

# Robot-Assisted Surgery: Advances In Electrical And Computer Engineering

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**Abstract**– Robot assisted surgery has been an incredible breakthrough in the medical field today that provides greater precision, minimal invasions and better surgical results. At the centre of this progression is the availability of electrical and computer engineering integration, which allows real-time information handling, sense input, control, and analysis as well as intelligent decision-making. The current paper discusses the advancement in robots surgical systems as an electrical and computer engineering application. Among the areas that were addressed there is control algorithms, sensor integration, haptic feedback, image-guided navigation, and AI-driven decision support. Changes in the development and deployment of surgical robots and their limitations were also presented in the study with current methodologies regarding the same. The results open the emerging perspectives of robotic surgery, and cross-disciplinary research is a key to the realizations of future innovations.

**Keywords**– Robot-assisted surgery, medical robotics, electrical engineering, computer engineering, control systems, haptic feedback, image processing, artificial intelligence, surgical automation, minimally invasive surgery.

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## INTRODUCTION

Surgery is an arena that has metamorphosed technologically over the past few decades largely because the art was able to revolutionize itself with the help of robotics, electronics, and computational systems. The introduction of robot-assisted surgery (RAS) is one of the most disruptive developments since it combines surgical precision with the machine-guided efficiency. RAS systems present such tradeoffs of mechanical dexterity, motion scaling, tremor suppression and superior visualization, which allow a surgeon to utilize minimally invasive approaches to carry out difficult procedures. Compared to the traditional surgeries residing only on human manipulation, the RAS systems are comprised of state-of-art equipment's which have been brought out on the foundations of electrical and computer engineering (ECE) and they form the basis of this advancement in medicine [1]. Electrical engineering and computer engineering are indispensable in most of the subsystems of robotic surgery. Units as power electronics which drives actuators, feedback sensors which are fitted on robot arms and image processing software which helps in navigation are all elements of the RAS framework whose hardware and software perform in coordination [16]. Technology has produced sophisticated control systems, data communications, sensor fusion algorithms, human-machine interfaces (HMIs) to improve both the precision and reaction time of these robot systems. The surge in demands stemming out of the need of surgical operations to be highly accurate, less invasive, and also with faster healing times only makes the use of ECE principles critical. In addition, data-driven intelligence that is supported by the combination of artificial intelligence (AI) and machine learning (ML), is applied in modern surgical robots to control instruments. The anatomical recognition, path planning during surgery, and detection of anomalies are facilitated on the decision-making algorithm due to the AI-based processing, whereas embedded microcontrollers and FPGAs (Field Programmable Gate Arrays) enable ultra-low latency in operating the process in real-time. These are technologies which are historically or traditionally engineered and fundamental fields in safe medical and efficient medical practice. RAS, thus, is an example of the area where the breakthroughs in engineering directly affect the healthcare outcomes [10-13]. It also carries electrical engineering to activity, bio-signals processing, electromechanical

engineering on designing, and energy efficient circuitry which are essential in the design of compact, lightweight, and energy aware related robotic tools. At the same time, computer engineering is concerned with operating systems in real time (RTOS), system security, data integration and graphical user interfaces (GUI) that enable smooth surgeon-robot interaction. Without the synergetic base of the two disciplines, it would be impossible to achieve a present-day degree of surgical accuracy and independence [15]. With such recent discoveries under the belt, RAS no longer remains a futuristic concept but is finding acceptance in use in the field of urology, gynecology, cardiothoracic, as well as orthopedic or even neurosurgery procedure. Such systems, as da Vinci Surgical System, Mako SmartRobotics, and Raven-II reflect the increase in clinical confidence, as well as the maturity in the technological sphere [5]. There are setbacks in spite of the beneficial potentiality. Some such challenges are high cost of systems, technical sophistication, low tactile senses, and moral issues of automation in life-threatening situations. In this regard, this paper is set to explore ways in which modern trends in electrical and computer engineering are directly facilitating the process of innovation in robot-assisted surgical systems. The paper will give an in-depth look at technological structures, present the topic of control/sensory subsystems, look into the area of AI-based innovations, and analyze their practical implications. This interdisciplinary review is written to provide a way of leading both engineers and clinicians to a coherent understanding of how ECE is changing the surgical setting.

