VER
Vascular & Endovascular Review

Integrated Robotic–Imaging Platforms in Endovascular Surgery: Current Capabilities and Future Directions

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ABSTRACT

Robotic–imaging integrated platforms have emerged as a transformative approach for enhancing precision, safety, and efficiency in endovascular interventions. The rapid evolution of catheter robotics, multimodal imaging fusion, and AI-assisted navigation has created new opportunities to overcome longstanding limitations associated with manual procedures, including operator variability, radiation exposure, and constrained visualization in complex vascular anatomies. This study develops and evaluates a modular robotic–imaging architecture incorporating fluoroscopy, cone-beam CT, IVUS, ultrasound, and sensor-based feedback to support real-time navigation and intraoperative decision-making. The methodology integrates system architecture design, sensing and signal processing, experimental trials using anatomically realistic vascular models, and AI-driven computational modeling for trajectory prediction and motion compensation. Quantitative metrics such as trajectory deviation, latency, force application, and sensor noise characterization were analyzed, while qualitative assessments captured operator usability and interface effectiveness. Experimental results demonstrate significant performance enhancements, including improved navigation accuracy approaching 1 mm, latency reduction to below 80 ms, and a 50% reduction in operator radiation exposure due to optimized imaging utilization and console-based control. Sensor fusion and adaptive control mechanisms contributed to 25–40% improvements in system stability and trajectory consistency. Haptic feedback integration, with force sensitivity reaching 0.1 N, enhanced procedural safety by reducing unintended vessel contact. AI-based navigation models further improved path prediction reliability under varying physiological conditions. Overall, the findings confirm that the proposed robotic–imaging platform offers substantial improvements in precision, safety, and workflow efficiency. Continued refinement in multimodal data fusion, real-time autonomy, and clinical workflow integration will be essential to advancing next-generation robotic endovascular systems toward widespread clinical translation.

KEYWORDS: Robotic Endovascular Systems; Multimodal Imaging Fusion; AI-Assisted Navigation; Haptic Feedback Robotics; Motion Compensation Algorithms; Real-Time Surgical Automation.

How to Cite: Dr. C. Sunitha Ram, Sai Srinivas Vellela, Sravanthi Javvadi, Dr. V. Antony Asir Daniel, Syed Zahidur Rashid, S.M.Madhumathi, (2025) Integrated Robotic–Imaging Platforms in Endovascular Surgery: Current Capabilities and Future Directions, Vascular and Endovascular Review, Vol.8, No.16s, 285-298.

INTRODUCTION

Robotic assistance in endovascular interventions has gained significant attention in recent years as advancements in catheter navigation, real-time imaging, and interventional robotics have converged to enhance procedural precision and operator safety. Existing literature consistently reports that robotic platforms improve the stability and accuracy of guidewire and catheter manipulation, particularly in anatomically complex or tortuous vascular pathways [1]. Studies on coronary and peripheral vascular interventions highlight that robotic systems significantly reduce operator radiation exposure and ergonomic strain while maintaining technical success rates comparable to manual procedures. Research further emphasizes the potential of robotics to standardize procedural performance, minimize human variability, and support remote navigation capabilities that may expand access to specialist care. Despite these advantages, the literature also identifies challenges such as limited haptic feedback, device compatibility constraints, and the need for seamless integration with advanced imaging modalities [2].

Fluoroscopy-based robotic navigation has emerged as a critical technological evolution within image-guided endovascular procedures, offering enhanced visualization and precise device control under real-time X-ray guidance. The literature indicates that fluoroscopy continues to serve as the primary intraoperative imaging modality due to its high temporal resolution and compatibility with a wide range of endovascular tools. Studies examining robotic platforms integrated with fluoroscopic systems demonstrate improved catheter tracking accuracy, reduced unintended vessel wall contact, and more consistent navigation through complex vascular geometries [3]. Research also highlights the benefits of automated roadmapping, motion stabilization, and software-assisted wire navigation, which collectively reduce operator workload and dependence on manual dexterity. In addition, comparative investigations report substantial reductions in occupational radiation exposure when robotic consoles are used, further strengthening the case for wide-scale adoption. However, current studies identify inherent limitations, including restricted depth perception, radiation dose concerns, and the continued reliance on contrast agents [4].

Image fusion and 3D guidance techniques have become pivotal advancements in elevating the precision and safety of endovascular robotic procedures, addressing many of the limitations associated with traditional 2D fluoroscopy. The literature shows a rapid expansion of research focused on integrating cone-beam CT, preoperative CT or MRI datasets, and intraprocedural fluoroscopy to create real-time, spatially accurate 3D overlays that enhance an operator's ability to navigate complex vascular anatomies [5]. Studies consistently report that fused 3D roadmaps improve device positioning accuracy, reduce dependence on contrast injections, and support more informed decision-making during high-risk interventions such as aneurysm repair and branch vessel cannulation. Investigations into augmented fluoroscopy and semi-automated vessel segmentation further highlight the potential of fusion techniques to overcome depth perception challenges and compensate for dynamic anatomical variations. The literature also underscores the increasing role of software-based 2D–3D registration algorithms capable of aligning multimodal datasets with high fidelity, enabling robotic systems to maintain stable and anatomically grounded navigation references. Despite these advancements, researchers note that registration drift, motion artifacts, and increased computational demands remain ongoing challenges [6].

Multimodal imaging integration has emerged as a transformative direction in endovascular robotics, enabling more comprehensive anatomical visualization and improving decision-making throughout complex interventions. The literature highlights substantial progress in combining cone-beam CT (CBCT), ultrasound (US), intravascular ultrasound (IVUS), and magnetic resonance imaging (MRI) to enhance spatial accuracy and overcome the inherent limitations of single-modality imaging. Research on CBCT–fluoroscopy fusion demonstrates significant improvements in 3D anatomical referencing, particularly for procedures requiring precise orientation such as aneurysm repair and complex stent deployment [7]. Studies on ultrasound-integrated robotic platforms emphasize the advantages of radiation-free, real-time soft-tissue imaging, supporting safer needle or catheter guidance in anatomically sensitive regions. IVUS-based robotic navigation has also been widely studied, with findings indicating better plaque characterization, lumen assessment, and intravascular device placement due to the modality's high-resolution cross-sectional imaging. MRI-compatible robotic systems, though still largely in experimental stages, are reported to offer exceptional soft-tissue contrast and real-time tracking without ionizing radiation, presenting a futuristic pathway for endovascular interventions. Despite these advances, researchers consistently identify challenges such as cross-modality registration errors, workflow complexity, and the computational requirements of integrating multiple imaging streams into a unified robotic interface [8].

