Advancing Embodied AI in Percutaneous Coronary Intervention Robots

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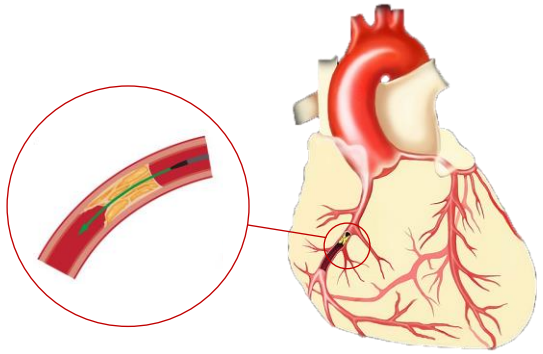
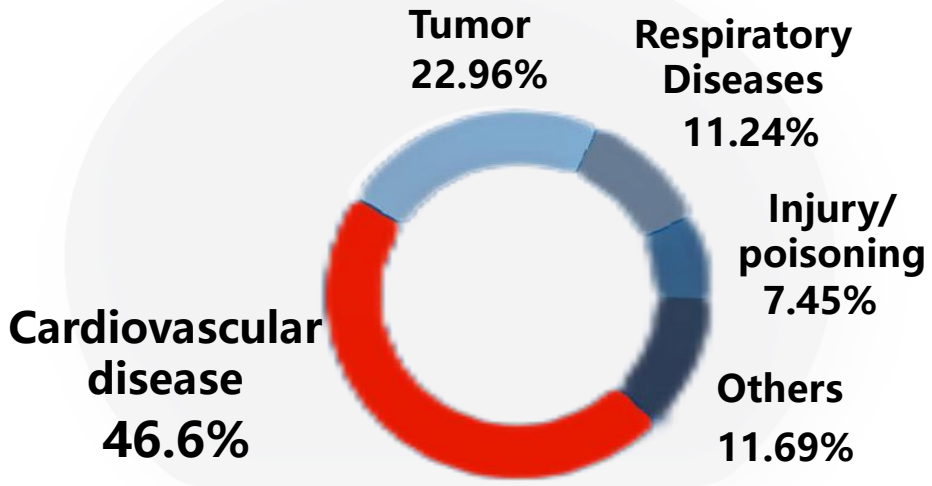
Background

Coronary Heart Disease: Diagnosis and Treatment in China

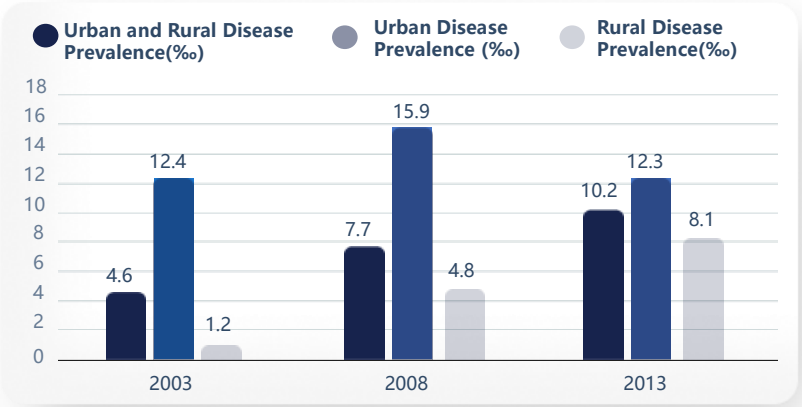


Disease Mortality Rates



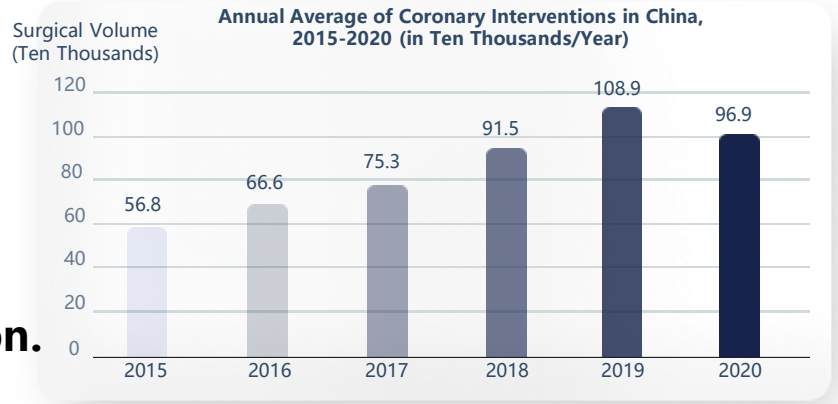
- Cardiovascular Patients in China: **330 Million**.
- Coronary Heart Disease Patients: **70 Million**.
- Common Age Group: **Individuals Over 60**.
- Frequent Conditions: Angina, Myocardial Infarction.

Increasingly Severe Health Issues



Trends in Coronary Heart Disease Prevalence

Growing Demand for PCI Procedures

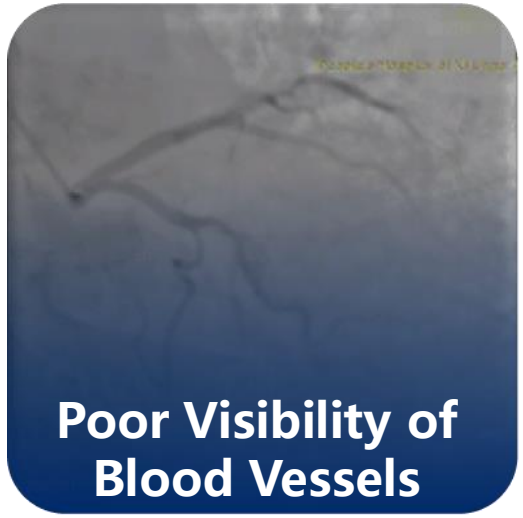


Trends in Volume of PCI Percedures

Background

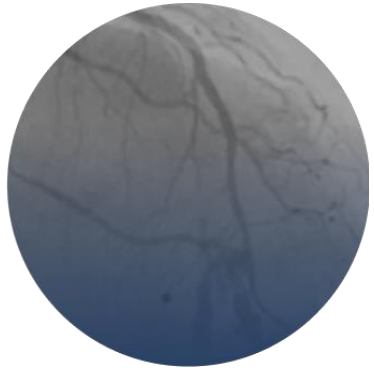
Clinical Pains in PCI Diagnosis and Treatment

