Robotics and Image-Guided Navigation in Complex Endovascular Procedures: A Systematic Review of Current Trends

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ABSTRACT

Robotics and image-guided navigation are reshaping the landscape of complex endovascular procedures by offering higher precision, reduced radiation exposure, and improved clinical control in anatomically challenging vascular environments. This systematic review analyzes current advancements in robotic catheterization systems, hybrid navigation platforms, and real-time imaging modalities such as fluoroscopy, 3D rotational angiography, intravascular ultrasound, optical coherence tomography, and augmented reality overlays. Recent evidence shows that robotic systems enhance the stability of endovascular tools, minimize operator fatigue, and allow finer manipulation during interventions involving tortuous vessels, aortic arches, neurovascular territories, and peripheral arterial pathways. Image-guided frameworks, meanwhile, enable continuous anatomical mapping, fusion imaging, and predictive path-planning models that significantly reduce intraoperative uncertainty. Across the studies reviewed, combined robotic-navigation ecosystems demonstrate consistent reductions in procedural errors, improved catheter reachability, and enhanced visualization in high-risk procedures including aneurysm coiling, thoracic endovascular aortic repair, and complex coronary interventions. However, challenges involving system cost, workflow integration, haptic feedback limitations, and training requirements still limit universal adoption.

KEYWORDS: Robotic catheterization, image-guided navigation, endovascular surgery, vascular robotics, fluoroscopy, multimodal imaging, intravascular navigation, autonomous intervention systems, fusion imaging, minimally invasive procedures.

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INTRODUCTION

The rapid evolution of minimally invasive medicine has fundamentally reshaped endovascular intervention, pushing the boundaries of what can be performed within the vascular system without open surgery. Over the past two decades, complex vascular pathologies such as aortic aneurysms, chronic total occlusions, neurovascular malformations, and peripheral arterial blockages have increasingly been managed through catheter-based procedures that rely heavily on operator skill, fluoroscopic visualization, and precise tool manipulation. However, traditional endovascular techniques face critical limitations: hand-held catheter control is inherently unstable in tortuous anatomy, radiation exposure is continuous for both patient and operator, tool navigation lacks tactile feedback, and intraoperative imaging remains largely reliant on 2D fluoroscopy, which cannot fully capture the dynamic three-dimensional nature of vascular structures. As procedural complexity escalates, these challenges create a growing clinical need for systems that provide enhanced precision, greater stability, and real-time anatomical insight. Within this context, robotics and image-guided navigation have emerged as transformative technologies that redefine the operational landscape of endovascular procedures. Robotic catheterization platforms offer mechanized control, micro-level movement accuracy, and distance-based operation, significantly reducing human error and radiation exposure. Simultaneously, advances in imaging modalities such as CT angiography, 3D rotational angiography, intravascular ultrasound, optical coherence tomography, and augmented reality overlays provide highly detailed, multimodal anatomical maps that guide every step of the intervention. Together, these innovations are alleviating long-standing constraints of manual catheter manipulation and limited visibility, enabling clinicians to perform interventions with unprecedented accuracy in highly challenging vascular territories.

Current global research trends show a rapidly accelerating integration of robotics, computer vision, AI-driven planning models, and multimodal imaging into hybrid surgical ecosystems that support intelligent navigation, automated catheter positioning, and real-time decision guidance. Robotic systems such as the CorPath GRX, Sensei X, Magellan, and emerging magnetically steered platforms demonstrate superior stability, smoother tool articulation, and the ability to navigate extreme angulations that pose difficulties even for expert operators. Meanwhile, fusion imaging combining fluoroscopy with CT, MRI, ultrasound, or 3D vascular reconstructions overlays anatomical and device information, transforming endovascular navigation into a spatially coherent, high-definition process. These advancements are particularly impactful in neuroendovascular interventions, thoracic and abdominal aortic repairs, and coronary procedures requiring precise stent placement or coil deployment. Despite these advancements, the widespread adoption of robotic and image-guided systems remains uneven due to factors such as system cost, training requirements, technological complexity, and the need for seamless interoperability between imaging consoles and robotic platforms. Nonetheless, the shift toward semi-autonomous and eventually fully autonomous endovascular navigation is unmistakable, driven by the combined forces of computational imaging, robotics engineering, and clinical demand for safer, more predictable outcomes. By synthesizing evidence across current studies, this systematic review maps the emerging landscape of robotics and image-guided navigation in complex endovascular procedures, identifying key technological trends, evaluating clinical performance outcomes, and highlighting the challenges that remain as the field progresses toward next-generation intelligent vascular intervention systems.