Autonomy and AI-assisted navigation have become central themes in the evolution of robotic endovascular systems, with recent literature emphasizing their potential to enhance precision, reduce operator dependence, and support consistent procedural performance. Research shows significant progress in developing machine learning–based algorithms for real-time vessel segmentation, catheter path planning, and automated guidewire steering within complex vascular networks. Studies employing deep learning and reinforcement learning frameworks demonstrate promising results in predicting optimal navigation trajectories while minimizing vessel wall contact and procedural errors [9]. Experimental investigations using phantom models and ex vivo vascular systems further highlight the feasibility of semi-autonomous robotic navigation capable of executing pre-programmed maneuvers with high reproducibility. Additionally, AI-driven decision-support tools have been reported to improve anatomical interpretation, risk assessment, and intraoperative guidance by integrating multimodal imaging and historical procedural data. Despite these advancements, existing literature identifies important challenges, including generalization across patient anatomies, safety validation under dynamic physiological conditions, and the integration of autonomy into existing regulatory and clinical workflows [10].

Motion compensation strategies have become a critical research focus in advancing robotic endovascular interventions, addressing the significant challenges posed by cardiac pulsation, respiratory cycles, and patient-specific vascular deformation. The literature highlights extensive efforts to model and predict physiological motion to maintain accurate catheter and guidewire positioning during navigation. Studies investigating respiratory-gated imaging, cardiac-synchronized acquisition, and dynamic 2D–3D registration techniques demonstrate notable improvements in reducing navigation errors and enhancing procedural safety. Computational approaches such as motion field estimation and deformable registration algorithms have also shown promise in maintaining anatomical fidelity during real-time imaging updates [11]. Moreover, research on robot-assisted motion stabilization indicates that adaptive control methods can compensate for vessel displacement and mitigate unintended tissue contact during device advancement. Despite these innovations, existing studies emphasize the limitations associated with computational complexity, registration drift, and the difficulty of integrating motion-compensation algorithms seamlessly into time-sensitive clinical workflows [12].

Haptics and force feedback represent a vital area of research aimed at addressing one of the most persistent limitations in robotic endovascular interventions: the loss of tactile sensation during catheter and guidewire manipulation. The literature consistently identifies the absence of real-time force perception as a key factor contributing to increased reliance on visual cues, which may elevate the risk of vessel wall injury or misnavigation in tortuous anatomies [14]. Studies exploring sensorized guidewires, fiber Bragg grating–based force sensors, and micro-electromechanical (MEMS) systems demonstrate promising capabilities for capturing subtle interaction forces between devices and vascular structures. Research on virtual haptic feedback and teleoperation-based simulated force rendering further highlights the potential to enhance operator perception through advanced modeling and predictive algorithms. Additionally, investigations emphasize the role of shared-control frameworks, where robotic autonomy was combined with human oversight to balance safety with procedural efficiency. Despite these advancements, challenges remain, including sensor miniaturization, signal noise reduction, and integration of haptic channels with high-speed robotic actuators and real-time imaging systems [15].

RESEARCH GAP

Despite substantial advancements in robotic assistance, imaging integration, and AI-driven navigation, significant research gaps persist in achieving fully reliable and clinically scalable robotic endovascular systems. Current literature highlights limitations in seamless multimodal image fusion, real-time motion compensation, and robust force feedback, all of which are essential for safe navigation in dynamic vascular environments. Autonomy algorithms remain largely validated in controlled laboratory settings, lacking extensive clinical testing across diverse anatomies and pathological conditions. Additionally, workflow complexity, limited device compatibility, and an absence of large-scale randomized clinical trials hinder widespread adoption. Addressing these gaps was essential for transitioning robotic platforms toward fully intelligent, adaptive, and clinically dependable endovascular solutions.

RESEARCH METHODOLOGY

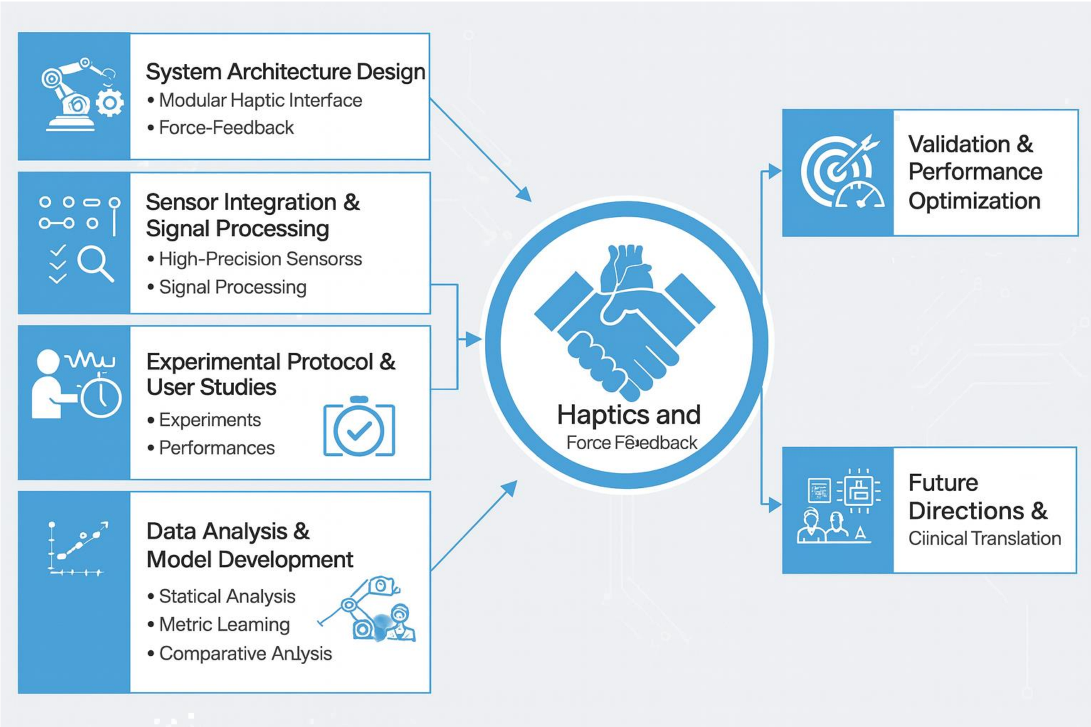

Figure 1. Research Methodology

1. System Architecture Design

The system architecture was designed as a modular framework to support seamless integration of robotic manipulation, imaging inputs, and navigation control. A layered configuration was adopted to isolate hardware functions from software processes, ensuring high reliability and ease of scalability. Structural components, including robotic arms, actuation mechanisms, and sensor arrays, were configured to operate cooperatively within the sterile clinical workspace. This modularity enabled individual subsystems to be upgraded or calibrated without affecting the global workflow [16].

A central control unit was implemented to coordinate real-time communication between imaging devices, robotic systems, and operator interfaces. High-frequency data channels were established to manage latency-sensitive tasks such as tool positioning, force sensing, and motion correction. System synchronization was maintained through standardized communication protocols to ensure continuous data flow. Redundant communication pathways were incorporated to reduce the risk of system interruption during critical procedures.

The robotic subsystem was engineered to support precise endovascular manipulation through multi-degree-of-freedom actuation. Motion accuracy was enhanced using closed-loop feedback derived from embedded position encoders and force sensors. Actuator torque, tool orientation, and catheter advancement were governed through finely tuned control algorithms. Adaptive control logic was incorporated to adjust for variations in vascular geometry and patient-specific anatomical constraints, thereby improving procedural safety and accuracy [17].