Clinical Pains



Complications and Consequences

Coronary Artery Perforation



Guide Wire Dislodgement

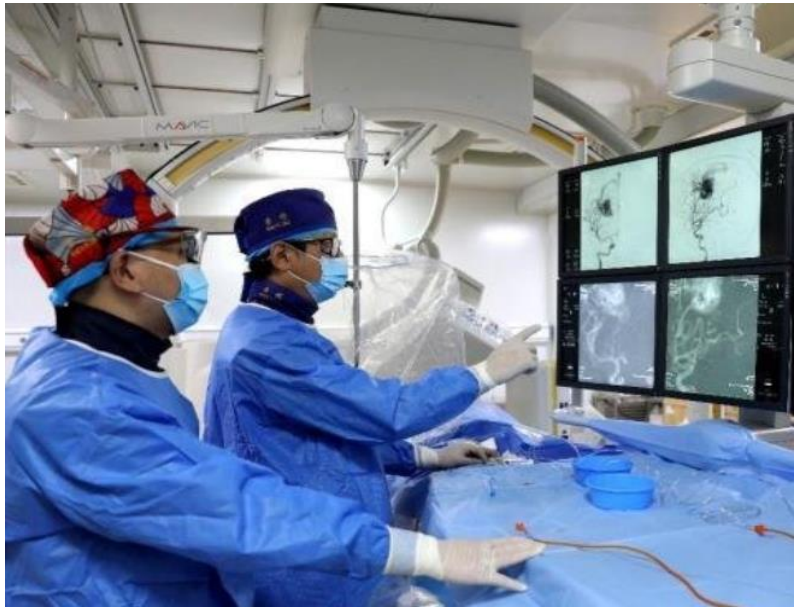
Further Leading to Serious Events such as Patient Mortality!

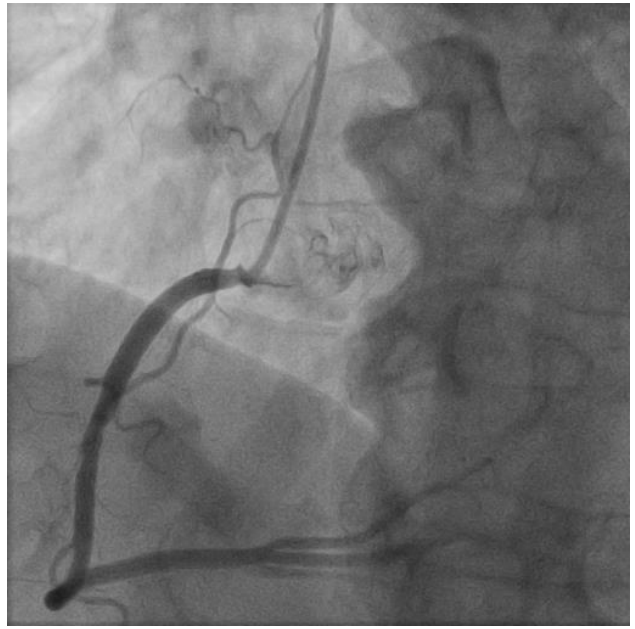
Precise Diagnosis and Intervention are Crucial to Avoiding Complications!

PCI Scene Perception and Decision-Making

Clinical Demands

- DSA images are considered the "gold standard" in PCI Procedure.
- Poor quality and have unclear vascular structures.
- Background noise and interference from neighboring structures.