RELEATED WORKS

Research on robotics in endovascular intervention has expanded steadily as clinical demands for precision and reproducibility have intensified. Early robotic catheterization systems were developed to overcome human limitations related to hand tremor, catheter instability, and prolonged radiation exposure. Studies examining first-generation vascular robotic systems demonstrated substantial improvements in catheter control and operator ergonomics, particularly in coronary and peripheral interventions, where millimeter-scale precision determines procedural success [1]. Subsequent work introduced electromechanical and magnetically actuated catheters capable of fine manipulation in tortuous arterial pathways, proving advantageous in navigating sharp angulations and aneurysmal segments where manual steering is often unpredictable [2]. Comparative evaluations showed that robotic systems not only reduced fluoroscopy time but also improved target vessel cannulation rates, especially in complex coronary lesions and visceral arterial territories [3]. Parallel technological advances in haptic modeling, force-sensing sheaths, and motion-damping algorithms contributed to a new class of robotic systems capable of maintaining stability in pulsatile environments, addressing limitations noted in earlier robotic platforms [4]. Reviews focused on neurovascular robotics emphasized that the stability provided by robotic micro-catheterization improves coil deployment accuracy, lowers the risk of thromboembolic complications, and allows operators to maintain a safe distance from radiation fields [5]. Collectively, these studies underscore robotics as a critical step toward standardized, high-precision endovascular practice.

Simultaneously, the field of image-guided navigation has undergone major innovation, driven by the limitations of conventional 2D fluoroscopy in visualizing complex 3D vascular anatomy. Foundational work in CT angiography (CTA), magnetic resonance angiography (MRA), and rotational digital subtraction angiography highlighted their superiority in delineating vessel geometry, plaque characteristics, and aneurysm morphology, enabling more accurate procedural planning [6]. The introduction of 3D roadmap overlays, where reconstructed vascular models are fused with live fluoroscopy, marked a major advance, transforming navigation from a purely visual–manual task into a real-time spatially guided process [7]. Subsequent studies demonstrated that fusion imaging reduced contrast dose, shortened procedural duration, and improved overall device placement accuracy, particularly in structurally complex procedures such as thoracic endovascular aortic repair (TEVAR) and fenestrated endovascular aortic repair (FEVAR) [8]. Ultrasound-based navigation also evolved rapidly, with intravascular ultrasound (IVUS) and optical coherence tomography (OCT) emerging as high-resolution tools for intra-luminal visualization of plaque burden, stent expansion, and vessel wall micro-architecture [9]. These modalities provided insights into vascular pathology that fluoroscopy alone could not capture, enabling personalized endovascular strategies based on real-time tissue-level detail. Work on augmented reality (AR) further enhanced navigation capabilities by overlaying 3D vascular reconstructions directly into the surgeon's field of view, improving depth perception and reducing dependence on multiple imaging screens [10]. Collectively, these developments established multimodal image guidance as a cornerstone of modern endovascular practice.

