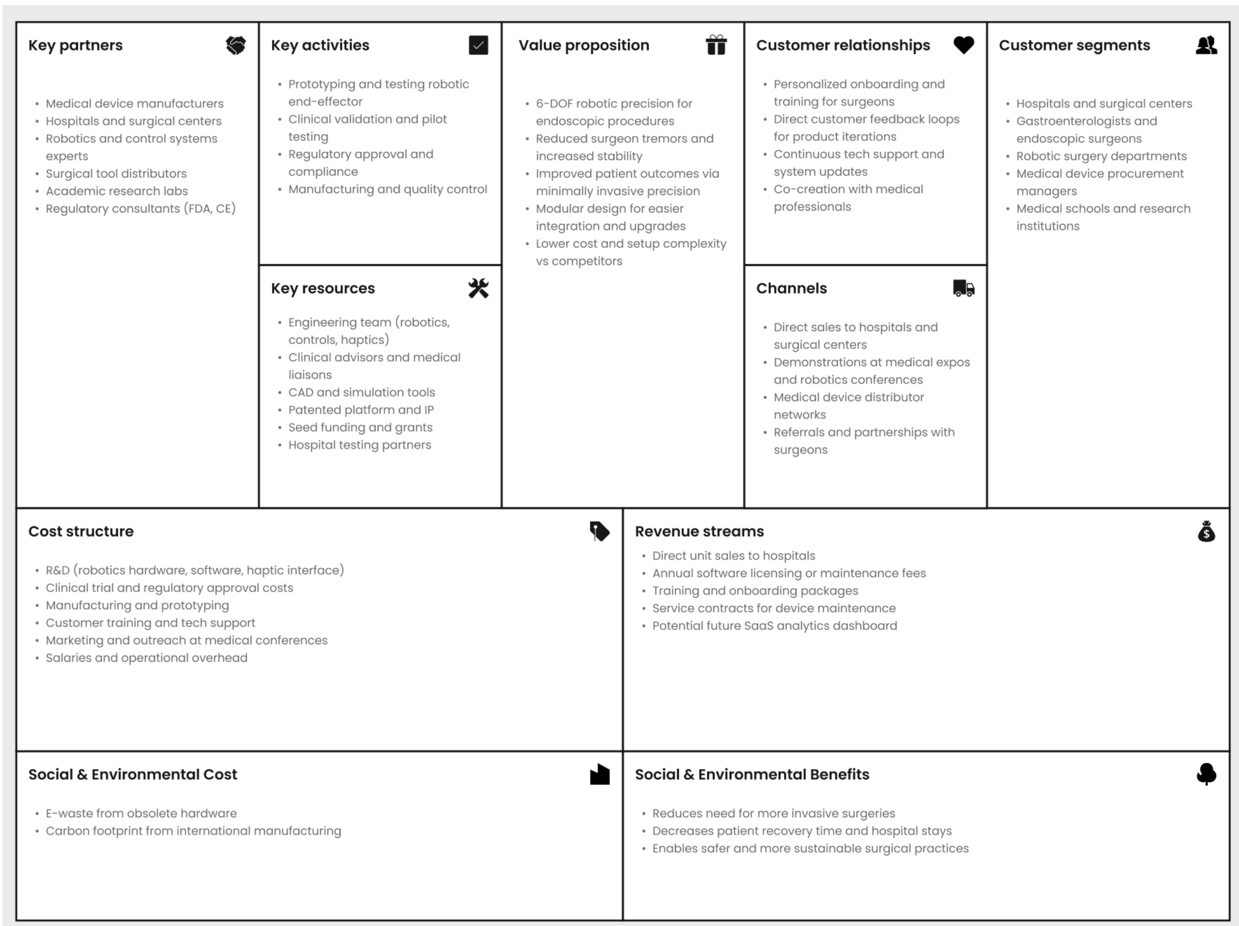

Fig 2: Business model Canvas

3.2 Competitors

Following are some of our competitors:

Manufacturer	Product/Technology	DOF	Key Features	Clinical Applications
Intuitive Surgical	da Vinci SP Surgical System	7	12mm articulating camera; 360° rotation; dual instrument channels	Urologic procedures, transoral surgery
Denso Robotics	VS-050 Robotic Endoscope Holder	6	100N payload capacity; 0.1mm repeatability	General laparoscopic procedures
PI Physik Instrumente	F-712.Hxx Photonics Alignment	6	Hexapod+NanoCube ® integration; 5nm resolution; 120mm/s speed	Endoscope manufacturing, fiber optic calibration
EndoChoice	Fuse Full-Spectrum Endoscopy	6	330° FOV; multi-lens array; AI-assisted polyp detection	Colorectal screening
Medtronic	PillCam SB3 Capsule Endoscope	6	Bidirectional communication; 158° FOV; 30fps capture	Small bowel imaging

3.3 Interviews

During interviews with medical professionals and technicians, several key limitations and inefficiencies in current endoscopic systems were identified. One recurring challenge involved navigating rigid scopes in confined anatomical spaces such as the ear canal. This frequently necessitates cumbersome maneuvers like ‘corkscrewing’ due to limited degrees of freedom (DOF), which can extend procedures by 15–20 minutes. In contrast, the proposed device, with enhanced DOF and more intuitive adjustability, could streamline orientation tasks significantly. Preoperative delays were also highlighted, particularly due to the setup of electromagnetic tracking systems and robotic interfaces, which not only consume valuable time (8–12 minutes) but have also led to accidental collisions during preparation. Since the new system avoids such complex magnetic calibrations, it offers a more efficient and safer setup process.

Device limitations were also shown to contribute to both cognitive and physical fatigue. The absence of roll-axis control in current tools has led to missed detection of lateral lesions, while servo motors embedded in XYZ stage systems degrade in accuracy after repeated use. By relocating high-precision servos outside the device and using durable cable-driven actuation, the new platform maintains long-term accuracy and avoids performance deterioration. Additionally, the need for modularity was emphasized, with proprietary systems causing costly repairs, as much as $23,000 for a single joint failure. A modular design compatible with existing endoscopes addresses this pain point, reducing long-term ownership costs.

Another area of concern was the lack of effective haptic feedback. Surgeons reported that a substantial amount of force is wasted during delicate procedures due to the absence of tactile cues. The new design incorporates haptic feedback through servo motor data, providing users with tactile information scaled to tissue stiffness. One expert suggested that matching resistance to tissue density gradients and automating certain functions like roll correction could reduce cognitive load by up to 40%. The solution's innovative control method—via a Stewart platform—enables programmable feedback, replicating nuanced force responses.

Compatibility issues between robotic platforms and scopes from different vendors were also cited, consuming an average of 22 minutes daily in adaptation time. By standardizing interfaces and creating a universal system, the proposed device removes these compatibility hurdles. Finally, training demands were another pain point. Mapping 3D viewer motion to physical hand movements is a significant learning curve, often requiring upwards of 80 cases to master. Augmented reality (AR) overlays showing instrument trajectory could cut this training requirement nearly in half, a feature that can be seamlessly integrated into the new device through its 6-DOF control and end-mounted camera system.

In summary, these insights directly informed the design of a next-generation, modular, cable-actuated, 6-DOF endoscopic system with external servo actuation, haptic feedback, and AR integration—addressing inefficiencies, improving safety, and shortening the learning curve.

3.4 Product needs in the market

- Enhanced Precision and Maneuverability: for improved control and precision during minimally invasive procedures.
    - Justification: One of the doctors we interviewed faced challenges navigating rigid scopes through constrained spaces like the ear canal, leading to increased time for surgery. The proposed 6-DOF Stewart platform solves these issues by enabling free translation and rotation across all axes
- Reduced Setup Complexity and Time: Simplifying preoperative steps
    - Justification: The nurse in our interview mentioned that setting up electromagnetic trackers adds 8–12 minutes pre-op and has led to accidental collisions with robotic arms during drape placement. Our Endopilot product avoids such complexities by eliminating magnetic actuation completely.
- Modular Design for Cost-Effectiveness and Serviceability
    - Justification: Potential supplier from our interview expressed frustration over the huge cost of repairs, emphasizing the need for modular components. Our Endopilot is able to retrofit into existing endoscopes, making it a cost-effective solution.
- Haptic Feedback for Improved Tactile Sensation: for improved force control and tissue interaction during surgery.
    - Justification: One of the doctors we interviewed said that most of her force input is wasted compensating for the lack of tactile cues in current systems. Another doctor

emphasized the need for variable resistance matching tissue density gradients. Endopilot could be integrated with servo motor data to provide the necessary haptic feedback.