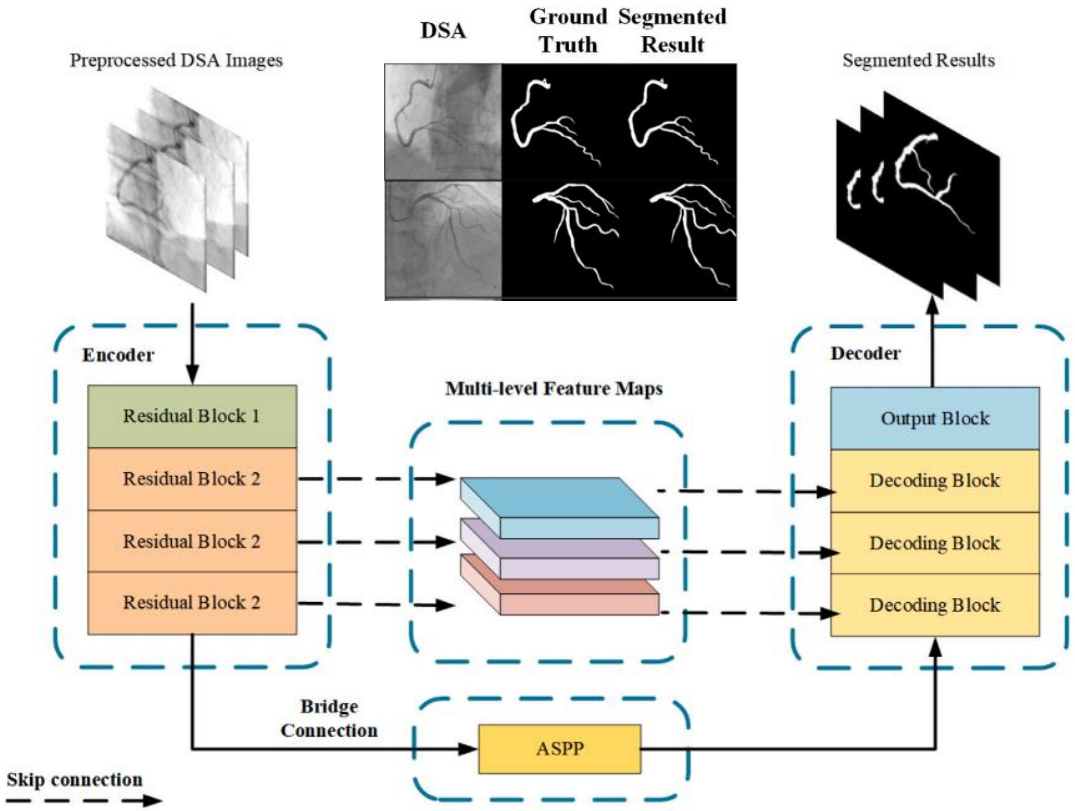


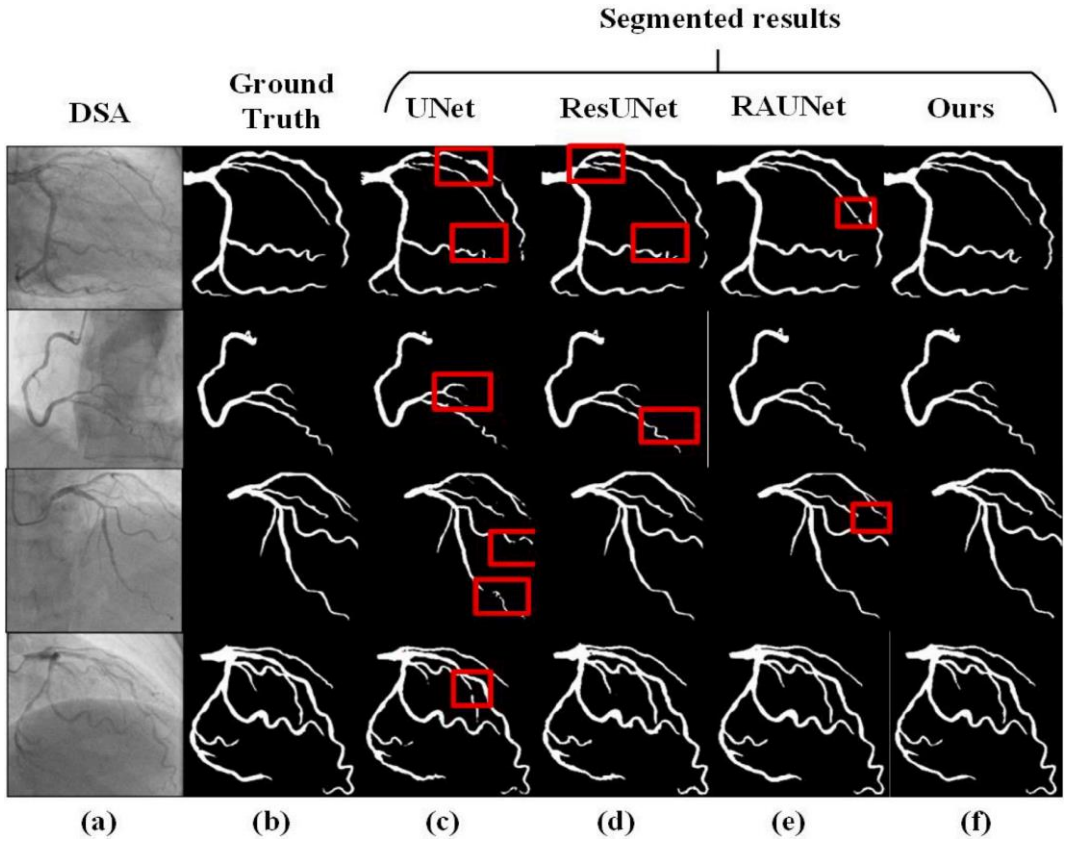


[1] Yao, T., Wang, C., Wang, X., Li, X., Jiang, Z., & Qi, P. (2023). Enhancing Percutaneous Coronary Intervention with heuristic path planning and deep-learning-based vascular segmentation. Computers in Biology and Medicine, 107540.

Semantic segmentation of Vessels

- **Method:** optimize the ResUNet++ with Coordinate Attention and Squeeze and Excitation network.
- **Validation:** real-world dataset.
- **Results:** our model presents best performance in segmenting tiny vessls of DSA images.