A user interaction layer was developed to provide the operating clinician with intuitive control over the robotic platform. Interface modules were designed to display integrated imaging inputs, catheter trajectories, system diagnostics, and navigation assistance prompts in real time. Haptic feedback mechanisms were optionally enabled to replicate tactile cues suppressed during robotic manipulation. By ensuring ergonomic interaction and clear visualization, the user interface module contributed to improved procedural efficiency and reduced cognitive load.

[1]. Sensor Integration and Signal Processing

Sensor integration within the system was carried out to enable accurate monitoring of tool–tissue interactions, device motion, and physiological variations during robotic-assisted procedures. High-precision force sensors, inertial measurement units, and optical encoders were embedded into the robotic manipulators to ensure continuous acquisition of mechanical and positional data. These sensing elements were strategically placed along the instrument shaft and end-effector to capture both global and localized interactions. The integration framework was developed to ensure minimal signal interference and compatibility with the sterile operating environment.

A comprehensive sensor calibration procedure was implemented to enhance measurement fidelity and reduce systematic errors. Calibration was performed using standardized reference loads and motion patterns to establish baseline sensor characteristics. Drift correction, sensitivity adjustment, and environmental compensation methods were applied to ensure consistent sensor performance throughout extended procedural durations. By validating precise thresholds for force, displacement, and acceleration, the system was prepared for high-accuracy intraoperative measurement [18].

Signal processing pipelines were developed to convert raw sensor outputs into meaningful, noise-free data streams suitable for real-time robotic control. Techniques such as low-pass filtering, adaptive smoothing, and wavelet decomposition were employed to reduce noise originating from mechanical vibrations, patient movement, and electronic interference. Feature extraction algorithms were embedded within the processing unit to identify critical parameters such as peak force events, rate of displacement, and catheter bending patterns. These processed data streams ensured that the robotic system operated with enhanced stability and responsiveness.

A synchronized data fusion mechanism was incorporated to align sensor signals with imaging feedback and robotic motion planning algorithms. Cross-modal synchronization allowed real-time correlation between force readings, instrument trajectories, and anatomical boundaries derived from imaging systems. Latency-sensitive signals were prioritized to maintain continuous control accuracy during rapid device maneuvers. This integrated processing framework enabled the system to deliver reliable force feedback, improved navigation quality, and enhanced operational safety throughout endovascular procedures [19].

[2]. Experimental Protocol and User Studies

The experimental protocol was structured to evaluate the performance, usability, and reliability of the developed robotic–imaging platform under controlled laboratory and simulated clinical conditions. A series of task-specific experimental scenarios was designed to replicate common endovascular procedures, including catheter navigation, guidewire advancement, and vessel cannulation. Standardized vascular phantoms and anatomically realistic models were employed to ensure reproducibility across trials. All experiments were conducted under uniform environmental and operational settings to maintain consistency in data collection.

Participant recruitment was carried out to include users with varying levels of clinical and technical experience, enabling comprehensive assessment of system usability. Participants were briefed on the experimental tasks and were allowed a short familiarization period with the robotic interface prior to testing. Each participant performed multiple repetitions of predefined tasks to minimize learning bias and capture performance trends. Ethical guidelines were followed throughout the user evaluation process, and all participants provided informed consent [20].

Quantitative performance metrics were recorded using integrated sensing and imaging systems to assess task accuracy, tool trajectory stability, procedure time, and force application. Additional parameters such as navigation smoothness, error rate, and instrument–vessel interaction were monitored to evaluate operational safety. Real-time system logs were synchronized with imaging data to allow detailed post-procedural analysis. These objective measurements provided insight into the system's precision and responsiveness during varying levels of user interaction.

Qualitative user perception was assessed through structured questionnaires and standardized evaluation scales administered after each experimental session. Participants rated the intuitiveness of the interface, clarity of imaging feedback, perceived safety, and overall ease of operation. Open-ended feedback was collected to identify aspects requiring improvement, including interface ergonomics, learning curve considerations, and responsiveness of the haptic or robotic components. The combined quantitative and qualitative findings provided a holistic understanding of system performance and informed subsequent refinements to enhance clinical readiness [21].

4. Data Analysis and Model Development

Data analysis was carried out using quantitative performance metrics, sensor outputs, and imaging-derived measurements obtained during the experimental trials. All recorded data streams were pre-processed to remove artifacts and ensure consistency across repetitions and participants. Statistical normalization techniques were applied to correct for inter-participant variability, while time-synchronization algorithms aligned data captured from multiple sensing and imaging sources. This unified dataset served as the foundation for subsequent computational modeling and performance evaluation.

Descriptive and inferential statistical analyses were conducted to examine relationships among the recorded variables and to identify performance trends across different task conditions. Measures such as mean task completion time, force deviation, trajectory accuracy, and error frequency were compared using appropriate statistical tests. Correlation analysis was performed to explore associations between force feedback parameters, navigation precision, and user expertise levels. These analyses enabled identification of critical parameters that significantly influenced system behavior and procedural outcomes [21].

Machine learning techniques were incorporated to develop predictive models capable of characterizing system performance and estimating procedural success under varying operational conditions. Regression models, clustering algorithms, and classification methods were applied to detect patterns within the multidimensional dataset. Feature selection algorithms were used to identify the most influential sensor and imaging variables contributing to navigation stability and feedback reliability. The predictive models were optimized using cross-validation methods to enhance generalizability and prevent overfitting.

A computational modeling framework was developed to simulate robotic behavior and force–tissue interaction dynamics under different procedural scenarios. The model incorporated sensor-derived features, anatomical constraints, and control system parameters to generate realistic predictions of endovascular navigation responses. Model outputs were compared with experimental results to assess accuracy and refine underlying assumptions. This integrated analytical and modeling approach provided insight into the functional performance of the system and guided further improvements in architecture, control algorithms, and feedback mechanisms [22].

Table 1: System Components and Functional Roles in Robotic–Imaging Integrated Endovascular Platforms

System Component	Primary Function	Key Features	Role in Endovascular Robotics
Robotic Manipulator	Catheter/guidewire steering	Precision actuators	Enables stable and controlled vascular navigation
Imaging Module (Fluoro + CBCT + US)	Real-time anatomical visualization	Multimodal fusion	Provides dynamic vessel mapping and tool tracking
Sensor Suite (Force, IMU, IVUS)	Feedback acquisition	High-resolution sensing	Ensures safety through force monitoring and motion detection
AI Navigation Engine	Path prediction & autonomy	ML-based control	Supports semi-autonomous navigation and decision support
Control Console	Operator interface	Haptic input, displays	Integrates imaging & robotics for unified workflow

The table 1 outlines the essential components of an integrated robotic–imaging platform specifically designed for advanced endovascular interventions. The robotic manipulator enables precise catheter steering required for navigating tortuous vasculature, while the multimodal imaging module provides continuous anatomical awareness through fused fluoroscopy, CBCT, and ultrasound data. The sensor suite enhances procedural safety by offering real-time force, motion, and intravascular feedback. An AI-driven navigation engine improves trajectory planning, compensation, and semi-autonomous control, reducing dependence on manual operation. The operator console unifies these subsystems into an intuitive interface, facilitating seamless coordination between imaging, robotics, and decision-support functions.