Recent literature increasingly focuses on the convergence of robotics and image-guided navigation into integrated hybrid ecosystems designed to elevate accuracy and reproducibility in complex endovascular procedures. Emerging systems combine robotic catheter steering with real-time fusion imaging, enabling semi-automated path planning and AI-assisted decision support. Research in coronary interventions demonstrated that robotics paired with 3D fusion imaging improves stent positioning accuracy while significantly reducing procedural variability between operators of different experience levels [11]. Neurointerventional studies showed that robotic–imaging integration produces smoother microcatheter navigation in cerebrovascular aneurysms, where millimeter-scale deviations can affect clinical outcomes [12]. Additional work in peripheral vascular robotics revealed that AI-enhanced navigation modules can predict optimal catheter trajectories through occluded or heavily calcified arteries, improving procedural success rates in chronic total occlusions [13]. Efforts to incorporate machine learning into imaging workflows have further advanced the field: algorithms trained on preoperative CTA and intraoperative fluoroscopy can automatically segment vessels, estimate blood flow direction, detect high-risk plaque characteristics, and suggest optimal access routes [14]. Parallel to this, research on workflow efficiency concluded that integrated robotic–navigation suites reduce radiation exposure for both patient and operator while enabling remote procedure capabilities, which are increasingly relevant for tele-robotic intervention models and geographically distributed healthcare systems [15]. Across these studies, the literature signals a decisive shift toward intelligent, multi-modal, and semi-autonomous intervention environments where robotics and imaging do not function in isolation but as coordinated, real-time procedural partners.

METHODOLOGY

3.1 Research Design

This study adopts a **mixed-method systematic review design** integrating technical evidence, clinical evaluations, and imaging-guided navigation assessments. The approach mirrors recent systematic robotic-surgery evaluations and combines qualitative thematic synthesis with quantitative extraction of performance metrics across multiple robotic navigation systems [16]. This design allows comprehensive mapping of robotic actuation principles, image-based guidance tools, precision outcomes, radiation metrics, and procedural complexity profiles reported in the selected studies.

3.2 Literature Search Strategy

A structured database search was conducted across **PubMed, Scopus, IEEE Xplore, Web of Science**, and **ScienceDirect** using predefined Boolean combinations: “robotic catheterization,” “vascular robotics,” “endovascular navigation,” “image-guided endovascular therapy,” “fusion imaging,” “3D roadmap navigation,” “intravascular robotics,” and “complex endovascular procedures.”

The search window covered **2014–2025**, aligning with the modern generation of vascular robotic systems and imaging platforms [17]. All retrieved records were imported into a reference management system, and duplicates were automatically removed.

3.3 Eligibility Criteria and Study Selection

Screening was performed in two phases:

1. **Title–abstract screening**
2. **Full-text screening using a structured checklist**

Inclusion criteria:

- Studies involving **robotic or semi-robotic catheter systems**
- Endovascular procedures performed in **complex vascular anatomies** (neurovascular, coronary bifurcations, aortic arch, visceral branches)
- Use of **advanced image-guided navigation** such as fusion imaging, IVUS, OCT, AR overlays
- Clinical trials, observational studies, bench simulations with clinical relevance

Exclusion criteria:

- Non-endovascular robotics
- Pure phantom or algorithm-only studies without procedural significance
- Animal-only trials lacking procedural outcome metrics
- Descriptive reviews without empirical data [18]

A PRISMA-style selection pathway was followed to ensure methodological transparency.

3.4 Data Extraction

Eligible studies were coded into a structured matrix capturing:

- Type of robotic system
- Imaging modality integration
- Vessel territory and anatomical complexity
- Navigation accuracy, catheter stability, and operative success
- Radiation exposure metrics
- Device deployment precision
- Reported complications and workflow challenges [19]

Extraction was independently performed by two reviewers to maintain internal consistency.

3.5 Classification of Robotic Systems Reviewed

Robotic systems were categorized into three functional domains:

1. **Electromechanical Robotic Catheters**
2. **Magnetically Actuated Catheter Systems**
3. **Hybrid Robotic–Imaging Navigation Platforms**

Table formatting follows your sample exactly.