- User-Friendly Learning Curve with AR/VR Integration: Reduce training time for new users.
    - Justification: One of the doctors suggested that an AR overlay projecting instrument trajectory could drastically cut fellowship training cases. Our product has the capability to integrate with AR/VR technology.

4. Concept Selection

Our process began with broad exploration from tendon-driven and cable-actuated systems to full robotic arms. We applied a Pugh Matrix using eight criteria: precision, miniaturisation, control complexity, manufacturability, cost, response time, reliability, and power consumption.

Highest weightings: Precision, manufacturability, and cost.

Unexpected finding: A telescopic spring system initially scored best, but ultimately lacked the desired DOF.

Final decision: Stewart platform selected for superior 6-DOF performance, modularity, and controllability.

Scale 1-5	Precision	Miniaturization Feasibility	Control Complexity	Manufacturing Feasibility	Cost	Response Time	Reliability	Power Requirements	Total Score	
Weight	20	5	10	20	20	10	10	5		
Mini Stewart Platform for Endoscope Control	5	5	5	5	5	5	5	4	39	2
Mini Prismatic Shape Memory Alloy	3	5	2	2	1	4	4	5	26	
Electro-Osmotic Actuator	1	1	1	1	1	1	1	1	8	
Lead Screw Mechanism	5	4	5	5	5	4	4	4	36	
6-DOF SMA Embedded Tube	3	5	2	2	1	4	4	5	26	
Telescopic Fork Spring Mechanism	5	5	5	5	5	5	5	5	40	1
Micromachined Rack and Pinion Actuator	5	3	5	5	5	5	5	5	38	3
Pneumatic Bellows	2	4	4	5	5	5	5	5	35	
Liquid Crystal Elastomer (Light-Activated)	1	1	1	1	1	1	1	1	8	
Hydrogel (Temperature-Activated)	1	1	1	1	1	1	1	1	8	
Capsule Endoscopy	3	5	3	3	2	1	3	5	25	
Origami-Based Capsule Endoscopes	3	5	3	3	2	1	3	5	25	
Magnetically Driven Endoscopy	5	4	5	5	5	4	4	4	36	
Poly-Actuated Endoscopy	5	4	5	5	5	4	4	4	36	
Motor-Actuated Endoscopy	5	3	5	5	5	5	5	5	38	4
Robotic Serial Chain Cable Actuated Endoscopy	5	5	1	1	1	5	1	1	20	
Use of Stewart Platform and Cable driven mechanism	5	5	5	5	5	5	5	4	39	2
Use of Linear Shape Memory Alloy materials	3	5	2	2	1	4	4	5	26	
Bending Endoscope using SMA coils	3	5	2	2	1	4	4	5	26	
Origami based Capsule Endoscopes	3	5	3	3	2	1	3	5	25	