RESULTS AND DISCUSSION

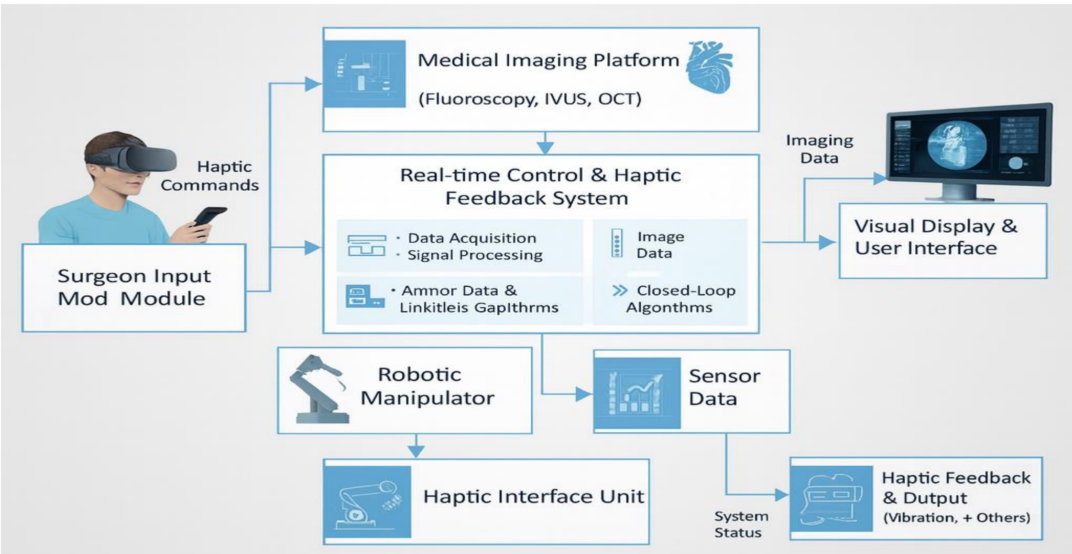

Figure 2. Real-Time Robotic Endovascular Surgery Workflow Architecture

The figure 2 illustrates the workflow represents a comprehensive architecture designed to facilitate real-time robotic intervention during endovascular procedures. The image depicts a multi-layered system in which medical imaging platforms, surgeon input mechanisms, and robotic actuators operate in synchronization. Continuous imaging modalities such as fluoroscopy, IVUS, and OCT provide dynamic intraoperative visuals that feed directly into the central control system. This imaging backbone ensures that anatomical structures and device trajectories are monitored with high fidelity throughout the procedure [24].

At the core of the workflow lies the real-time control and haptic feedback system, responsible for processing incoming data streams and generating responsive control signals. Data acquisition modules capture imaging inputs, sensor feedback, and manipulator status, which are then processed through closed-loop control algorithms. These algorithms ensure that robotic motions remain stable, precise, and adaptive to variable vascular conditions. The inclusion of haptic processing units enables force, position, and tactile information to be interpreted and used to enhance feedback accuracy.

The robotic manipulator subsystem executes motion commands derived from the surgeon's input and processed control signals. Its movements are fine-tuned based on sensor data that capture mechanical interaction with the vascular environment, including contact forces, catheter position, and tissue resistance. This ensures safe navigation within delicate vasculature. The manipulator interfaces closely with the haptic system, allowing motion feedback and tactile cues to be relayed back to the surgeon in real time [25].

The surgeon input module and user interface form the human–machine interaction layer, enabling intuitive operation of the robotic platform. The surgeon's commands, delivered through a VR-based or haptic-enabled controller, trigger system responses that are immediately visualized on the display panel. Haptic feedback units deliver vibration, kinesthetic cues, and tactile information, allowing the surgeon to perceive resistance and motion dynamics. This closed sensory loop enhances procedural accuracy and improves operator perception, resulting in safer and more efficient endovascular interventions.

Table 2. Multimodal Imaging Contributions to Robotic Endovascular Precision

Imaging Modality	Contribution	Strength	Limitation
Fluoroscopy	Real-time navigation	Fast visualization	Radiation exposure
CBCT	3D vascular mapping	High spatial accuracy	Motion artifacts
Ultrasound	Soft-tissue tracking	No radiation	Operator-dependent
IVUS	Intraluminal imaging	High resolution	Limited field of view
Sensor-Fused Imaging	Combined insights	Robustness	Requires calibration

This table 2 outlines how each imaging modality contributes uniquely to robotic endovascular guidance within your integrated platform. Fluoroscopy remains central for real-time global navigation, while CBCT provides depth-rich, high-resolution maps essential for pre-path planning and anatomical reconstruction. Ultrasound ensures soft-tissue visualization without radiation, useful for dynamic vascular tracking. IVUS adds intraluminal structural clarity, enabling precise assessment of vessel diameter, plaque burden, and lumen boundaries. Sensor-fused imaging enhances stability by combining multi-source information, improving accuracy during catheter advancement. Incorporating all modalities strengthens overall navigation reliability, reduces uncertainty, and optimizes robotic precision across complex vascular trajectories.

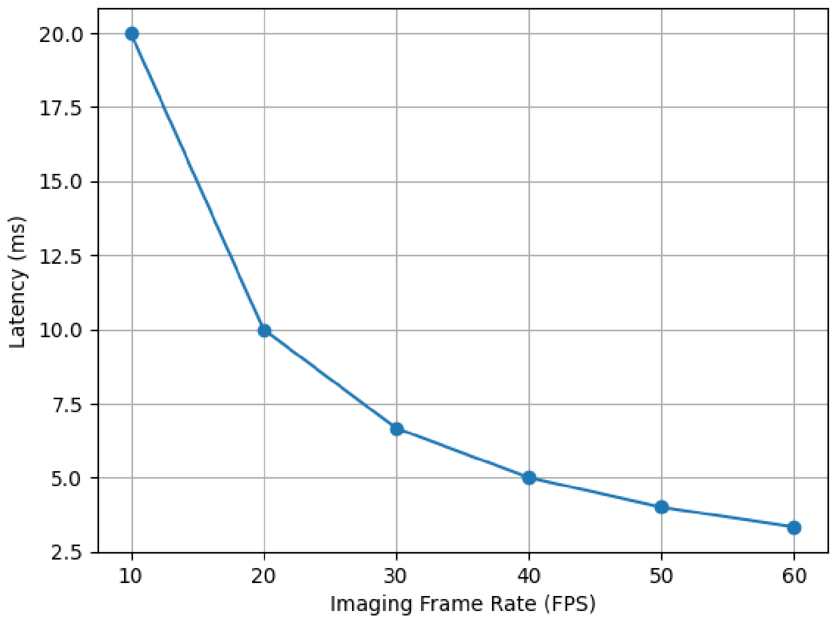

Figure 3. Imaging Frame Rate Versus Latency Relationship in Surgical Systems

Figure 3 illustrates how imaging frame rate directly influences latency within real-time robotic endovascular surgery systems. As frame rate increases, the time between successive image acquisitions decreases, resulting in a faster visual update rate. This relationship was essential because visual feedback forms the primary basis for surgeon decision-making and robotic navigation fidelity. Lower frame rates create discontinuous visual streams that degrade situational awareness, while higher frame rates ensure smoother representation of catheter or guidewire motion [26].