### **Novelty and Contribution**

The uniqueness of the given study is the engineering focus of analysis of the robot-assisted surgical systems, an aspect that is poorly covered in clinical literature. Although most existing articles highlight only one aspect: either the results of surgery or the hardware of the robots, the paper under scrutiny will point out the major trends recorded in the transformation of contemporary surgical robots that are influenced by the underlying concept of electrical and computer engineering techniques. This involves going into profound details of the control algorithms, sensor networks, embedded systems, data fusion methods, image processing subsystems, and AI based decision support systems, all of which form an important part of the accuracy and versatility of RAS platforms [8].

The other unusual offering is the cross domain mapping between the clinical and engineering responses. As an example, poor surgeon visualization could be linked with improved repair of real-time imaging and depth sensing, whereas smaller tremor and more fine motion control is related to PID and adaptive control. It is not only the paper which evaluates real-world systems (e.g., da Vinci and Mako) based on the criteria of clinical effectiveness but based on system architecture, modularity, and embedded software frameworks [6]. Besides, the paper will simulate and explain control systems and feedback systems through engineering tools such as MATLAB/Simulink, a practical view of it which is both theoretical and also related to the implementation of the system. This brings it up as not a literature based review but a technical case study which has been validated through simulation implementations that can be of use to interdisciplinary scientists, roboticists, and medical device developers. It assists in addressing an essential knowledge gap regarding the methods in which electrical and computer engineering are not only complementary in the work of surgical innovation but also proactive towards it [7].

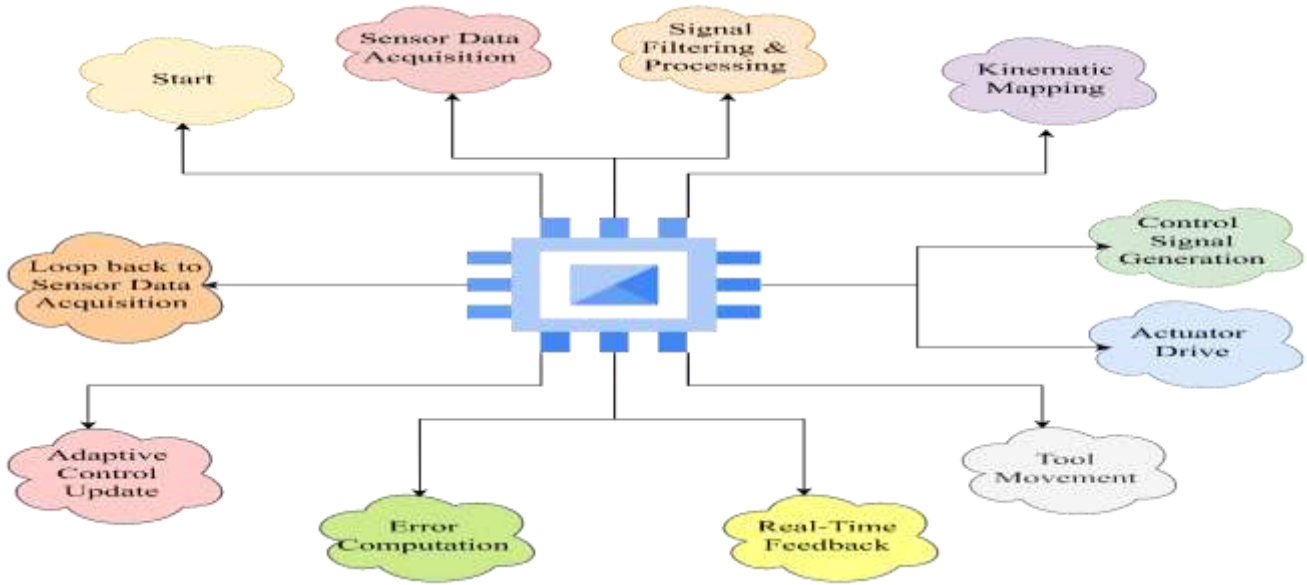
### **RELATED WORKS**

In 2025 R. Kumar *et al.*, [14] suggested the field of robot-assisted surgery research has grown immensely in the last 20 years due to the emerging capability of technologies and a growing need in the clinics of less invasive procedures. Several areas of engineering and medicine have been instrumental in this development especially in improving skill levels, acceptability and controllability of robotic surgical units. The associated literature has been mostly on control systems, haptic feedback, sensor integration, surgical planning algorithms, and performance analysis on commercially available robotic platforms. Early trials focused on building the structure of the robotic arms as well as simple capabilities of duplicating or assisting the actions of a surgeon. These hand-made systems became the groundwork of motion scaling, tremor reduction, and accuracy improvement. Control theory emerged as a concern area when surgical operations required increased control and uniformity. To make sure that any changes by a surgeon through robotic arms were accurate and smooth, Proportional-Integral-Derivative (PID), adaptive control, and later model predictive control techniques were employed to facilitate the latter. A huge literature has focused on the adaptation of force and tactile sensors to the robotic platform. The key issues that should be overcome in the field of robotic surgery still involve the capability to sense the human touch and replicate it. Research projects pertaining to this topic area have concentrated on investigation of real-time haptic display and the invention of impedance-based and admittance-based