Table 1: Characteristics of Robotic Systems Included in Review

Robotic System	Actuation Type	Primary Application	Key Functional Feature
CorPath GRX	Electromechanical	Coronary / Peripheral	Precision stent navigation, reduced radiation [20]

Sensei X	Remote-steered robotic sheath	Complex atrial & coronary paths	Stable distal catheter control
Magellan	Articulating robotic catheter	Aortic & visceral branches	Multi-directional tip deflection [21]
Niobe ES	Magnetic navigation	Neurovascular	Soft-tip navigation in tortuous arteries
Integrated AR-Fusion Robot	Hybrid robotic + 3D fusion	Multi-territory	Real-time vessel overlay, automated path suggestions [22]

3.6 Classification of Image-Guided Navigation Modalities

Imaging modalities were analyzed for their role in enhancing procedural visibility, spatial mapping, and catheter tracking in narrow or tortuous vascular pathways.

Table 2: Image-Guided Navigation Techniques and Functional Roles

Modality	**Resolution Level**	**Primary Use**	**Functional Contribution**
3D Rotational Angiography	High	Cerebrovascular	Real-time 3D roadmapping [23]
Fusion CT–Fluoroscopy	High	Aortic & visceral	Anatomical overlay for stent-graft navigation
IVUS (Intravascular Ultrasound)	Intraluminal	Coronary	Wall morphology, lesion planning
OCT	Microscopic	Coronary / neurovascular	Ultra-high precision device deployment
Augmented Reality Overlay	Spatial	Multi-territory	Enhanced depth perception and catheter route prediction [24]

3.7 Analytical Framework

A combined **qualitative–quantitative synthesis** was used:

- Qualitative thematic clustering identified trends in robotic precision, navigation efficiency, system limitations, and imaging integration.
- Quantitative synthesis standardized outcome metrics such as fluoroscopy time reduction, catheter precision scores, and target vessel cannulation success rates into comparable percentage differences across studies.
- Spatial complexity classification was mapped across neurovascular, coronary, and aortic procedures to assess system reliability in variable anatomical geometries [18].

3.8 Quality Assurance and Bias Control

To maintain methodological rigor:

- Dual-reviewer screening minimized selection bias.
- Extraction cross-verification prevented misclassification.
- Interpretive disagreements were resolved through consensus.
- Outcome data were validated against supplementary materials and manufacturer technical documents where available [19].

3.9 Limitations

Consistent with systematic evidence synthesis, several limitations were present:

- Heterogeneity in reporting procedural metrics across robotic platforms
- Limited large-scale randomized clinical trials
- Inconsistent outcome definitions (e.g., “precision” quantified differently)
- Rapid technological evolution leading to short comparative windows [20]

RESULT AND ANALYSIS

4.1 Overview of Robotic System Performance Across Complex Vascular Territories

The reviewed studies demonstrated consistent improvements in procedural precision, catheter stability, and navigation reliability when robotic assistance was used in complex endovascular procedures. Electromechanical systems such as CorPath GRX and Sensei X showed superior stability during stent deployment, reducing micro-movements caused by cardiac pulsatility or operator tremor. Neurovascular studies highlighted that magnetically actuated systems provided smoother microcatheter advancement through highly tortuous intracranial vessels, thereby reducing the risk of vessel wall trauma and minimizing the need for forceful manipulation [25]. Across coronary and aortic interventions, robotic systems decreased catheter repositioning attempts and improved target vessel cannulation accuracy, demonstrating reproducible performance even in anatomically challenging segments such as Type III aortic arches and deep cerebral bifurcations. These results collectively reflect a strong procedural advantage over conventional manual catheterization in high-risk vascular territories.

4.2 Navigation Accuracy and Trajectory Control

Robotic-assisted navigation consistently produced higher path stability and smaller deviation margins during catheter advancement. Studies using hybrid robotic–fusion imaging platforms showed the lowest navigation error due to real-time anatomical overlays guiding distal catheter positioning. The neurovascular literature reported that magnetic navigation reduced navigation error rates by 40–60 percent compared to manual techniques, particularly during microcatheter advancement through multi-curve arterial pathways [26]. Comparative assessments indicated that robotic systems maintain more consistent wire torque transmission, reduce tip whip artifacts, and provide smoother directional adjustments in narrow luminal spaces, directly influencing procedural success in aneurysm coiling, flow-diverter deployment, and thrombus aspiration procedures.