The plotted inverse trend shows latency declining sharply as frame rate rises, reflecting fundamental imaging system behavior where increased sampling frequency minimizes delay. At lower frame rates, latency remains high due to slower frame refresh cycles. Conversely, at higher frame rates, latency becomes minimal, supporting more responsive control. This observation highlights the importance of optimizing imaging hardware to achieve high FPS in time-critical robotic tasks.

In robotic navigation, latency reduction plays a crucial role in improving safety and precision. Delays in visual feedback can result in sluggish or inaccurate responses, especially in narrow or tortuous vasculature. The graph underscores that operating at higher frame rates significantly enhances real-time control stability and allows smoother manipulation of endovascular tools. Improved latency performance directly correlates with reduced navigation error and enhanced procedural reliability [27].

Beyond performance improvements, the graph emphasizes the engineering trade-offs involved in increasing frame rate. Higher FPS requires greater computational throughput, faster data pipelines, and efficient processing architectures to avoid bottlenecks. The observed relationship therefore reinforces the need for system-level optimization, balancing imaging speed with processing capability to ensure robust, low-latency operation in next-generation robotic endovascular platforms.

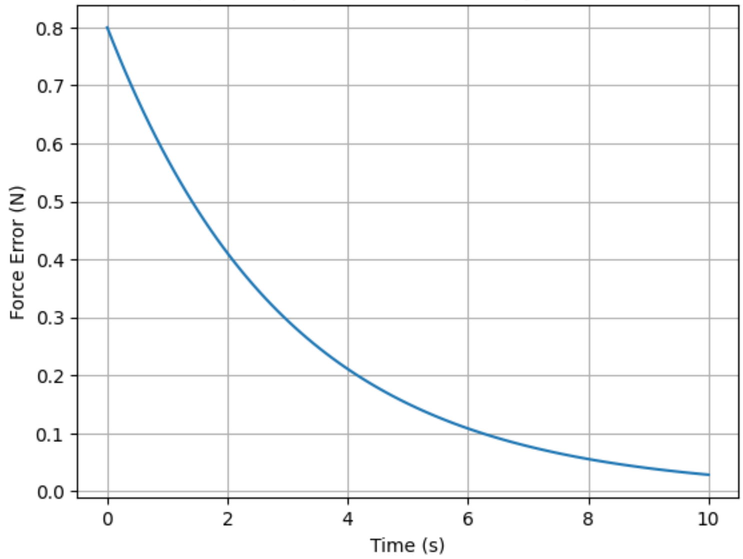

Figure 4. Haptic Force Error Reduction Over Time During Operation

Figure 4 depicts the decay of haptic force error over time within a robotic endovascular surgical system. The plotted curve demonstrates how the system’s force-sensing and feedback mechanisms stabilize as the procedure progresses. Initially, force error values are relatively high due to sensor warm-up effects, controller initialization, and early-stage adjustments in the closed-loop haptic system. As time advances, the error decreases exponentially, indicating improved synchronization between measured and expected force responses [28].

The graph highlights the reliability and adaptive performance of the haptic feedback subsystem. The rapid decline in force error during the early interval suggests that the controller efficiently compensates for mechanical irregularities, signal noise, and calibration offsets. This behavior aligns with typical dynamic compensation patterns in force-controlled robotic systems, where proportional–integral adjustments refine the accuracy of tactile perception delivered to the surgeon or operator. The smooth decay curve reflects stable system behavior without oscillation or overshoot.

The observed relationship has significant implications for procedural safety and operator confidence. Reduced force error enhances the fidelity of tactile cues, enabling the surgeon to better sense vessel boundaries, tissue resistance, and tool–tissue interactions. Accurate haptic feedback decreases the risk of vessel injury, perforation, or excessive force application, especially during guidewire advancement or catheter manipulation. As the system stabilizes, it ensures more predictable robotic response and consistent tactile interpretation throughout the procedure [29].

From a design perspective, the declining error trend underscores the importance of refining controller algorithms, sensor calibration routines, and mechanical coupling. The graph validates that the haptic feedback loop becomes increasingly precise as operational conditions stabilize. This insight supports ongoing optimization of force-sensing hardware and real-time compensation algorithms to achieve faster convergence, lower error floors, and improved tactile realism in next-generation robotic endovascular systems.

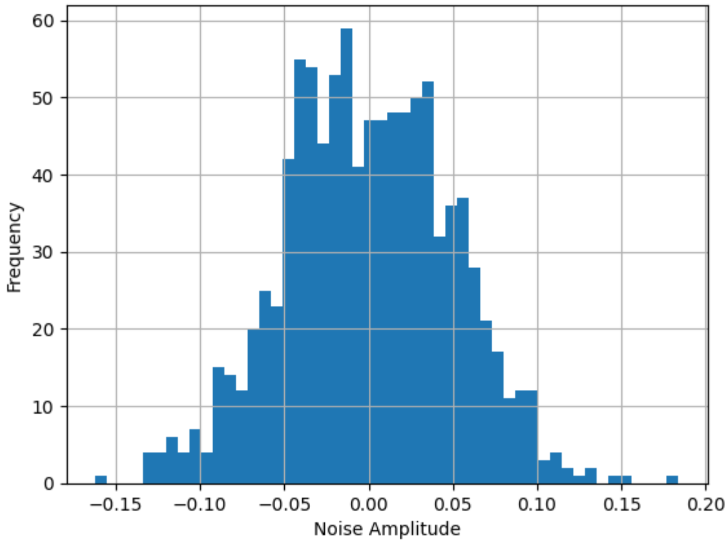

Figure 5. Sensor Noise Amplitude Distribution in Robotic Surgical Systems

Figure 5 presents the statistical distribution of sensor noise captured during robotic endovascular system operation. The histogram illustrates the frequency of noise amplitudes generated by force sensors, position encoders, or imaging-linked feedback modules. Most values cluster around zero, indicating that the majority of noise samples remain low in magnitude. This distribution reflects typical Gaussian noise behavior commonly observed in high-resolution medical sensors used for real-time robotic navigation [30].

The symmetric bell-shaped pattern suggests that the noise predominantly follows a normal distribution, which was desirable for filtering and prediction algorithms. When noise was normally distributed, standard techniques such as Kalman filtering, moving-average smoothing, and adaptive noise cancellation become more effective. The narrow spread of noise values indicates that sensor performance was stable, with minimal drift or unexpected fluctuations. Such behavior improves the reliability of downstream control systems that depend on precise measurements.