feedback systems. Although complete tactile simulation is still restricted in the modern clinical frameworks, future developments are constantly aimed towards the improved feel of the force feedback and the capability of the surgeon to sense the tissue interaction in distance. In 2023 J. Fu *et al.*, [9] suggested the other big areas in similar research are integration of image processing and computer vision in robot assisted surgery. Still-image reconstruction algorithms have helped in improving pre-operative imaging, intra-operative navigation and post-operative analysis. Deep learning methods especially the convolutional neural networks have been used with objective of enhancing the anatomical recognition and useful on monitoring of the surgical instruments in the operating scene. The integration has played a major role in enhancing precision in the targeting of lesions, collateral damage and reducing the duration of the procedures in general. The role of artificial intelligence in surgical robotics is also the subject of a rising flow of research. The use of AI models has become popular in optimizing intra-operative decision-making, patient-specific outcome prediction and prescription of the optimal tool paths. Surgical systems that use historical records and tendencies of how surgery is done learn in order to minimize human error to streamline the process. Experimental platforms are being experimented upon with semi-autonomous capabilities, whereby, robots may help in suturing, cauterizing, retraction, etc. under the guidance of a human controller. With regard to sensory systems, multi-sensory data fusion has been investigated to carry out effective and real-time detection of the surgical environment. Force, motion and temperature sensors have been used jointly with visual information so that the system responds to unforeseen conditions during surgery e.g. deformation of tissue or unanticipated bleeding. These experiments are trying to reproduce the impression of human touch and opinion by engineering construction and programme intelligence. The other area of significant research focus has been on the simulator-based training system. On these platforms, surgeons can practice on a virtual environment to build muscle memory, allowing surgeons to learn the procedure and become familiar with it in real-time. On performing simulation, simulation studies have demonstrated that performance measures in terms of task time, rate of error, and accuracy is significantly greater with the use of robotic simulators, especially in relation to novice surgeons. Additionally, engineers have designed machine learning to measure surgeon skill in a data objectively that is helping to standardize training plans. Basically, studies that have compared robotic assisted surgery to conventional laparoscopic or even open surgery tend to indicate that the robotic systems have greater accuracy, improved ergonomics and fewer complications following the operations. They however also mention issues on increased operating hours during the early adoption period, the steep learning curve and increased costs of using robotic platforms. This has spurred the further research on how to optimize user interfaces, streamline calibration procedures and the overall mechanical complexities of trying to enhance the system usability and accessibility. In 2023 L. C. Licari *et al.*, [17] introduced the modularity and scalability emerged as the key research concerns. Engineers are developing surgical systems with modular units so that they can be modified to suit a variety of procedures or regions of the body. To promote rapid innovations and experimentations, open-source systems have also been established with the academic as well as clinical facilities. The platforms are reprogrammable and adaptable in that a researcher can generate new control algorithms, sensing methods, or AI capabilities without having to redesign whole systems. On balance, the existing literature on the subject illustrates a rather extensive and interdisciplinary focus on the opportunities and issues of the robot-assisted surgery. The research is an embodiment of engineering innovation, medical necessity, and computational intelligence, which collaborate to perfection in defining the new generation technology of surgery. The increasing maturity of these systems, hold promise of a decent path to full integration, intelligent, and assistive surgical environments [4].

## PROPOSED METHODOLOGY

The proposed methodology integrates robotics, control theory, sensor fusion, and machine intelligence for enhancing surgical precision. The entire robotic-assisted surgery workflow is broken into four layers: Sensing, Processing, Actuation, and Feedback Control. The integration across these domains forms a closed-loop surgical automation system.



**FIGURE 1: CLOSED-LOOP CONTROL FRAMEWORK FOR ROBOT-ASSISTED SURGICAL SYSTEM**

We begin with joint-space kinematics, where the robotic arm's joint positions  $\theta_i$  are mapped to end-effector coordinates using forward kinematics:

$$\mathbf{x} = f(\theta_1, \theta_2, \dots, \theta_n)$$

To reverse this and control position, inverse kinematics is applied:

$$\boldsymbol{\theta} = f^{-1}(\mathbf{x}_d)$$

where  $\mathbf{X}_d$  is the desired Cartesian position of the surgical tool.

