

FreeGrip manipulator for surgical robot

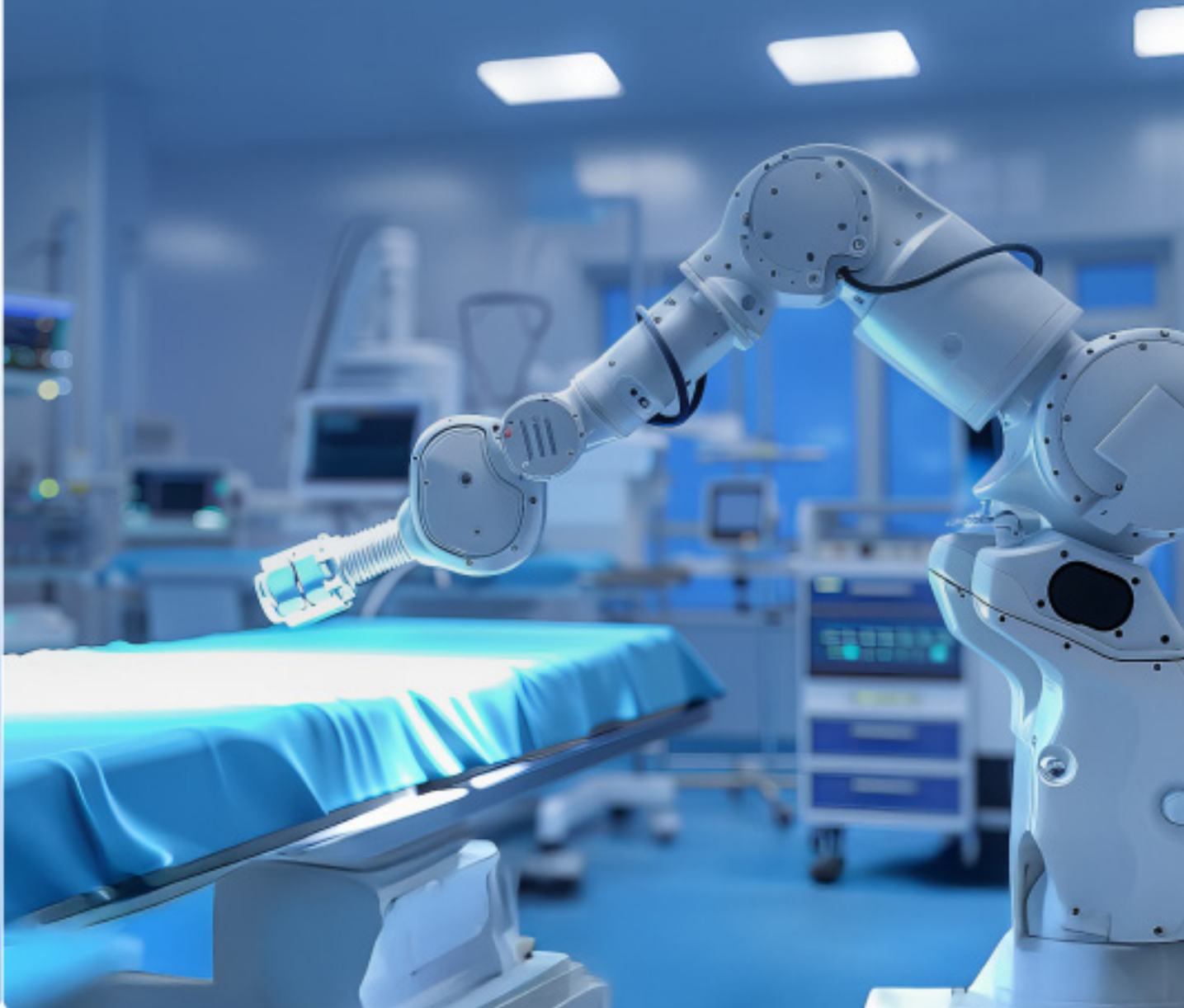


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Abbreviations

DOF	Degrees of Freedom
IMU	Inertial Measurement Unit
CAD	Computer Aided Design
PoC	Proof of Concept
CCF	Cross Correlation Function

Abstract

As the field of robot-assisted minimally invasive surgery (MIS) rapidly advances, the focus is shifting beyond robotic arms and visualization software toward enhancing the human-machine interface that ultimately defines surgical precision. Despite their sophistication, today's master consoles often remain bulky, ergonomically inadequate and disconnected from the surgical team environment. This disconnection can result in operator fatigue and hinder effective communication during prolonged or high-stakes procedures [1,2].