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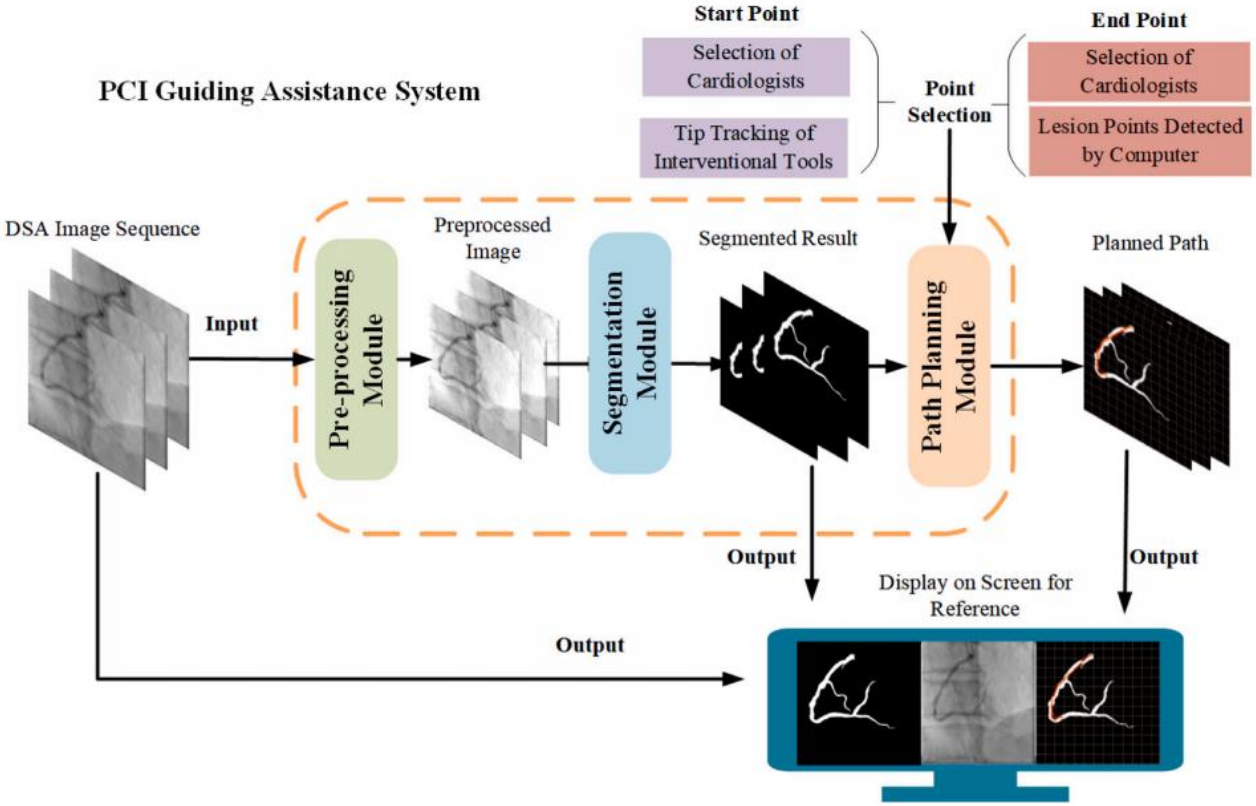
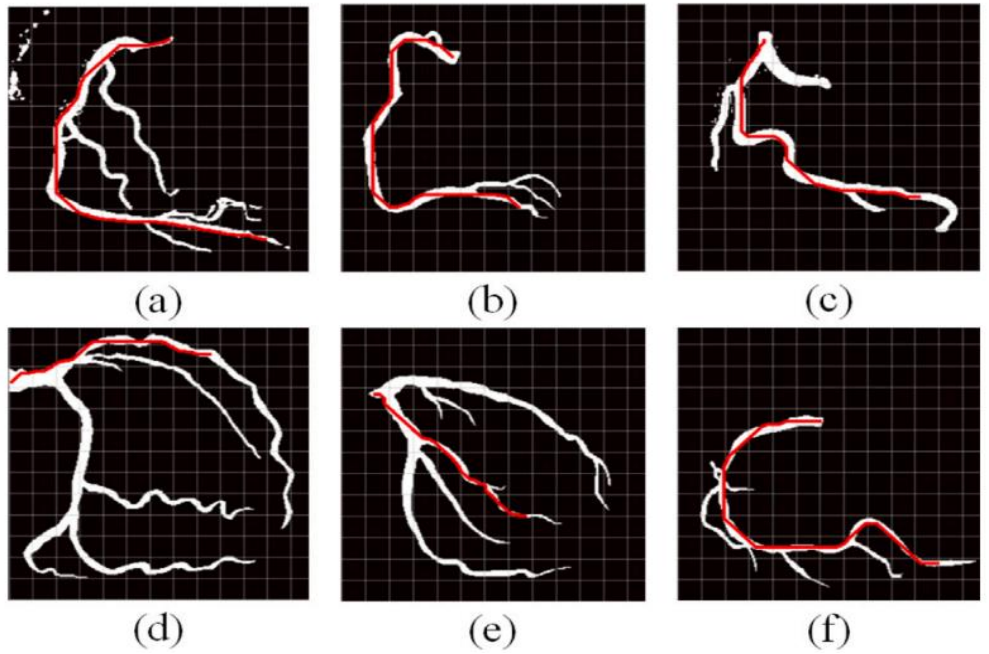
PCI Scene Perception and Decision-Making

DSA-image-based interventional path-planning

- Automated interventional path planning based on precise anatomical mapping.
- Safe and efficient interventional navigation through constrained optimization.
- Towards seamless human-robot collaboration in PCI procedures.