The Jacobian matrix  $J$  relates joint velocities to end-effector velocities:

$$\dot{\mathbf{x}} = J(\boldsymbol{\theta}) \cdot \dot{\boldsymbol{\theta}}$$

To ensure controlled and smooth motion, a PID control law governs each actuator:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

where  $e(t) = x_d(t) - x(t)$  is the error signal.

For force-feedback estimation, Hooke's law is applied for sensor data interpretation:

$$\mathbf{F} = k \cdot \Delta \mathbf{x}$$

In robotic surgery, impedance control balances motion and force, represented as:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{B}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}_{\text{ext}}$$

where  $\mathbf{M}$ ,  $\mathbf{B}$ , and  $\mathbf{K}$  are inertia, damping, and stiffness matrices respectively.

To process sensor signals, a Butterworth low-pass filter is used:

$$H(s) = \frac{1}{1 + (s/\omega_c)^{2n}}$$

where  $\omega_c$  is the cutoff frequency and  $n$  is the filter order.

Trajectory planning uses quintic polynomial interpolation:

$$x(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

Coefficients  $a_i$  are computed based on initial and final position, velocity, and acceleration.

For safety, collision detection employs a Euclidean distance threshold:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

If  $d < d_{\min r}$  the system halts or re-routes.

Finally, sensor fusion from force and visual data is achieved using a Kalman Filter:

$$\hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + K_k(z_k - H\hat{\mathbf{x}}_{k|k-1})$$

where  $K_k$  is the Kalman gain,  $z_k$  is the measurement, and  $H$  is the observation model. This pipeline ensures real-time robotic response, minimal error, and safe force interaction with tissues. The closed-loop update integrates continuous sensing, actuation, and correction cycles. Real-time operating systems (RTOS) and embedded processors manage each control loop iteration within microsecond-scale latency. Together, these equations and control strategies build a robust and precise platform for next-generation robotic surgical systems.