Fig 3: Pugh Matrix

5. Design Process

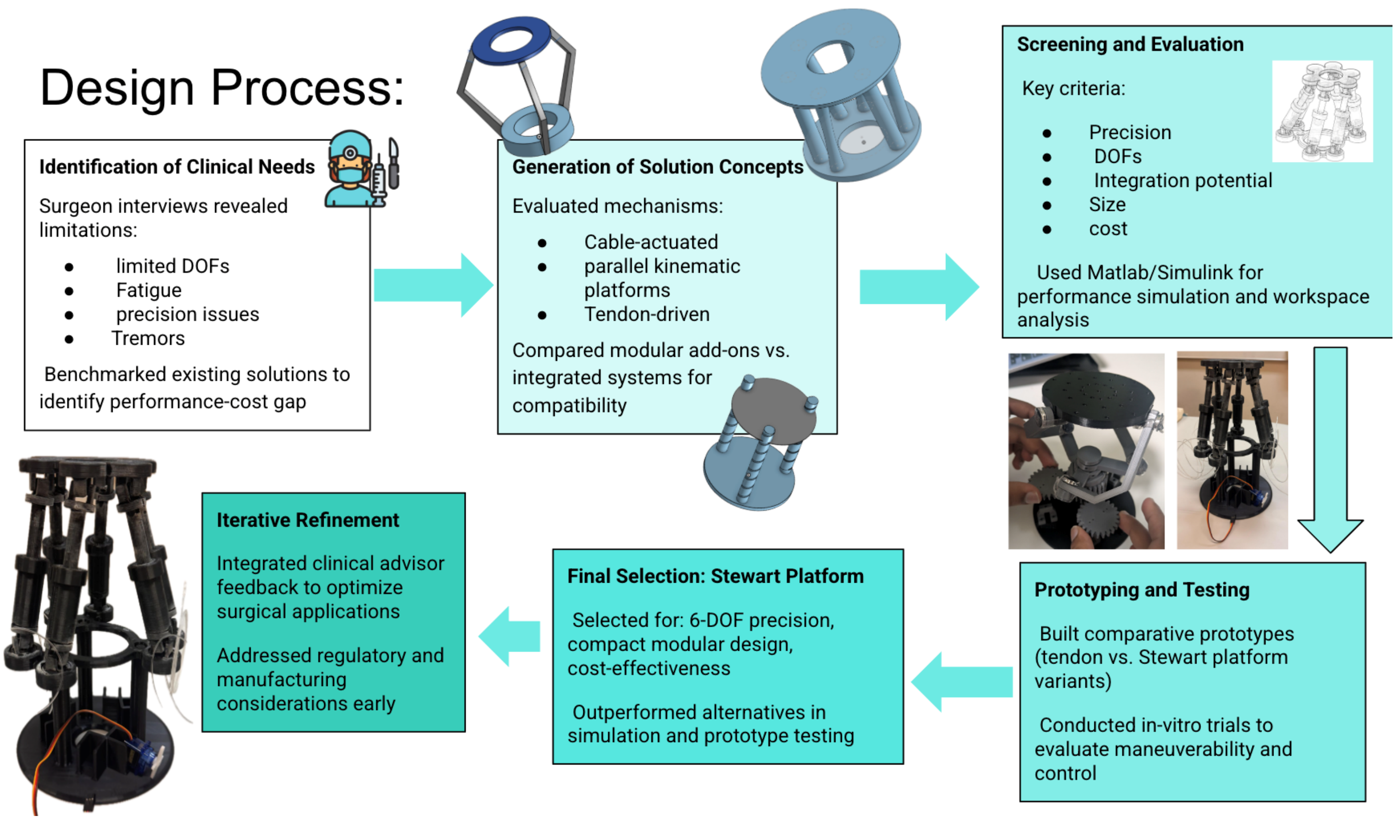

Fig 4: Iterative design process

6. Graphical User Interface (GUI)

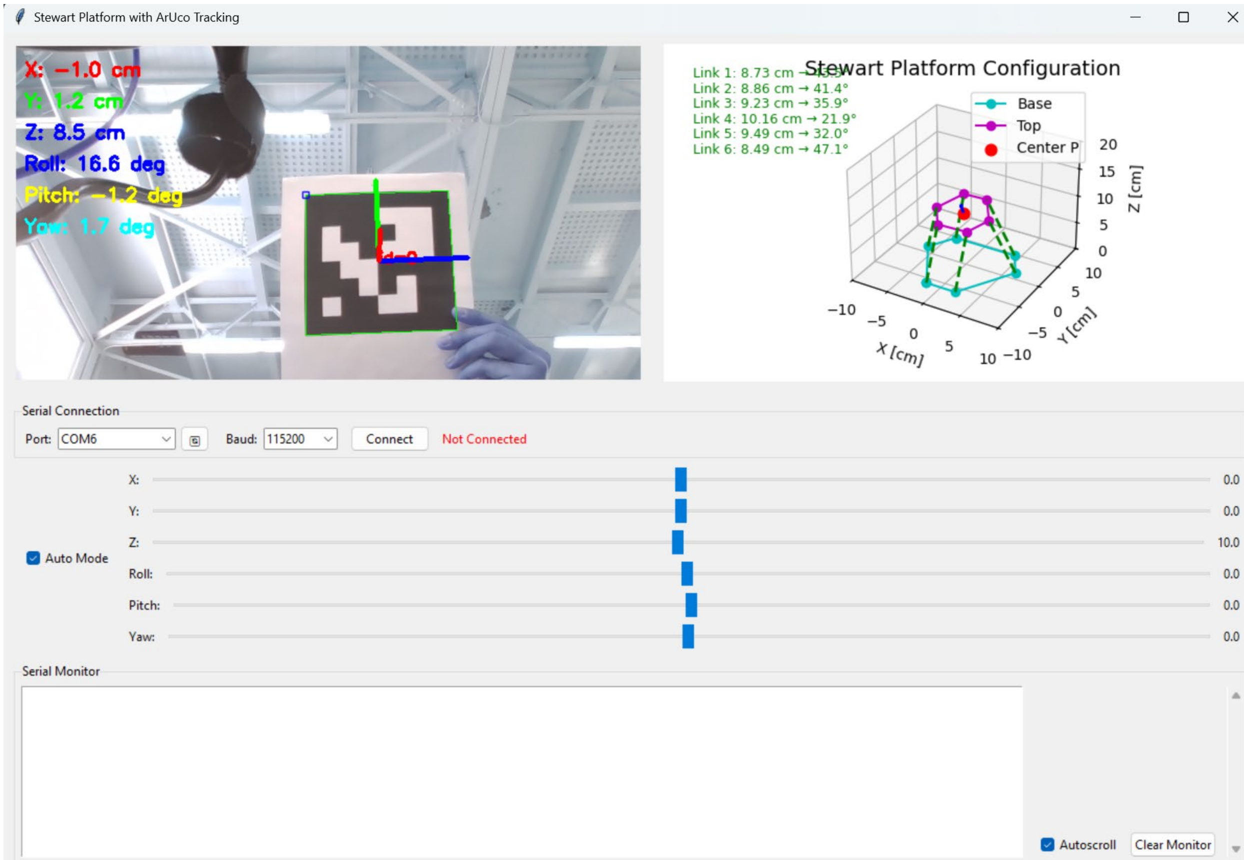

Fig 5: Graphical user interface built using Python

The GUI allows two operating modes: manual mode and auto mode. In the former, users can input x, y, z, roll, pitch, and yaw values using sliders. In the latter, these values are mapped to movement in an ArUco marker. The program uses OpenCV to track the marker in real time, and update values based on the marker's position. Both modes are accompanied by a simulation in the GUI that visualizes the robot's pose with the updated values. This simulation lists the lengths of each linkage arm, which are values sent out by the ESP32 back to Python. The GUI indicates when the lengths detected from the ArUco marker are out of bounds. The data gleaned from user input is stored as a position in space. Thereafter, the ESP32 calculates the necessary angular displacement of the motor to achieve the new linkage length based on the received position values. The PWM signals are sent out to control all 6 motors.

7. Control Logic and Code Overview

[complete code in appendix]

```
DEFINE basePoints ← fixed coordinates on lower platform
DEFINE topPointsRel ← relative coordinates on upper platform