To address these persistent challenges, HCLTech has developed FreeGrip. A next-generation, compact, remote and detachable master manipulator, engineered to elevate the surgeon's control experience and improve system adaptability in dynamic operating room environments. Built with a lightweight and ergonomic design, FreeGrip integrates an Inertial Measurement Unit (IMU) capable of tracking three degrees of freedom (3 DoF), along with a potentiometric sensor that enables an additional one degree of freedom (1 DoF). This configuration allows for highly accurate capture and replication of fingertip motions, ensuring the intuitive and responsive control essential in robotic surgical procedures. The Proof of Concept (PoC) was subjected to rigorous testing across key performance indicators, including repeatability, accuracy, resolution, speed and dynamic response.

The system demonstrated 1° repeatability even at speeds of up to 720 degrees per second, along with a fine 0.05 mm sensitivity in linear displacement—metrics that underscore FreeGrip's potential as a transformative human-interface technology in surgical robotics. While the current prototype shows strong promise, it is currently limited by its requirement for a fixed reference position and the need for manual calibration, both of which present clear opportunities for future optimization. This whitepaper explores how FreeGrip not only addresses longstanding ergonomic and communication limitations in robotic surgery, but also sets the stage for a new generation of digitally enhanced, surgeon-centric systems. For technology leaders, healthcare innovators and R&D teams, it offers valuable insights into the next frontier of precision surgery, redefined by intelligent engineering.

Introduction

In recent years, the field of clinical practice has seen a substantial increase in the embracing of robot-assisted MIS. Robotic surgery has reached a high level of maturity, but current control consoles are bulky and limit technological advancements. Operating these robots often requires significant effort from the user, both mentally and physically, due to the intricate control systems and the need for precise movements over extended periods [2]. Also, current surgical consoles isolate the surgeon from the team, creating communication challenges [3].

The ergonomic drawbacks of traditional consoles are not merely operational inconveniences. They carry measurable clinical risks. According to one study, approximately 8.1% of robotic surgeries are converted to open or manual procedures due to complications arising from discomfort, system complexity or loss of precise control [4]. In addition, the heavy and rigid physical architecture of conventional interfaces limits the flexibility to quickly detach or reconfigure systems during high-pressure scenarios, particularly in dynamic or emergency contexts [5].

Several studies have been attempted to address some of these shortcomings using a Head-Mounted Master Interface integrated with a surgical robot system, Augmented Reality (AR) interface through various hand gestures, integrating sensory gloves, such as the HTC Vive tracker and Manus Meta Prime 3 XR etc., improvising control and intuitiveness. Preliminary evaluations show high accuracy and ease of use, suggesting potential for further innovations [3,5].

However, the system can be further improved in size, user-friendliness, ease of dismantling and weight. In this whitepaper, a FreeGrip manipulator that leverages motion capture technology to enhance surgical experience has been studied. To overcome the above limitations, a preliminary PoC model of a compact, detachable master manipulator that can be integrated with the motion capture system or used as a standalone system is proposed.

This system employs an Inertial Measurement Unit (IMU) based on three Degrees of Freedom (DoF) motion tracking to replicate all necessary fingertip movements required in robotic surgery. The design emphasizes ergonomics, ease of handling, repeatability and lightweight construction. A series of experiments were conducted and the results were analyzed to study the feasibility of the FreeGrip manipulator in achieving repeatability, accuracy, resolution, speed and transient response.

Methodology and architecture

The study on the FreeGrip manipulator began by selecting appropriate sensors based on literature, requirements and constraints. Later, the study focused on the ideation and design of the manipulator. Ideas were generated, refined and finalized to meet the literature and product requirements.

A CAD model of the manipulator was developed, including an IMU sensor and electronics, with a focus on ergonomic aspects. The model was 3D printed and integrated. The motion simulation was performed using a Python platform to visualize the manipulator's movements in 3D space. The final phase of the study involved conducting experimental studies on the proposed manipulator to analyze the static and dynamic performance of the IMU-based tracking technology.