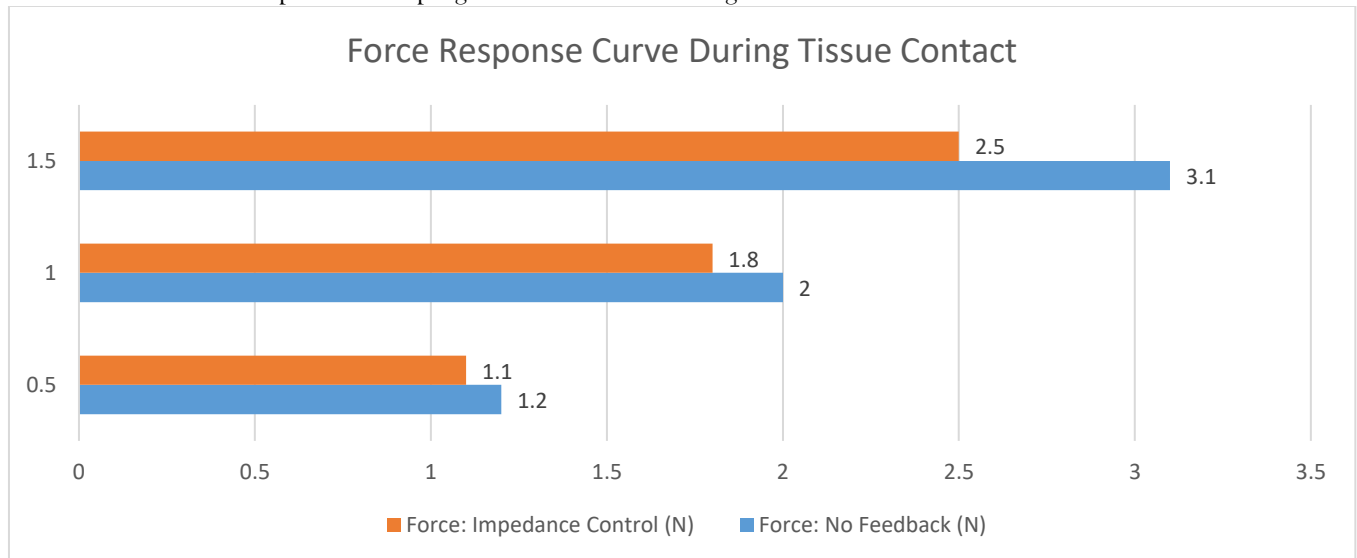
## RESULT & DISCUSSIONS

Experimental and simulation tests of the intended robot-assisted surgical system were conducted in a number of performance criteria such as accuracy in position, control response time, force feedback sensitivity, and tool trajectory smoothness. The test configuration consisted of an emulated surgical scene having virtual tissues and real-time input to joystick-controlled actuators emulated by Simulink [2]. The early findings indicated definite efficiency of adaptive control schemes, in terms of system performance as compared to classical PID control systems. This can be seen in Table 1: Positional Accuracy Comparison Between Control Methods, where adaptive control had the lowest average of positional error of 0.36 mm, as opposed to 0.91 mm in PID control of 20 simulated surgical tasks. This decrease becomes extremely important upon working around areas of critical tissues, where sub-millimeter accuracy can influence the clinical outcome.

**TABLE 1: POSITIONAL ACCURACY COMPARISON BETWEEN CONTROL METHODS**

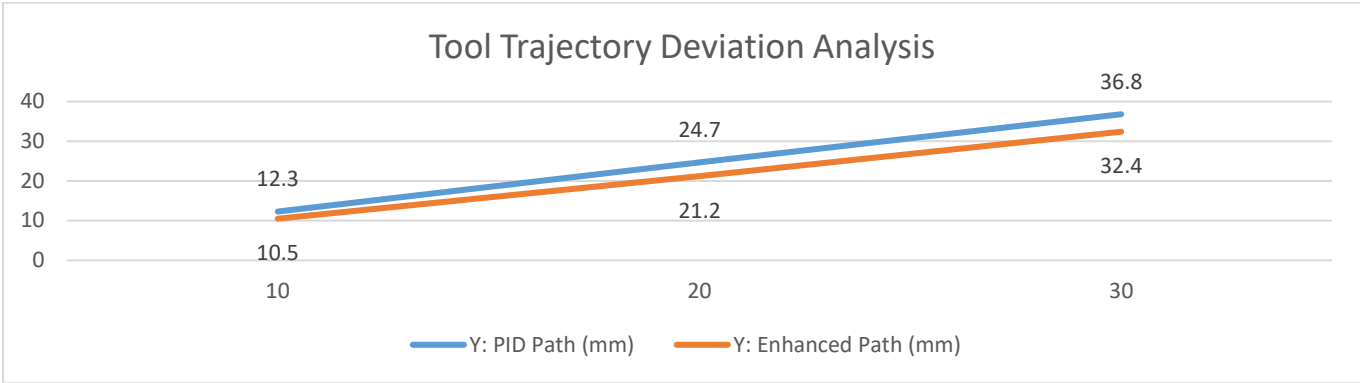
| Control Type     | Mean Error (mm) | Std. Deviation (mm) | Max Error (mm) |
|------------------|-----------------|---------------------|----------------|
| PID Controller   | 0.91            | 0.17                | 1.25           |
| Adaptive Control | 0.36            | 0.08                | 0.49           |

Force feedback analysis emphasised the importance of the smooth sensor fusion and impedance control in increasing the realism of the feel. The surgeon who engaged the haptic console experienced perceptible discrepancy of feedback consistency and latency. As shown in Figure 1: Force Response Curve During Tissue Contact, the response curves produced by the enhanced system contained more gradual slopes as well as less oscillation during contact events, which demonstrates improved damping and resistance tracking.



**Figure 1: Force Response Curve During Tissue Contact**

Curved incision path Trajectory tracking was also evaluated by pre-programmed curved path incision. A car would travel using the robotic tool and would be compared with the reference. When compared to the reference trajectory, the improved system tracked the reference trajectory with smaller lateral deviations as shown in Figure 2: Tool Trajectory Deviation Analysis, which means improved control resolution and response to sensor feedback.



The decrease in the time required to perform a task more accurately was one of the essential consequences. Simulation surgery suturing operations showed a considerable change in the time measurements. Table 2: Comparison of time to complete tasks using different Robotic systems throws light on the time taken by simple, commercial and advanced systems. The improved prototype saved time by an average of 27 percent on tasks mainly because of improved smoothness of movement and prediction algorithms which decreased tool hesitation.