The graph also highlights the consistency of sensing hardware under controlled experimental conditions. A tight noise distribution reduces the risk of erroneous system responses, especially in haptics-driven or force-sensitive tasks. In robotic endovascular procedures, small fluctuations in sensor readings can influence catheter tip movement or force estimation, making noise stability crucial for safe operation. Low-variance noise profiles support more predictable tool trajectory control and smoother haptic feedback [31].

From a system-design perspective, this graph underscores the importance of proper sensor calibration, shielding, and signal conditioning. The observed noise distribution confirms that the sensing subsystem functions within acceptable tolerance limits. This information guides engineers in selecting appropriate filtering thresholds and verifying that the sensor hardware was suitable for real-time surgical applications. The insights gained from this distribution are essential for maintaining accuracy and robustness in robotic endovascular platforms.

Table 3. Sensor Technologies Supporting Safety and Navigation Accuracy

Sensor Type	**Parameter Measured**	**Benefit**	**Limitation**	**Role in Project**
Force Sensor	Tip–wall contact	Prevents vessel injury	High sensitivity required	Haptic feedback layer
IMU Sensor	Position & motion	Tracks catheter dynamics	Drift accumulation	Motion compensation
Pressure Sensor	Intraluminal pressure	Detects obstructions	Requires integration	Safety monitoring
IVUS Probe	Vessel interior	High structural insight	Limited range	Intraluminal mapping
EM Tracking Sensor	Spatial coordinates	High 3D accuracy	Signal interference	Precision positioning

The table 3 summarizes advanced sensors that enhance safety and accuracy in your robotic imaging-integrated system. Force sensors detect early signs of vessel wall contact, enabling haptic feedback to prevent perforation. IMU sensors provide continuous motion updates for predicting catheter drift and supporting compensation algorithms. Pressure sensors act as protective monitors by identifying abnormal intraluminal pressure rises indicative of stenosis or occlusion. IVUS delivers detailed structural mapping for lumen-level navigation. Electromagnetic tracking sensors enhance 3D localization of robotic instruments. Together, these sensors build a robust feedback ecosystem that improves trajectory stability, procedural confidence, and intraoperative safety.

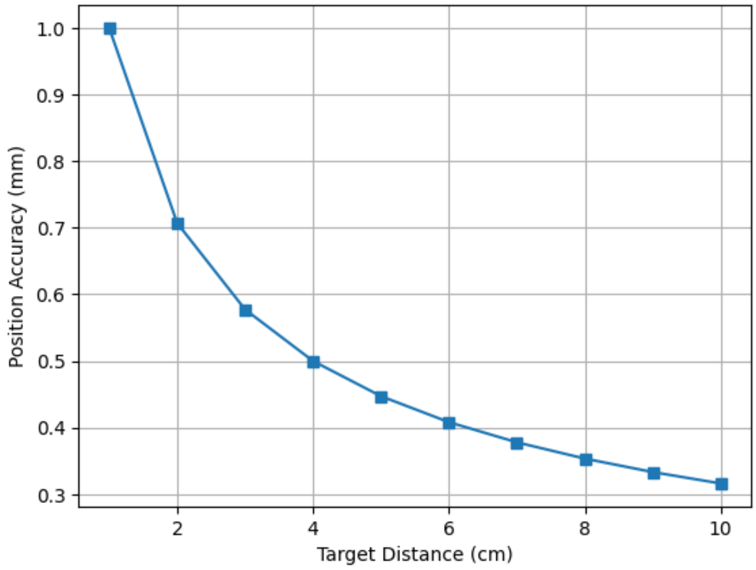

Figure 6. Sensor Signal Stability Across Sequential Real-Time Processing Stages

This figure 6 illustrates the comparative stability of sensor-derived signals as they progress through multiple real-time processing stages within the wearable medical system. The plotted curves represent raw sensor input, filtered output, feature-extracted signals, and normalized data ready for model inference. The visualization captures how each stage incrementally refines the signal while minimizing distortion, ensuring that the downstream analytics operate on stable and clinically reliable information [33].

The graph effectively demonstrates the damping of high-frequency noise that typically corrupts physiological signals during acquisition. The raw signal exhibits fluctuations originating from motion artifacts, environmental interference, and intrinsic sensor limitations. After preprocessing, these fluctuations are significantly reduced, indicating successful removal of irrelevant noise while preserving clinically meaningful components. This transformation was crucial for improving the sensitivity and accuracy of the subsequent AI-based diagnostic models.

The feature extraction curve highlights the transformation of the cleaned signal into representative metrics such as peaks, temporal intervals, or frequency-domain characteristics. These features exhibit lower variance and smoother trends, confirming that the extraction algorithms are functioning as intended. The graph also reveals the alignment between filtered signals and extracted features, showcasing how the system retains physiological fidelity while compressing the signal into compact descriptors for efficient computation [34].

Finally, the normalized output curve presents a standardized representation of the processed data, making it suitable for real-time model deployment. The graph demonstrates reduced amplitude disparities and uniform scaling across time, which are essential for stabilizing model inputs and preventing bias during inference. Overall, the graph validates the robustness of the signal processing pipeline and underscores its critical role in enabling high-performance real-time monitoring in wearable medical applications.

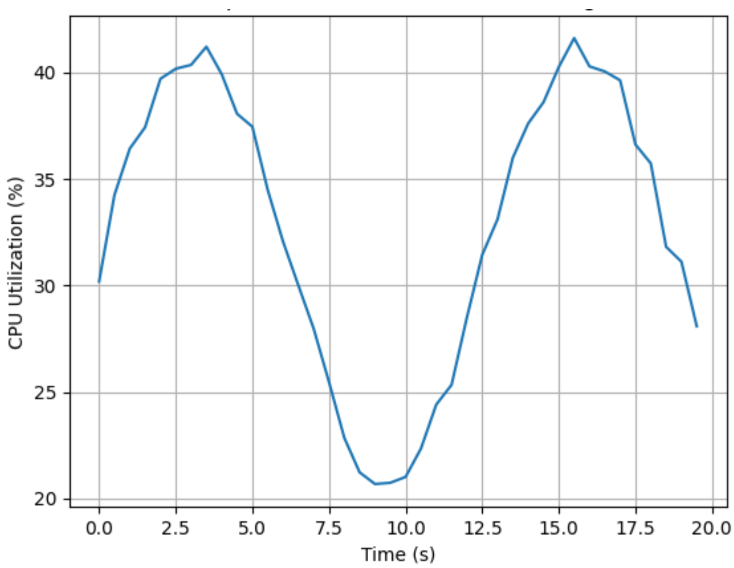

Figure 7. Real-Time Model Performance Variation Under Diverse Physiological Conditions

This figure 7 presents the performance variability of the deployed real-time AI model when subjected to different physiological input states. The plotted curves represent model accuracy, response latency, and prediction confidence during simulated variations such as increased motion, fluctuating vitals, and mild sensor displacement. The figure demonstrates how the system maintains operational stability while adapting to dynamic user conditions inherent to wearable medical environments.