INPUT pose ← {x, y, z, roll, pitch, yaw}
for i = 1 to 6 do
    top_global[i] ← ApplyRotationAndTranslation(topPointsRel[i], pose)
    dx ← top_global[i].x - basePoints[i].x
    dy ← top_global[i].y - basePoints[i].y
    dz ← top_global[i].z - basePoints[i].z
    linkLength[i] ← √(dx² + dy² + dz²)
end for

for i = 1 to 6 do
    if linkLength[i] < LINK_MIN_CM then
        linkLength[i] ← LINK_MIN_CM
    else if linkLength[i] > LINK_MAX_CM then
        linkLength[i] ← LINK_MAX_CM
    end if
    angle[i] ← (LINK_MAX_CM - linkLength[i]) × (115 / (LINK_MAX_CM -
LINK_MIN_CM))
end for

for i = 1 to 6 do
    if angle[i] < 0 then angle[i] ← 0
    if angle[i] > 180 then angle[i] ← 180
    pwm[i] ← Map(angle[i], 0, 180, SERVO_MIN, SERVO_MAX)
    SendPWMToServo(i, pwm[i])
end for
```

8. Selected Concept Description ￼

The core of EndoPilot is a Stewart Platform, a parallel manipulator capable of precise 6-DOF motion. Our analytical model defines:

- Inverse kinematics: Actuator lengths computed from the desired platform pose.
- Forward kinematics: Pose determined from actuator inputs.
- Design features:
    - Base & top hexagonal platforms
    - SG90 servo-driven joints (initial proto)
    - ArUco marker feedback for teleoperation
    - CAD-validated miniaturisation for distal end integration