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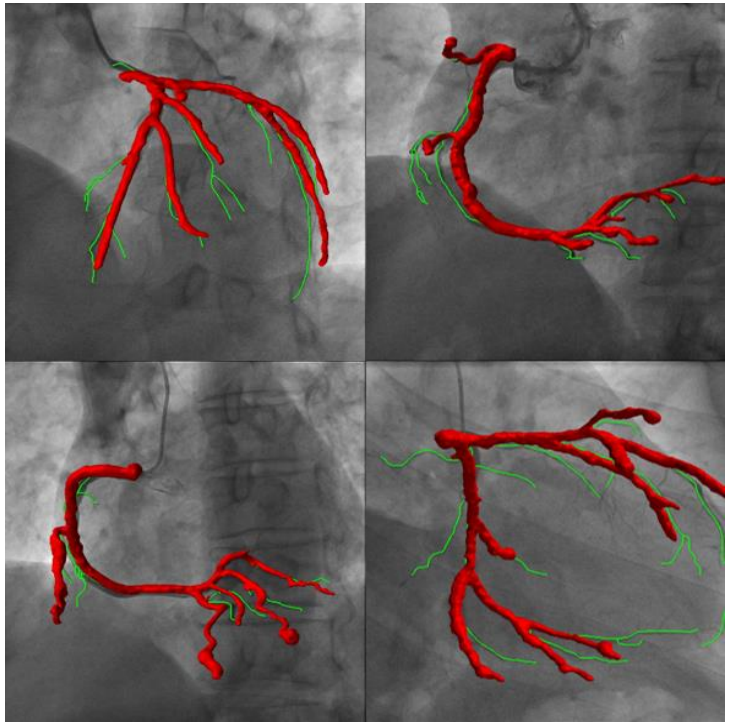
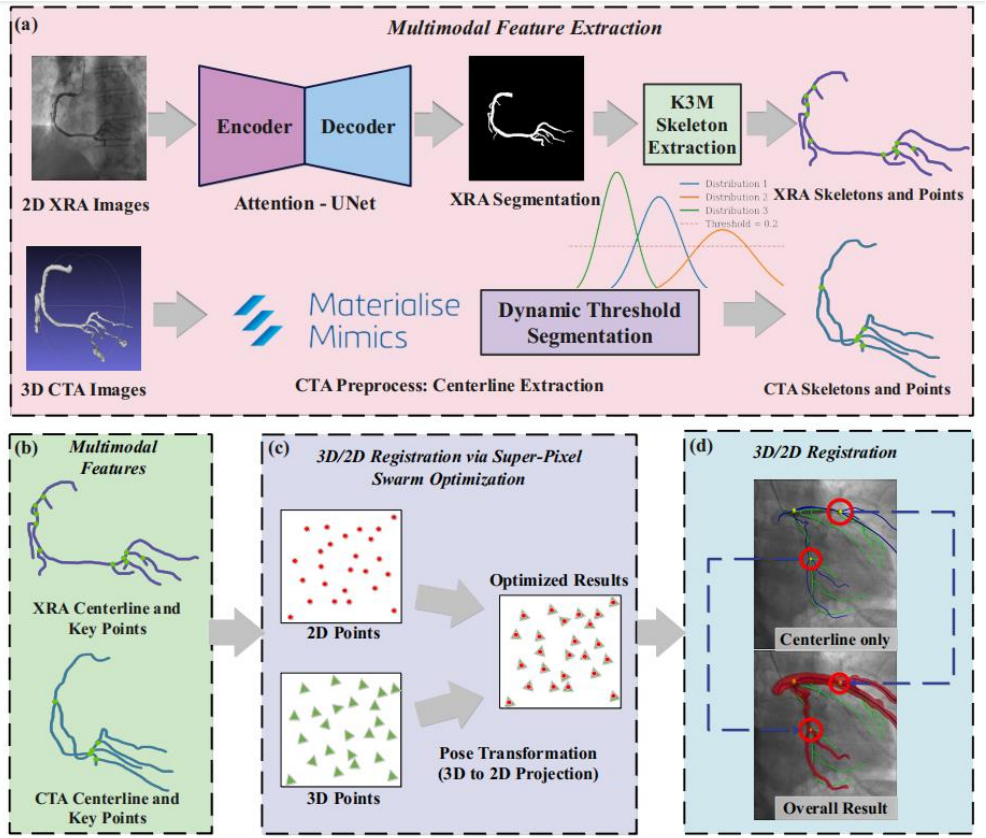
Intelligent Image-Guided PCI Procedure

2D-3D Coronary Artery Registration (2D-DSA/XRA images, 3D-CTA images)

- **Clinical needs:** DSA alone provides limited 2D vessel visualization during PCI, and intraoperative CTA updates for spatial guidance are not feasible.
- **Significance:** Combining a global 3D structural overview with real-time 2D operational views enhances the precision and safety of PCI procedures.