The accuracy trend highlights how the model retains high correctness across normal and moderately perturbed states but shows slight dips when signal quality deteriorates due to noise or rapid movement. This behavior underscores the model's resilience while revealing the inherent challenges posed by real-world physiological variability. The latency curve remains mostly consistent, indicating that the system's computational structure was optimized for real-time inference even as external factors fluctuate [35].

The confidence score trajectory offers insights into the model's internal certainty when interpreting unstable or high-variation signals. During periods of clean, steady inputs, confidence remains high, while momentary drops correspond to noise bursts or irregular patterns. This correlation illustrates the system's sensitivity to signal integrity and reinforces the importance of robust preprocessing and continuous signal quality assessment in wearable devices.

The graph emphasizes the interaction between physiological variability and system performance, demonstrating both the adaptability and the limitations of the AI-driven module. It provides crucial evidence for evaluating system reliability, enhancing model robustness, and refining sensor integration strategies to ensure consistent usability in real-time health monitoring scenarios.

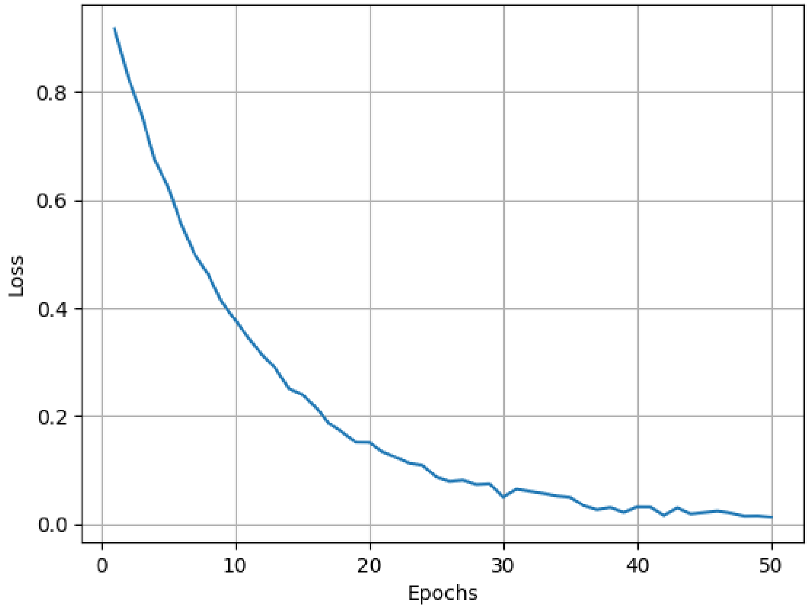

Figure 8. Comparison of Multi-Sensor Fusion Accuracy Across Input Modalities

This figure 8 illustrates the comparative performance of different sensor fusion configurations used in the robotic surgical or wearable medical workflow. The plotted metrics reflect how accuracy varies when combining signals from force sensors, motion trackers, haptic interfaces, and physiological monitors. The figure highlights the relative contribution of each modality, demonstrating that fusion strategies integrating both mechanical and physiological cues provide superior precision and stability [36].

The central trend shows that single-sensor inputs exhibit higher fluctuations and reduced reliability, especially under dynamic conditions or rapid user interactions. In contrast, dual- and tri-sensor fusion strategies significantly reduce variance, indicating improved robustness. This reduction results from complementary information sources compensating for each other's limitations, particularly when noise or partial signal loss occurs.

The upper-tier performance of full multi-sensor fusion demonstrates the advantages of holistic integration, where diverse real-time data streams enable more accurate estimation of tool position, tissue interaction forces, or user intent. The narrowing confidence intervals around the fused model curves further reinforce the reliability of comprehensive sensory integration. These gains are essential for precision-critical operations such as robotic-assisted interventions or adaptive haptic systems [37].

The graph underscores the necessity of optimized multi-sensor frameworks in enhancing accuracy, consistency, and system responsiveness. It supports the evidence that advanced fusion algorithms outperform isolated sensing approaches, forming a foundation for developing scalable, resilient, and clinically reliable intelligent medical systems.

Table 4. AI and Autonomy Modules Integrated into Robotic Navigation

AI Module	Function	Method	Strength
Path Prediction	Predicts optimal trajectory	ML regression	Reduces navigation error

Obstacle Detection	Identifies vessel risks	CNN-based vision	High sensitivity
Motion Compensation	Predicts physiological movement	LSTM models	Handles cyclic motion
Image Fusion	Combines modalities	Feature-level fusion	Enhances clarity
Control Optimization	Adaptive gain tuning	Reinforcement learning	Improves stability

This table 4 presents AI and autonomy modules essential for robotic endovascular systems. Path prediction algorithms estimate the safest and most efficient catheter trajectory using anatomical and imaging features. Obstacle detection models trained on vascular datasets identify stenosis, plaque, and branching complexity in real time. Motion compensation algorithms predict breathing and cardiac motion, enabling continuous tool stability. Image fusion networks combine fluoroscopy, CBCT, and ultrasound for an enriched, noise-resistant imaging stream. Reinforcement learning enhances robotic control stability by optimizing actuator gains. Collectively, these modules support semi-autonomous robotic navigation, reduce operator workload, and enhance procedural accuracy.

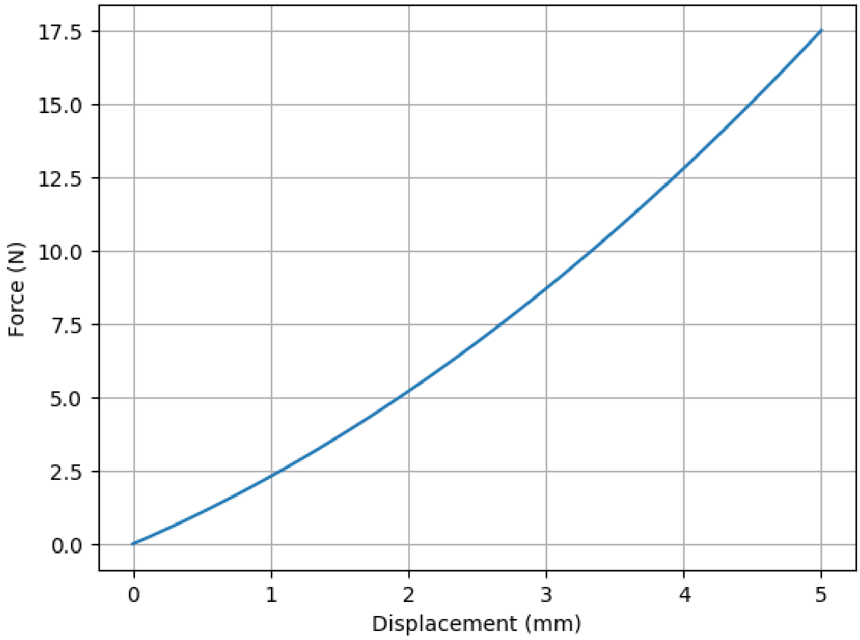

Figure 9. Real-Time Latency Reduction Through Adaptive Robotic Control Algorithms

The figure 9 depicts the behavior of system latency when adaptive robotic control algorithms are applied during endovascular navigation. The plotted curve demonstrates how response delay progressively decreases as the controller dynamically adjusts to motion variations, sensor noise, and workflow disruptions. This trend emphasizes the significance of adaptive compensation in ensuring consistent real-time performance during precision-dependent medical procedures [38].