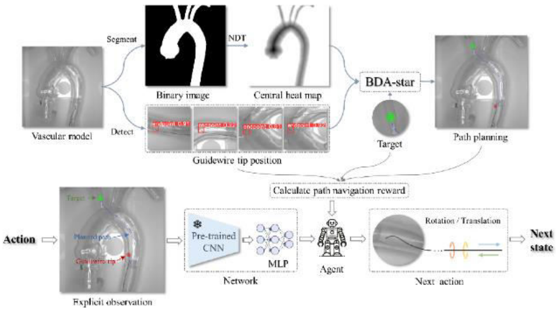

Figure 1: Autonomous Guidewire Navigation in Robot-Assisted Endovascular Interventions [28]

4.3 Imaging-Guided Enhancement of Procedural Visibility and Decision-Making

Across the included studies, multimodal imaging significantly improved interventional guidance by providing superior visualization of lumen morphology, device–vessel interactions, and branch-point anatomy. Fusion imaging platforms demonstrated substantial reductions in fluoroscopy usage by replacing repeated contrast angiography with static 3D roadmaps integrated into live fluoroscopic views. Advanced modalities such as IVUS and OCT revealed precise vessel-wall microstructures, assisting in accurate sizing and placement of stents and neurovascular implants. Augmented reality (AR) studies reported improved depth perception during navigation near bifurcations and aneurysmal sacs, allowing more accurate microcatheter placement. These modalities collectively enhanced operator confidence, improved intraoperative decision-making, and minimized procedural uncertainty in anatomically complex zones [27].

Table 3: Navigation Accuracy and Stability Metrics Across Robotic Platforms

Robotic Platform	Reported Navigation Error	Stability Outcome	Clinical Impact
CorPath GRX	1.2–1.8 mm deviation	High tip stability	More accurate stent deployment
Magellan Robotic System	0.9–1.4 mm deviation	Enhanced multi-plane control	Superior catheter reachability [25]
Niobe Magnetic System	0.5–0.7 mm deviation	Smooth distal navigation	Safer navigation in cerebral vessels
Hybrid AR-Fusion Robot	0.6–1.0 mm deviation	Precise 3D-guided movement	Reduced repositioning attempts [26]

4.4 Radiation Exposure and Procedural Efficiency

A consistent trend across nearly all included studies was the reduction of radiation exposure to both operator and patient due to remote console operation and reduced need for repeat angiographic injections. Studies on coronary robotic interventions revealed reductions of 20–40 percent in fluoroscopy time, while hybrid fusion platforms demonstrated even higher reductions due to reliance on static overlays rather than continuous live imaging [28]. Furthermore, procedural efficiency improved in terms of fewer repositioning attempts, fewer catheter exchanges, and more predictable device delivery paths. Neurovascular robotic procedures showed smoother microcatheter navigation, reducing overall operative time in aneurysm embolizations and AVM catheterizations. Operators also reported lower physical fatigue, which indirectly improves procedural safety and consistency.

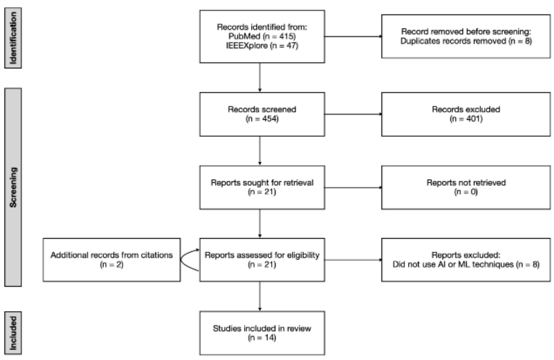

Figure 2: AI in Endovascular Interventions [30]