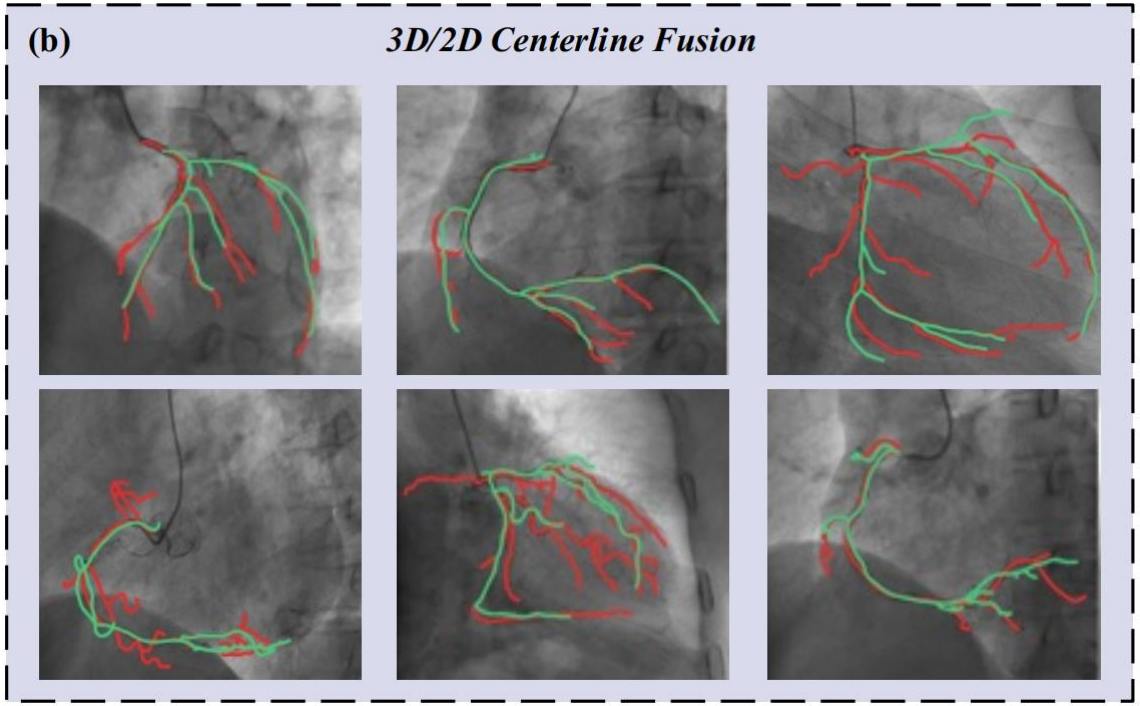


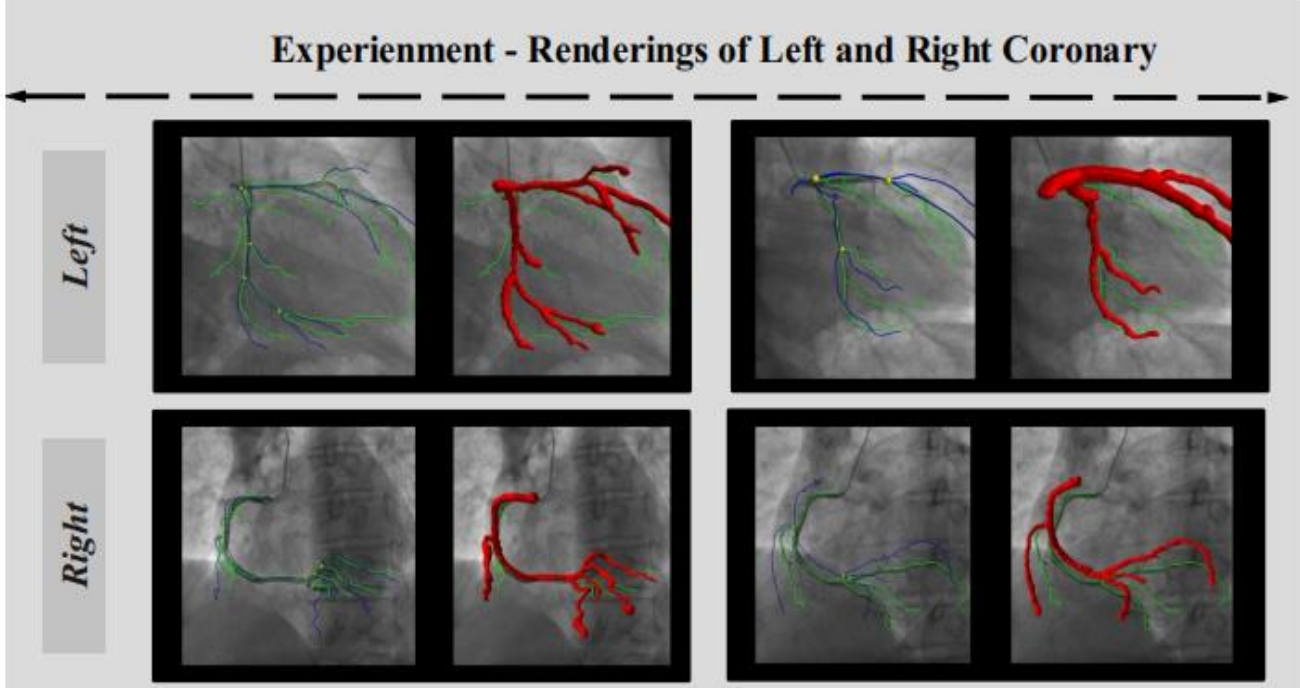


[1] Qi, P., Qu, W., Yao, T., Ma, H., et al. (2024). A Two-stage 2D-3D Coronary Artery Registration Method based on Super-pixel Particle Swarm Optimization. IEEE Transactions on Computational Imaging. (under review)

2D-3D Coronary Artery Registration (2D-DSA/XRA images, 3D-CTA images)

- **Feature Extraction Module:** Extraction of key points from multi-dimensional images.
- **Registration Module:** Utilization of particle swarm optimization algorithms to find the optimal match between key points in multimodal images.
- **Results:** High accuracy and robustness in the task of 2D-3D coronary artery image registration.