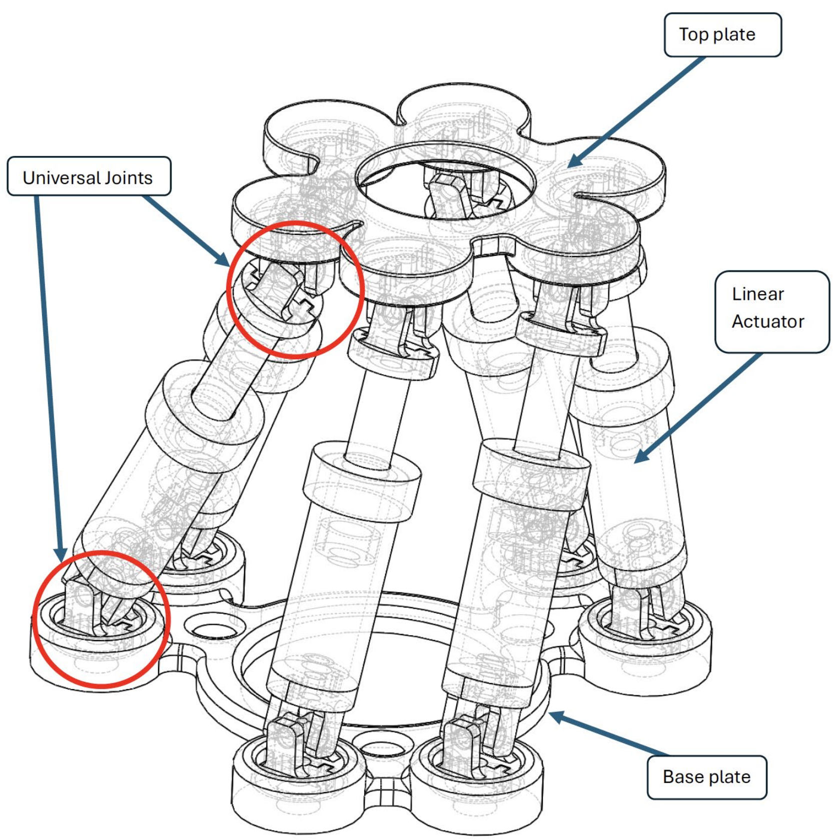

Fig 6: Analytical Model of Endoscope – Stewart Platform

9. Prototypes and System Integration

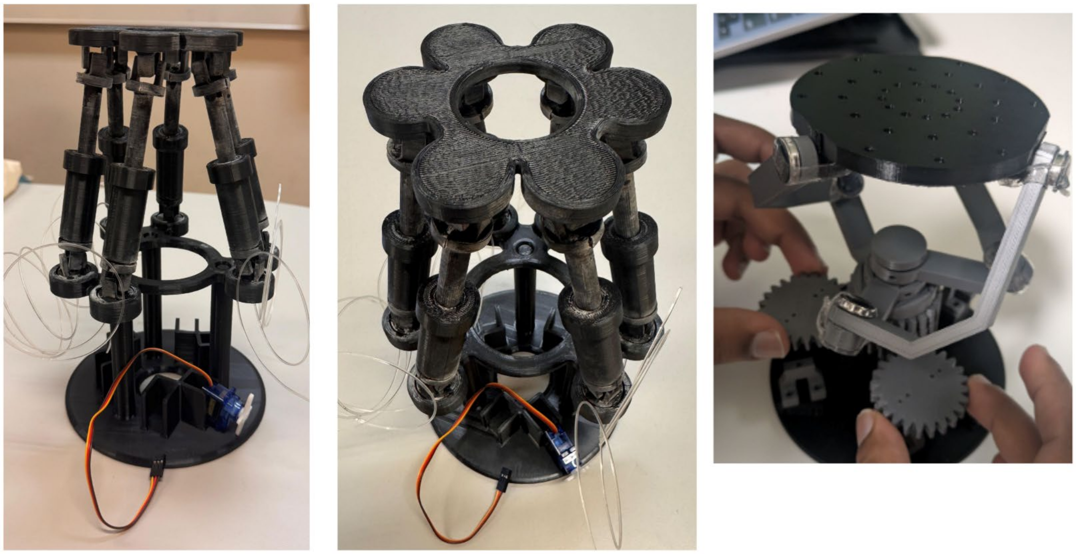

Fig 7: Final 2 Prototypes

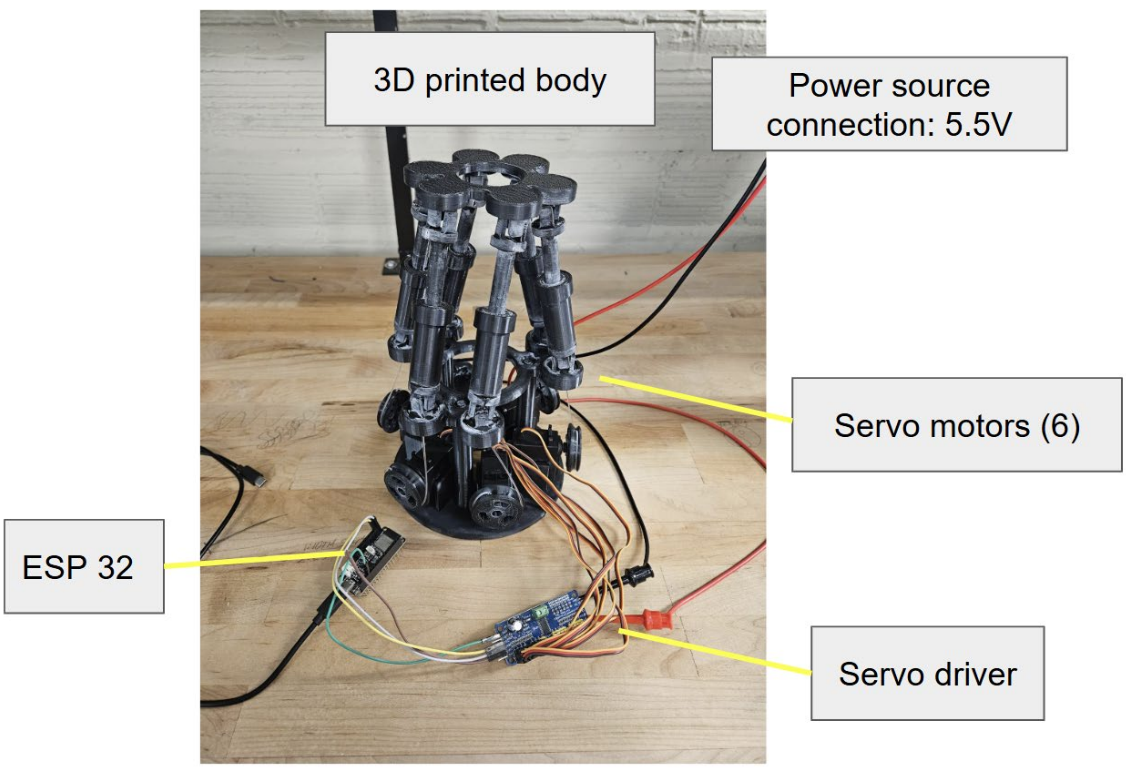

Fig 8: Final system integration

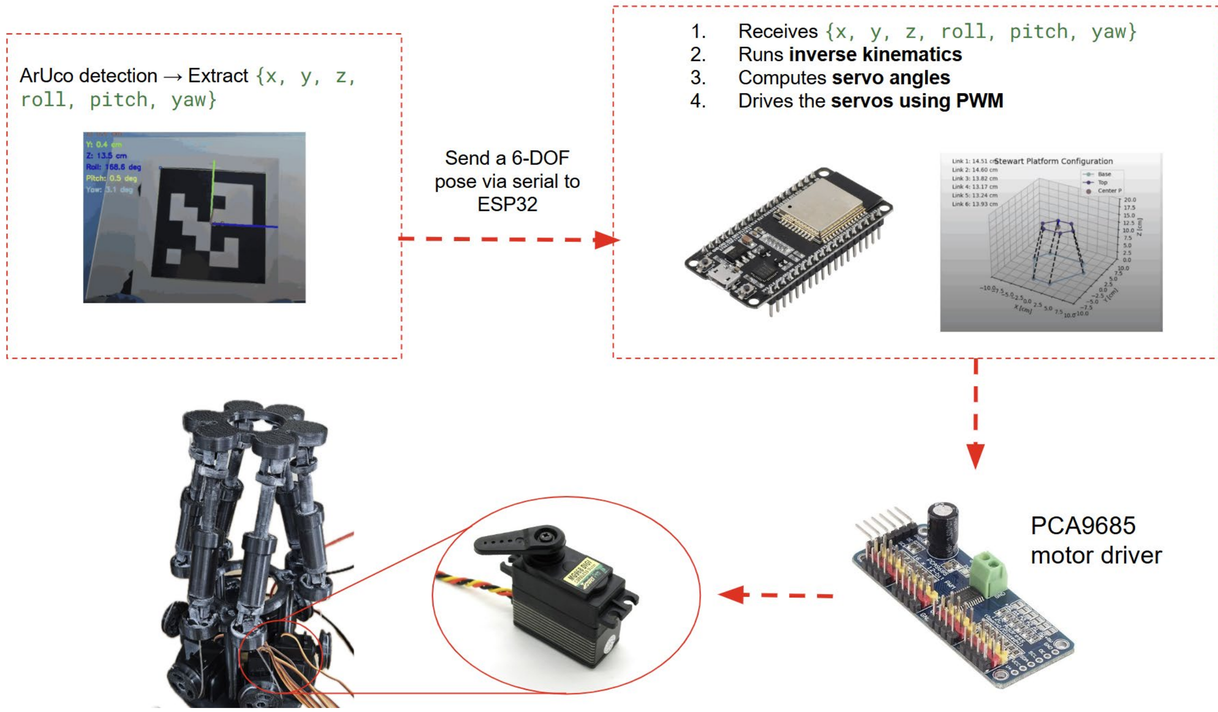

Fig 9: Mechatronic system and workflow

10. Team Reflections and Lessons Learned

Our project team worked across mechanical, electrical, clinical, and business domains. Here's what we reflected on:

- What went well:
    - Strong technical diversity collaboration
    - Multiple working prototypes in a limited time
    - Hands-on understanding of robotic kinematics
- What could be improved:
    - Earlier engagement with users for feedback on UI/control
    - More structured testing metrics to measure improvement
    - Improved time management around integration challenges