The overall architecture of the surgeon's console in the surgical robot system comprises displays, control systems, sensing modules, a haptic feedback system, a vision-based tracker and an IMU-based manipulator (interest of the current study), as shown in Fig. 1

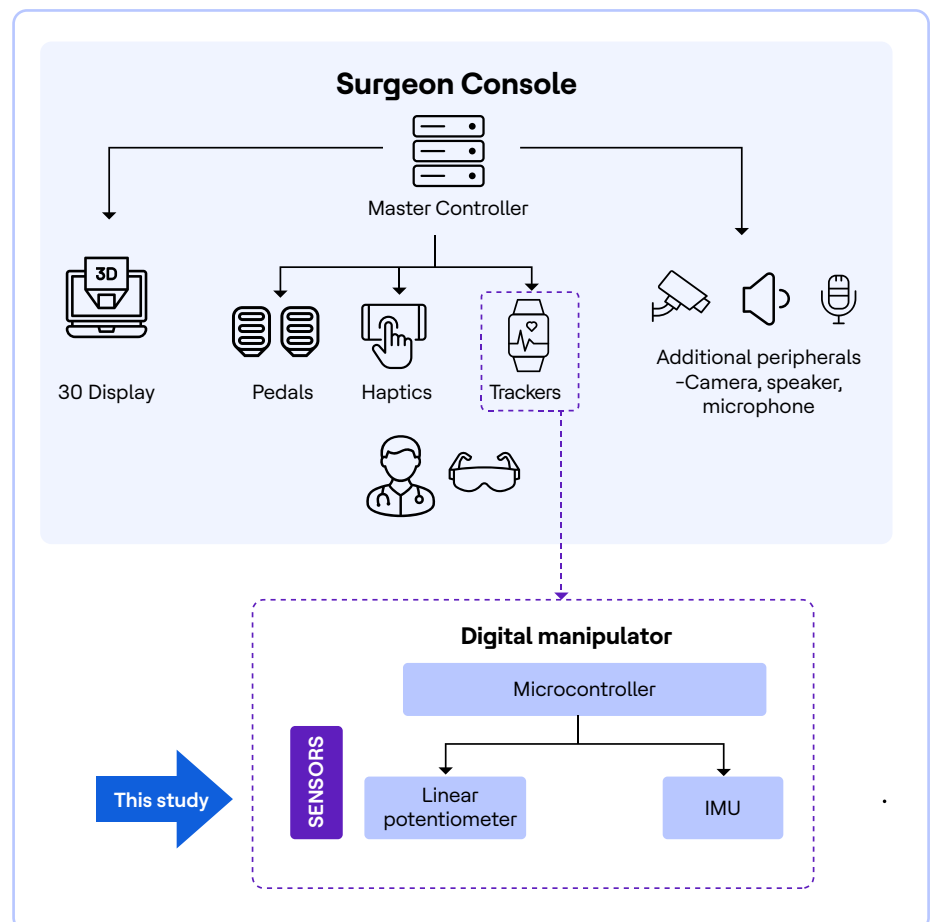


Fig 1 PoC Architecture of the surgeon's console for a typical surgical robotic system

The overall general architecture of the surgical robot's surgeon console comprises viewing modules (monitors and optional displays), optical tracking, a haptic feedback system, a power supply and the IMU-based manipulator, as shown in Fig 1.

The manipulator, developed as a PoC, includes sensors, a cylindrical handle enclosure, a power supply and a microcontroller that processes data using serial, analog and I2C communication.

The sensor module comprises an IMU-based sensor for tracking orientation (wrist movements) and a linear potentiometer for linear finger motion (pinching motion). The surgeon interacts with the handle, which integrates these sensors with a feedback mechanism to ensure accurate and responsive control during surgical procedures.

Computation algorithm

The orientation is represented as quaternion (Eqn. 1), rotation matrix and set of Euler angles. The model describes the conversion of rotational vector inputs from an Inertial Measurement Unit (IMU) into Euler angles—namely Yaw, Pitch and Roll. This is achieved by employing the following equations, 2-4,

Quaternion, $q=W+Xi+Yj+Zk$ Eqn.1

Yaw = $\arctan 2 (2.0x((XxY)+(ZxW)),(X^2-Y^2-Z^2+W^2))$ Eqn.2

Pitch = $\arcsin (-2.0x(XxZ-YxW)\sqrt{(X^2+Y^2+Z^2+W^2)})$ Eqn.3

Roll = $\arctan 2 (2.0x((YxZ)+(XxW)),(-X^2-Y^2+Z^2+W^2))$ Eqn.4

X, Y, Z (vector part) and W (scalar part) represent the components of the quaternion, which is a complex number system that extends the concept of rotation in 3-dimensional space.

Modeling and design

The evolution of the PoC design for FreeGrip handles has led to a concept that emphasizes ergonomics, specifically a two-finger precision grip that mirrors the natural dexterity of the human hand [6,7]. This semi-cylindrical handle will significantly reduce neck and finger discomfort among surgeons, with no wrist discomfort reported.