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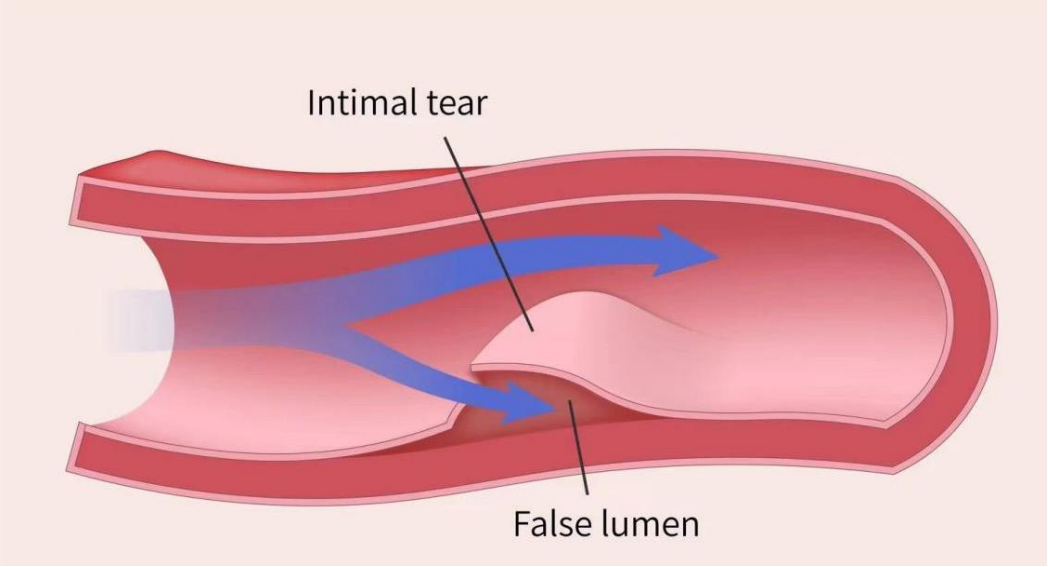
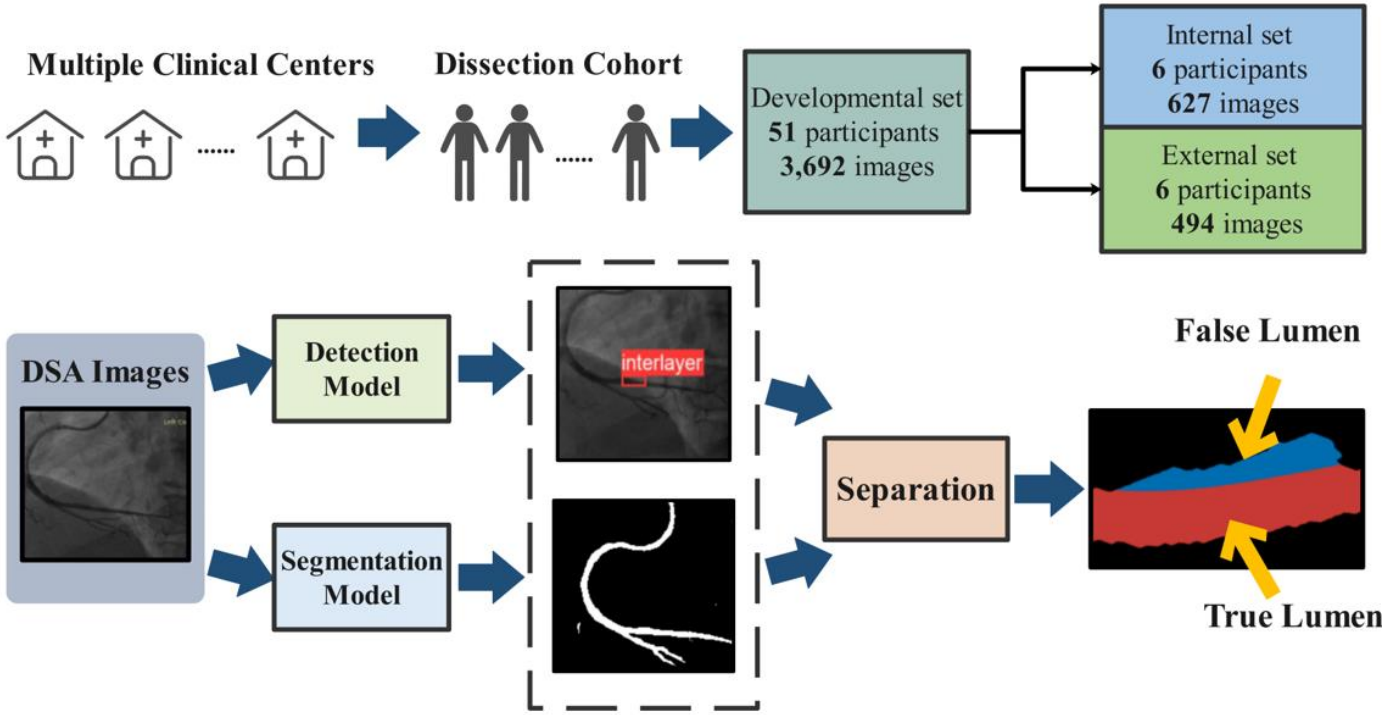
Intelligent Image-Guided PCI Procedure

PCI planning with Coronary Artery Dissection

- **Dection Module:** YOLO-based model identifies the unique spike-like structure of dissection.
- **Segmentation Module:** Robust and rotation-invariant segmentation of vascular from DSA images.
- **Visualization Module:** Delineating the vessel structure, distinguishing FLs from true lumens (TLs), and creating visual representations of the dissection area.





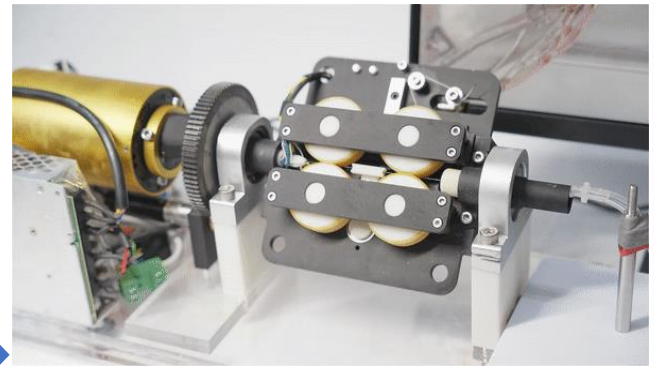
[1] "A Safe Planning of Percutaneous Coronary Intervention for Coronary Artery Dissection: A Retrospective Analysis", Radiology. (to be submitted)