- Lessons learned:
    - “Simple but robust” solutions often outperform advanced but hard-to-implement ones
    - Analytical modelling (kinematics) is crucial for robotic surgery tools
    - Clear, cross-functional communication is critical in medtech development

Appendix

Code Calculation of the base and the top points

```
// Stewart Platform geometry
static const float basePoints[6][3] = {
    {-2, -6, 0}, {2, -6, 0},
    {3*sqrtf(3) + 1, 3 - sqrtf(3), 0},
    {3*sqrtf(3) - 1, 3 + sqrtf(3), 0},
    {-3*sqrtf(3) + 1, 3 + sqrtf(3), 0},
    {-3*sqrtf(3) - 1, 3 - sqrtf(3), 0}
};
static const float topPointsRel[6][3] = {
    {-2, -3, 0}, {2, -3, 0},
    {1.5*sqrtf(3) + 1, 1.5 - sqrtf(3), 0},
    {1.5*sqrtf(3) - 1, 1.5 + sqrtf(3), 0},
    {-1.5*sqrtf(3) + 1, 1.5 + sqrtf(3), 0},
    {-1.5*sqrtf(3) - 1, 1.5 - sqrtf(3), 0}
};
```

i. Calculation of link lengths

```
// Calculate leg length (distance from base to top point)
    float dx = top_global[0] - basePoints[i][0];
    float dy = top_global[1] - basePoints[i][1];
    float dz = top_global[2] - basePoints[i][2];
    float length = sqrtf(dx*dx + dy*dy + dz*dz);
```

2. Servo Control
    a. Maps lengths to servo angle

```
// Map leg length to servo angle
float map_length_to_angle(float length_cm) {
    if (length_cm < LINK_MIN_CM) length_cm = LINK_MIN_CM;
    if (length_cm > LINK_MAX_CM) length_cm = LINK_MAX_CM;
    // Linear mapping: 11.6cm -> 0°, 8.3cm -> 115°
    return (LINK_MAX_CM - length_cm) * (115.0 / (LINK_MAX_CM - LINK_MIN_CM));
}
```

    b. Maps servo angle to PWM

```
// Convert angle to PWM value
uint16_t angle_to_pwm(float angle) {
    if (angle < 0) angle = 0;
    if (angle > 180) angle = 180;
    return (uint16_t)map_float(angle, 0, 180, SERVO_MIN, SERVO_MAX);
}
```

- - - - - x - - - - - o - - - - - x - - - - - o - - - - - x - - - - -