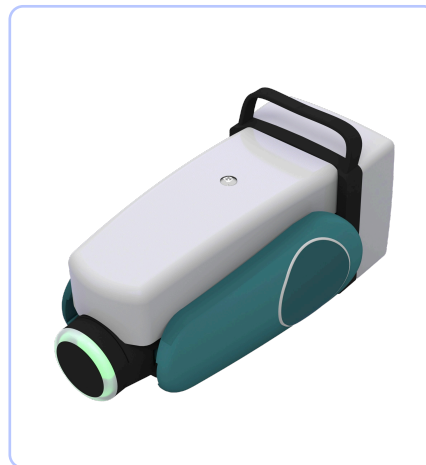


Fig 2. Assembly view of FreeGrip

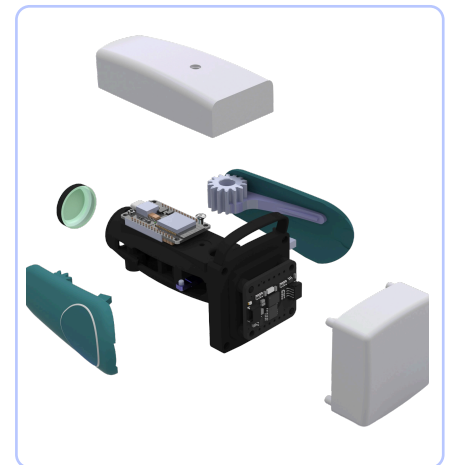


Fig 3. Exploded view of FreeGrip

Therefore, these ergonomic features are incorporated into the PoC model to enhance comfort and precision in surgical performance. Handles with a precision grip are preferred to enable surgeons to operate with greater accuracy and reduced physical strain. Figures 2 and 3 show the 3D model and the exploded view.

Test plan

To examine the sensor characteristics and their appropriateness, a preliminary PoC laboratory model is fabricated, incorporating an IMU sensor (Bosch, Model No: BNO085), a controller (SAMD21) and data captured through a Python platform running on a PC. The auto-calibration feature facilitates the sensor's recalibration whenever it is activated.

A comprehensive experimental plan was developed to evaluate a system's performance, focusing on its range, repeatability, accuracy and transient response, as shown in Figure 4.

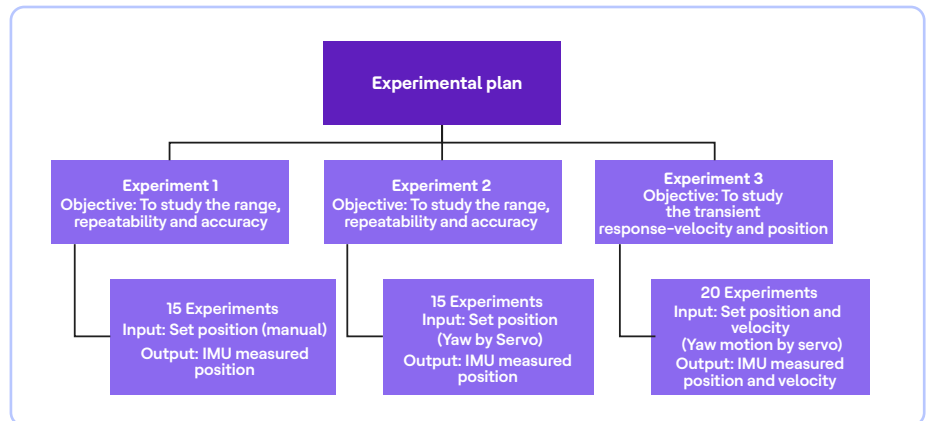


Fig 4. Experimental plan

Measurement setup

Figure 5 shows the experimental setup for three series of testing. The first of the three experiments (A) tested the system's operational range and repeatability by conducting 15 trials in which the system's position was manually set and measured with an IMU. The details are given in Table 1.

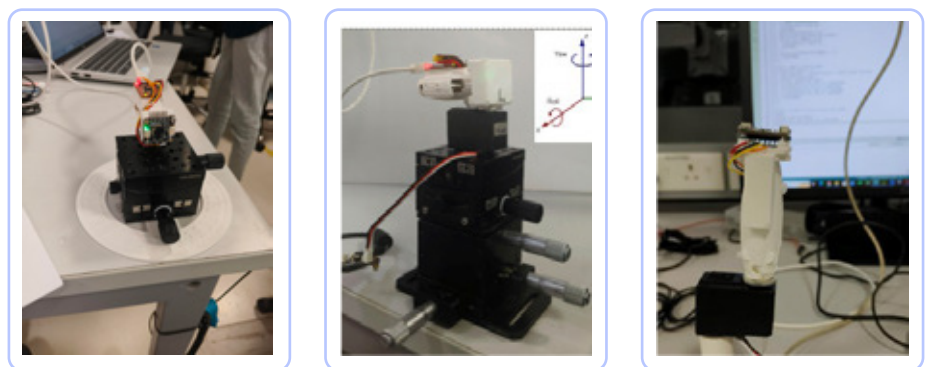


Fig 5 Experimental setup (A, B and C)

The second experiment (B) follows the same goals but explores a different input method by using a servo to control yaw motion. Through 15 trials, a comparative study between the IMU-measured positions and those from the first experiment was performed to assess the impact of input methods on performance.