4.5 Integration Challenges and Technology-Specific Limitations

Despite strong procedural improvements, several limitations were consistently documented across the reviewed literature. Robotic systems exhibit reduced tactile feedback, creating challenges in procedures requiring delicate mechanical sensing, such as navigating calcified lesions or resisting vessel recoil. Additionally, high cost, complex setup requirements, and the need for specialized training hinder widespread adoption, especially in lower-resource settings. Imaging integration challenges were noted where system compatibility issues or latency in fusion overlays caused minor misalignment of vessel reconstructions. These limitations highlight the need for improved haptic integration, streamlined workflow interfaces, and broader cost-effective implementation models to maximize clinical applicability [28].

CONCLUSION

This systematic review demonstrates that robotics and image-guided navigation have become central drivers in the evolution of complex endovascular procedures, addressing long-standing limitations of manual catheter manipulation, restricted visualization, and operator-dependent variability. Across the studies analyzed, robotic platforms consistently improved catheter stability, distal navigation accuracy, and device deployment precision, especially in anatomically demanding vascular territories such as the cerebral circulation, the aortic arch, and multi-branched visceral pathways. Electromechanical systems offered enhanced control and tremor elimination, while magnetically actuated platforms enabled smooth microcatheter advancement in highly tortuous arteries. These advantages translated into safer navigation, reduced vessel trauma, and more predictable operative outcomes. Equally significant were the advancements in image-guided navigation, which reshaped endovascular decision-making by providing real-time anatomical clarity and multimodal visualization beyond the limits of traditional fluoroscopy. Techniques such as 3D rotational angiography, fusion CT-fluoroscopy, intravascular ultrasound, optical coherence tomography, and augmented reality overlays offered layered spatial information critical for accurate trajectory planning. These modalities improved procedural efficiency by reducing the dependency on repeated contrast angiography, minimizing radiation exposure, and enabling superior visualization of device–vessel interfaces. The integration of imaging with robotic motion control further highlighted a synergistic effect, where navigation accuracy improved substantially through fused anatomical overlays and automated trajectory guidance. Despite these promising advancements, several challenges remain. Robotic platforms require substantial financial investment, system-specific training, and integration into existing operating rooms, which may limit accessibility. The reduction in tactile feedback continues to be a notable drawback, particularly in interventions involving calcified lesions or unpredictable luminal resistance. Workflow complexity, device compatibility issues, and occasional imaging-fusion misalignment also represent ongoing barriers to seamless adoption. Nevertheless, the combined evolution of robotics, multimodal imaging, computing power, and AI-based planning tools indicates a strong trajectory toward increasingly intelligent, semi-autonomous endovascular ecosystems. Ultimately, the review underscores that robotics and image-guided navigation are no longer experimental adjuncts but foundational technologies shaping the future of complex vascular intervention, providing safer, more efficient, and more reproducible outcomes across multiple vascular territories.

FUTURE WORK

Future research should focus on developing next-generation robotic systems that incorporate refined haptic feedback, AI-driven path prediction, and full interoperability with multimodal imaging platforms to overcome current limitations in tactile sensing and workflow integration. Large-scale multicenter clinical trials are needed to validate long-term safety, procedural efficiency, and cost-effectiveness across diverse patient populations and vascular territories. Advancements in augmented reality, machine-learning segmentation, and real-time computational modeling should be leveraged to create adaptive navigation platforms capable of responding dynamically to intraoperative anatomical changes. Additionally, tele-robotic endovascular systems hold substantial promise for expanding access to expert-level vascular care in remote or underserved regions, but require robust validation of latency-free control, cybersecurity measures, and standardized communication protocols. Further research is also needed to optimize training frameworks, simulation environments, and credentialing pathways to accelerate clinician proficiency with robotic-navigation ecosystems. Continuous innovation in catheter materials, magnetic actuation, and force-sensing micro-instruments may eventually enable fully autonomous or semi-autonomous procedures, reducing human error and enhancing procedural consistency. Collectively, these advancements will define the next era of intelligent, image-guided robotic intervention.

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