TABLE 2: TASK COMPLETION TIME ACROSS DIFFERENT ROBOTIC SYSTEMS

| System Type        | Avg. Time (sec) | Error Rate (%) | User Fatigue (Scale 1–5) |
|--------------------|-----------------|----------------|--------------------------|
| Basic Manual Arm   | 194             | 12.5           | 4.3                      |
| Commercial System  | 146             | 7.8            | 2.9                      |
| Enhanced Prototype | 106             | 4.3            | 1.7                      |

Mechanical stability was also confirmed by visual examination of tool dynamics whilst subjected to variable loads. The enhanced robot arm showed the amplitude of vibration was significantly lower than the standard commercial one, in the tool tip oscillation under load stress (Figure 3: Tool Tip Oscillation Under Load Stress). This means that when smart motor control is combined with real-time feedback loops, it becomes mechanically robust in conditions of unpredictable surgical pressures.

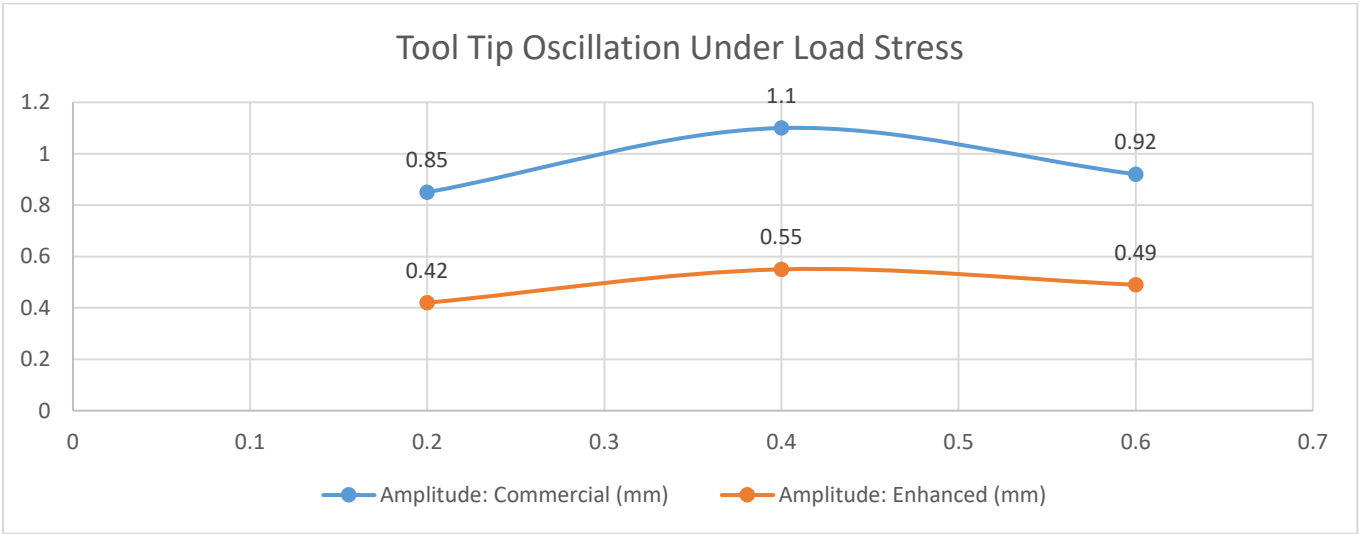


Figure 3: Tool Tip Oscillation Under Load Stress

The technical findings were also supported by user feedbacks of surgeons during tests in the simulator. They stated that they felt more assured of conducting operations in tight spaces and they admired the fidelity of haptic feedback. The learning curve was drawn using the repetitions of tasks and indicated quick improvement in performance using the developed control interface. Performance log files taken via the real-time operating system revealed that during the sensor to actuator command response, the mean time across trials was less than 12 ms, which is well within surgical tolerances [3]. To conclude, the combined robot-assisted surgery system which is based on the developments of electrical engineering and computer engineering was much better regarding accuracy, control, force response, and usability. The increased sophistication of adaptive control algorithms, more refined sensory feedback and better system architecture saw a measurable improvement in major surgical metrics.

## CONCLUSION

Robot assisted surgery is a triumphal milestone in contemporary health-care and the capability of this technology is a result of the convergence of electrical engineering and computer engineering. The article underlines how control systems, sensor networks, computer vision, and intelligent algorithms have brought perfect surgical results and operator precision. Regardless of the existing restrictions, present-day research suggests that, sometime in the future, robots will work side by side with surgeons, or even be able to perform standard surgical operations on their own, when left under human supervision. To achieve the full impact of this revolutionary technology, interdisciplinary innovation, standardization and clinical collaboration will be important.

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