		Experiment series A	Experiment series B	Experiment series C
Factors		3, Roll, Pitch and Yaw	3, Roll, Pitch and Yaw	Position and Speed
Levels	Levels	5 Levels	5 Levels	Speed: 720, 132, 90, 60
	Yaw	-15, -9.5, 0, 3, 15	-15.0, -8.0, 0, 3.0, 15.0	0 to -45, 0 to +45,
	Pitch	-15, -11.0, 0, 6.5, 15	-13.0, -5.0, 0, 7.0, 12.0	0 to -90, 0 to +90,
	Roll	-15, -2.5, 0, 1, 15	- 8.0, -3.0, 0, 10.0, 15.0	-90 to + 90
No of iterations		3	3	3
Reference		Roll and Pitch: Goniometer	Set Position – Yaw: Servo Roll and Pitch: Goniometer	Set Position – Yaw: Servo Roll and Pitch: Goniometer

The third experiment (C) will examine the system's dynamic response to rapid changes by setting five position ranges and four velocities for execution with servo-controlled Yaw motion and measuring the velocity and position over extended range and period with the IMU. The output is recorded through a PC for further analysis.

Test results

Repeatability is more critical than accuracy for surgical systems because it guarantees consistent system responses to the surgeon's handle movements. This consistency allows surgeons to build a reliable sense of control and anticipation. If the system reliably replicates the surgeon's movements with the robotic arm, the surgeon can correct minor positioning inaccuracies.

The data inferred from the first experiment series, labeled as A, revealed a significant correlation across the three iterations, indicating the consistent performance of the IMU sensor in capturing the target positions, as shown in Fig 6 for Yaw, Pitch and Roll motions. The repeatability of the roll measurements obtained through the IMU sensor is 1.08 deg. The repeatability of the Yaw and Pitch measurement by the IMU sensor is 3.4 degrees and 1.12 degrees, respectively.

This metric reflects the sensor's ability to reproduce the roll angle readings consistently across multiple trials. Furthermore, the accuracy of the roll measurements was determined to be 2.50 degrees.