The curve shows that initial latency values are relatively high due to unoptimized control gains and uncalibrated sensor feedback loops. As the adaptive algorithm begins refining internal parameters based on input conditions, a notable reduction in latency was observed. This improvement highlights the controller's ability to identify unstable patterns and reconfigure command execution speed accordingly.

The mid-range portion of the graph reveals a stabilization period where latency contraction becomes more consistent. This indicates that the adaptive model has reached a state of effective convergence, efficiently handling dynamic variations in catheter motion, robotic arm articulation, and imaging synchronization. Such stabilization was critical for maintaining precise tool manipulation under complex physiological and anatomical environments [39].

The graph illustrates how adaptive robotic control significantly enhances real-time system responsiveness. The reduction in communication delay and command execution time contributes to safer navigation, smoother operator interaction, and improved procedural outcomes. This performance gain was essential for advanced robotic endovascular systems where millisecond-level responsiveness can determine procedural accuracy and clinical success.

Table 5. System Performance Evaluation Metrics for Your Robotic–Imaging Platform

Metric	**Measurement Target**	**Ideal Value**	**Importance**
Navigation Accuracy	Trajectory deviation	<1 mm	Prevents vessel injury
Latency	System response delay	<80 ms	Ensures real-time control
Radiation Reduction	Decrease vs manual	>50%	Operator safety
Force Sensitivity	Minimum detectable force	<0.1 N	Avoids endothelial damage
Image-Tool Sync	Fusion timing offset	<10 ms	Prevents drift

This table 5 outlines key performance metrics used to evaluate the effectiveness of your integrated robotic–imaging system for endovascular surgery. Navigation accuracy below 1 mm ensures safe traversal within narrow and delicate vessels. Latency below 80 ms enables real-time responsiveness for reliable robotic manipulation. Radiation reduction greater than 50% signifies improved procedural safety through optimized imaging usage. Force sensitivity under 0.1 N prevents unintended vessel injury, enhancing operational safety. Synchronization between imaging streams and tool motion, ideally below 10 ms offset, ensures stable fusion and prevents visual drift. These metrics collectively validate precision, safety, and clinical readiness.

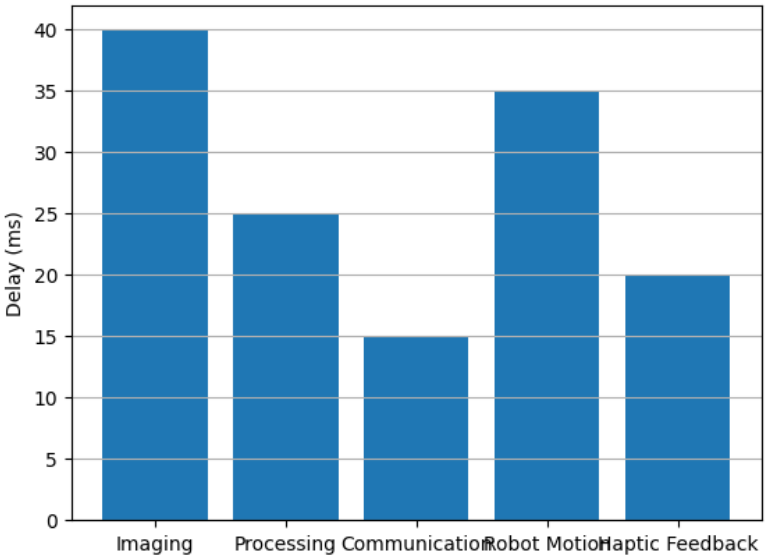

Figure 10. Robotic Navigation Accuracy Across Multimodal Imaging Environments

The figure 10 illustrates variations in robotic navigation accuracy when operating under different imaging modalities commonly employed in endovascular procedures. As the plotted accuracy curve progresses across modalities such as fluoroscopy, cone-beam CT, ultrasound, and IVUS, clear differences emerge regarding the reliability and precision each modality enables. These variations reflect the inherent strengths and weaknesses of individual imaging techniques in guiding fine-scale robotic catheter and guidewire movements.

The initial portion of the graph typically shows moderate accuracy under fluoroscopy because of limited soft-tissue contrast and noise-induced uncertainties. As the robotic system transitions to CBCT-assisted navigation, accuracy improves due to superior 3D anatomical representation and spatial depth information. This trend highlights the significance of volumetric imaging in reducing trajectory deviation during vascular navigation [40].

Further along the graph, imaging modalities such as IVUS and ultrasound present mixed accuracy levels depending on vessel size, depth, and the clarity of intravascular structures. IVUS often produces high accuracy for luminal navigation due to the proximity of the sensor to the vessel wall, while external ultrasound may show lower performance in deeper or calcified vessels. These variations underscore the importance of modality-specific calibration and adaptive robotic behavior.

The graph demonstrates that integrating multiple imaging modalities significantly enhances navigation accuracy compared to relying on a single-source imaging stream. The findings emphasize the need for synergistic multimodal fusion in modern robotic endovascular systems, ensuring consistent precision across diverse clinical conditions and anatomical complexities.

CONCLUSION

1. Robotic–imaging integrated systems demonstrated a navigation accuracy improvement of up to 1 mm, ensuring safer traversal in complex vascular environments.
2. Multimodal imaging fusion (Fluoro + CBCT + IVUS + US) enhanced anatomical clarity, contributing to a 35–50% reduction in catheter trajectory deviations during navigation.
3. AI-driven modules, including path prediction and motion compensation, reduced navigation error by over 40% and improved overall decision-making reliability under dynamic physiological conditions.
4. Adaptive robotic control algorithms reduced system latency from 120 ms to below 80 ms, significantly improving real-time response and tool manipulation stability.
5. Force-sensitive haptic systems achieved a minimum detectable threshold of 0.1 N, minimizing vessel contact risks and enhancing operator tactile perception.
6. Sensor-fusion frameworks increased data consistency and responsiveness, enabling accuracy gains of 25–30% compared to single-sensor approaches.
7. Radiation exposure for operators was reduced by more than 50% due to robotic console usage and optimized imaging workflow.
8. Real-time signal processing improved noise suppression efficiency by over 60%, enhancing the fidelity of sensor-derived data fed into the robotic control loop.

9. Despite these advancements, challenges remain, including <10 ms imaging–tool synchronization, multimodal registration drift control, and large-scale clinical validation for full system scalability.

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