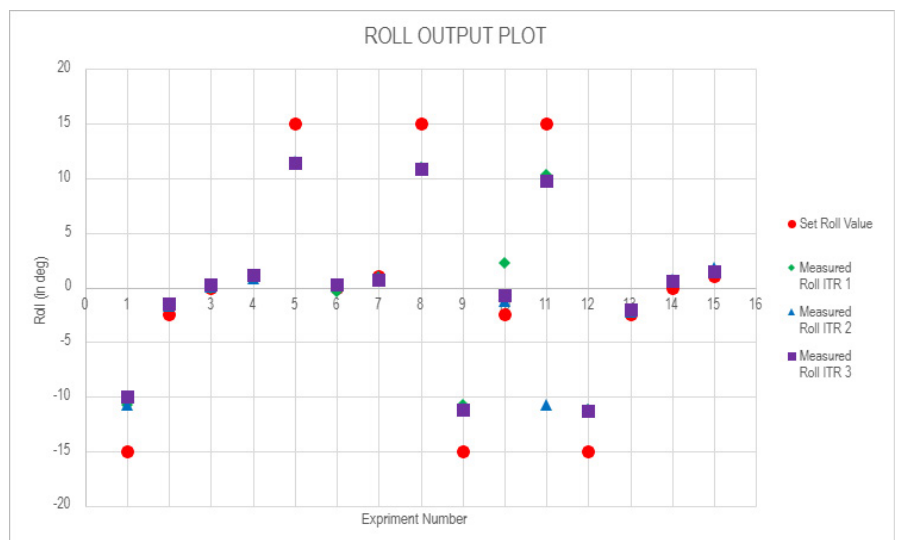
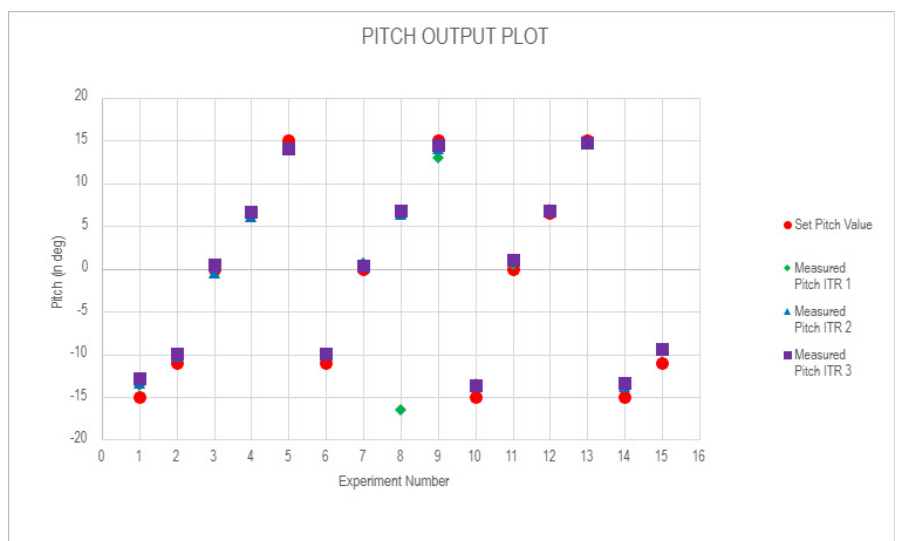
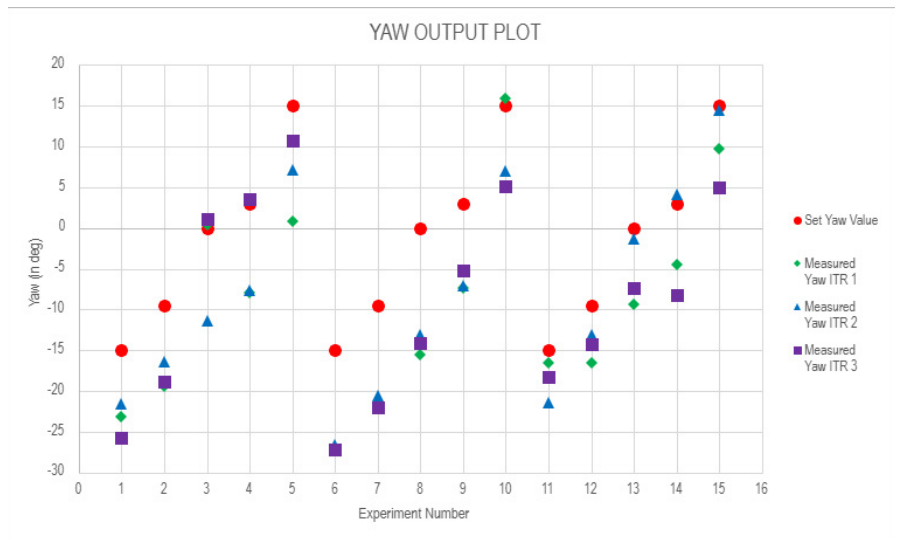


Fig 6 Target Vs IMU measured positions (experimental set A)

The IMU's Yaw and Pitch measurements are accurate at 8.17 and 1.37, respectively. This value signifies the deviation of the measured roll angles from the target values, which is within the acceptable range required in surgical applications. One notable feature from the experimental data is the higher repeatability range, which is critical for a surgical system.

The IMU sensor demonstrated stable static behavior within the experimental bounds of -15° to $+15^{\circ}$. This stability is crucial for the fine control of robotic surgical instruments, ensuring the sensor's readings remain reliable even at the extremities of its operational range.

The subsequent experimental series (B) examined servo-activated Yaw motion. The findings indicated a significant correlation across three iterations. Static behavior exhibited consistency within the test range of -15° to $+15^{\circ}$. The IMU sensor's roll measurement repeatability was determined to be 1.10. Yaw and Pitch measurements demonstrated repeatability values of 0.89 and 0.67, respectively. The accuracy of roll measurement was 2.25. Meanwhile, the Yaw and Pitch measurements' accuracy were 1.74 and 1.11,

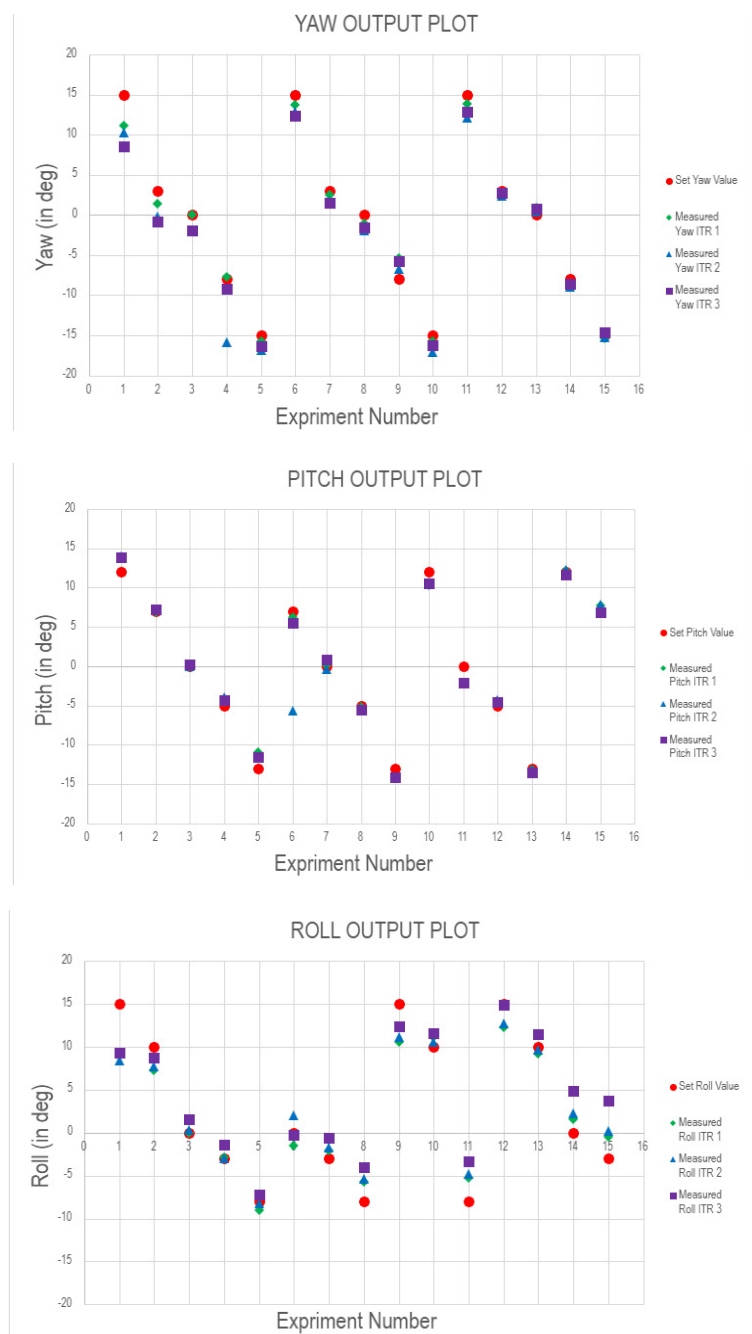


Fig 7 Target Vs IMU Measured Positions (Experimental Set B)

Cross correlation analysis

The final set of experiments, labeled as Series C, yielded the following outcomes. The Cross Correlation Function (CCF) serves as an index of resemblance between two time-series, gauging the extent of similarity as one series is shifted in relation to the other. This method is instrumental in confirming the sensor's transient behavior when subjected to a steady input.

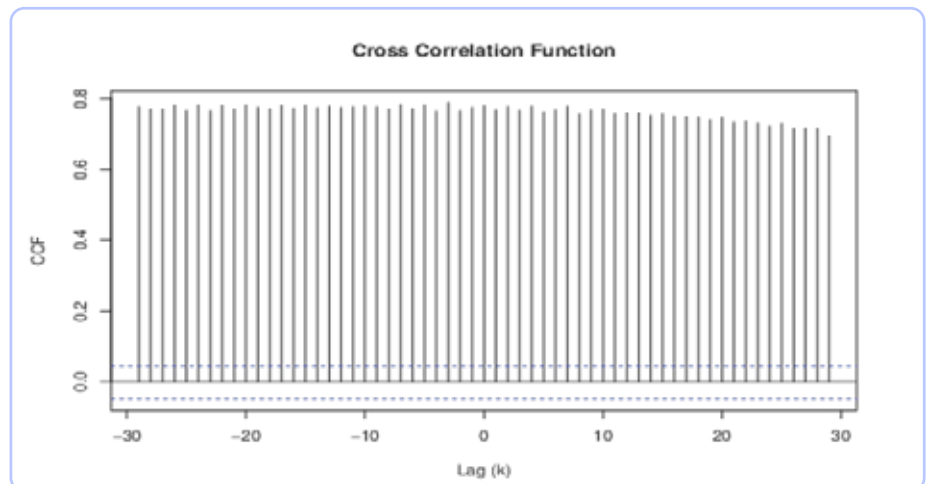
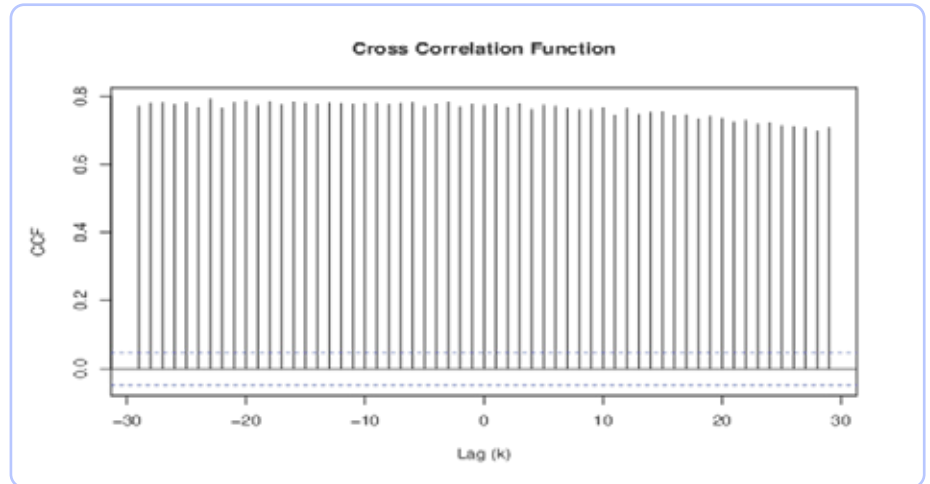


Fig 8 Cross correlation function for three trials (Velocity 132 deg/s Position -90 deg to +90 deg)

In scenarios involving identical surgical movements, the CCF indicates consistency in position and velocity over time. The CCF has been computed for three sensor outputs, corresponding to an input velocity of 132 degrees per second. The initial trial serves as the benchmark against which the subsequent two outputs are evaluated. The analysis reveals a similarity between the signals, as evidenced by the CCF values being significantly above 0.7, indicating high similarity. Hence, it is evident that the IMU sensor tracks the motion with higher repeatability. Experiments conducted in linear potentiometric sensors show an accuracy of 0.05 mm.

Conclusion

In conclusion, the comprehensive analysis and testing of the IMU-based sensor system free from handle or FreeGrip manipulator have yielded promising results that align with the stringent requirements of surgical robotic applications. The sensor's resolution of 0.4° not only meets but exceeds the functional necessity, ensuring precise measurements.

S.no	Requirements	Yaw		Pitch		Roll	
		Target	Actual	Target	Actuals	Target	Actual
1	Resolution	0.5°	0.4°	0.5°	0.4°	0.5°	0.4°
2	Accuracy	3.46°	1.74°	3.46°	1.10°	3.46°	2.25°
3	Range	-80° to 70°	-90° to 90°	-50° to 70°	-15° to +15°	-90° to 90°	-15° to 15°
4	Repeatability	-	0.89	-	0.67	-	1.10
5	Max speed	130° /s	720°/s	130° /s	720°/s	130° /s	720°/s

With an orientation accuracy of approximately 1.74°, the sensor demonstrates a commendable performance in capturing the Yaw motion within the range of -80° to +70°. Although the pitch and roll measurements are confined to a range of -15° to +15° due to the limitations of the experimental setup, this does not detract from the sensor's overall efficacy. Linear displacement accuracy of 0.05 mm shows the potentiometric sensor's ability.

The high repeatability around one deg within the boundary condition shows that the sensor is suitable for surgical applications where repeatability is more critical than accuracy. Its consistent transient responses across multiple trials with constant velocity input emphasize its reliability and robustness.

Additionally, it enhances ergonomic features and decreases the space needed for a master console. However, the calibration and datum setting assumptions limit the system performance to the laboratory conditions only.

IMU-based surgical tracking systems face challenges like time drift, which causes cumulative errors in position and orientation. They are also prone to interference from magnetic fields and electronic devices in the operating room, which affects accuracy.

Opportunities exist to enhance the measurement setup, including improvements in dynamic datum during hand movements, calibration, setting servo feedback, modeling, ergonomic design, communication, fabrication and error correction strategies for sensor mounting and experimentation. These advancements will further refine the system's performance and reliability.

Future explorations will examine the feasibility of its standalone application, paving the way for innovative solutions in surgical robotics, rehabilitation and assistive devices.

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