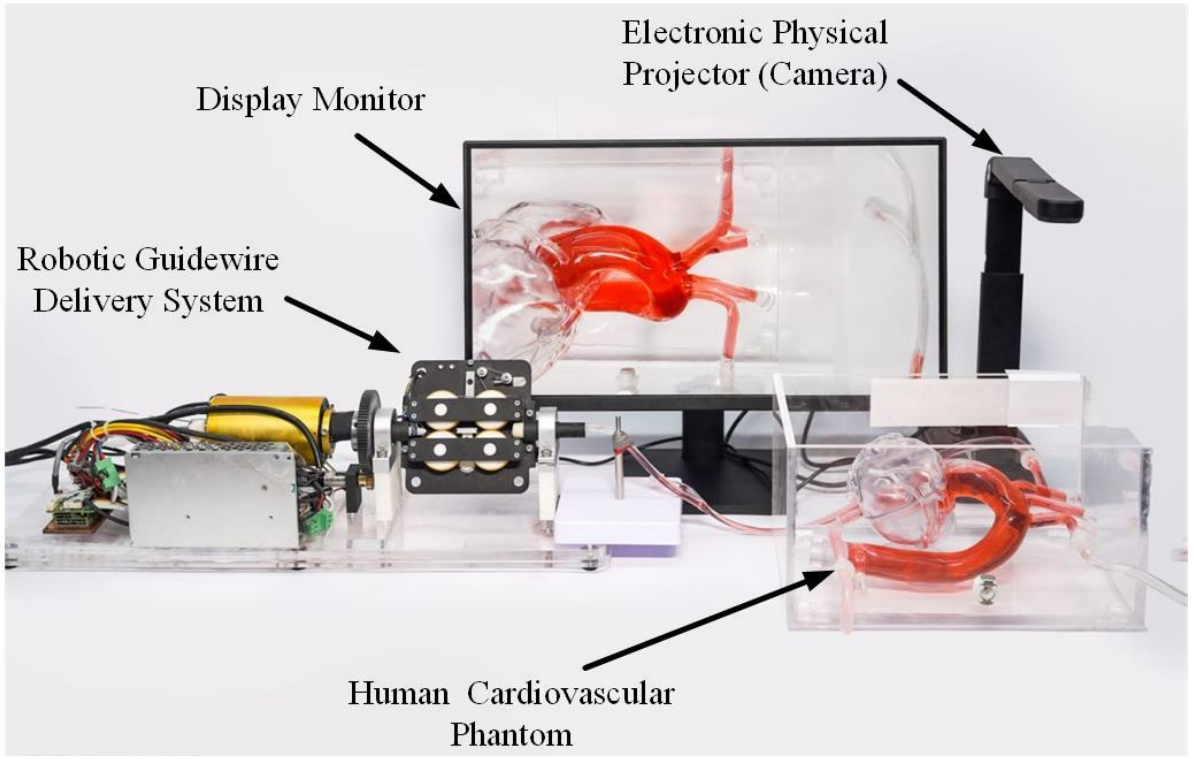
Previous Work

Guidewire Gripping and Manipulation

☐ Cardiologist's Hands: guidewire gripping and manipulation device in PCI Procedures

- **Significance:** Enhancing procedural accuracy, reducing complication risk, improving surgical efficiency, and patient experience.
- **Pushing and Rotating: 2 DOFs* .**
- **Pushing Manipulation Accuracy: 0.5mm.**





*Kuo, C. H., Dai, J. S., & Dasgupta, P. (2012). Kinematic design considerations for minimally invasive surgical robots: an overview. The International Journal of Medical Robotics and Computer Assisted Surgery, 8(2), 127-145.

Ongoing Work

Task-Level Automation in PCI Procedures

During a demanding and protracted four-hour PCI procedure, renowned cardiologist Junbo Ge (academician of the Chinese Academy of Sciences), experienced hand cramps.

- **Intense focus and pressure on cardiologists for extended periods**
- **Safety concerns and errors due to fatigue**
- **Human factors in quality and efficiency**

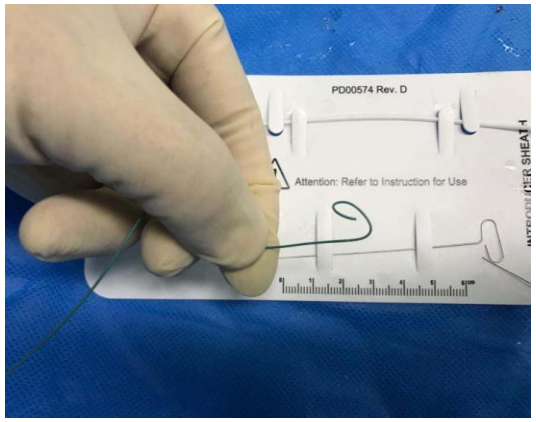
Eliminating human factors and reducing the workload are important

Solution: Automate some intervention steps by robots

Ongoing Work

Automation in Robotic Surgery

- **Automation in robot-assisted PCI with advanced algorithm and adaptive structure**
  - enhancing accuracy, reducing workload and minimizing radiation exposure.



Definition of Level of Autonomy in Robotic Surgery (Guang-Zhong Yang '17)

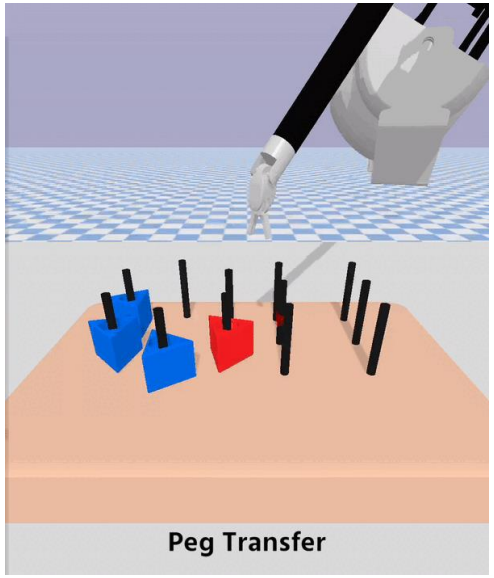
Ongoing Work

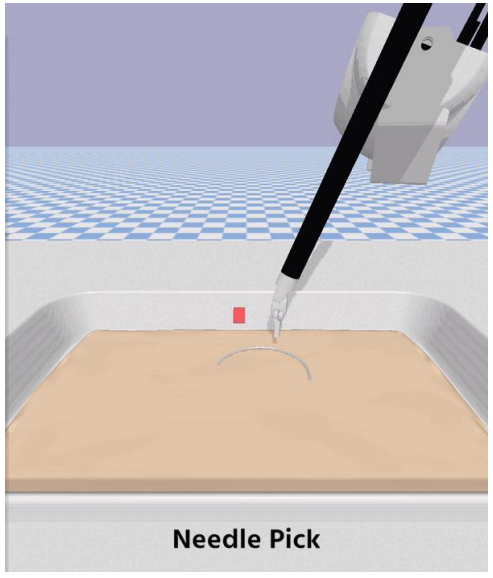
Robot-assisted PCI Procedure: RL-driven Robotics

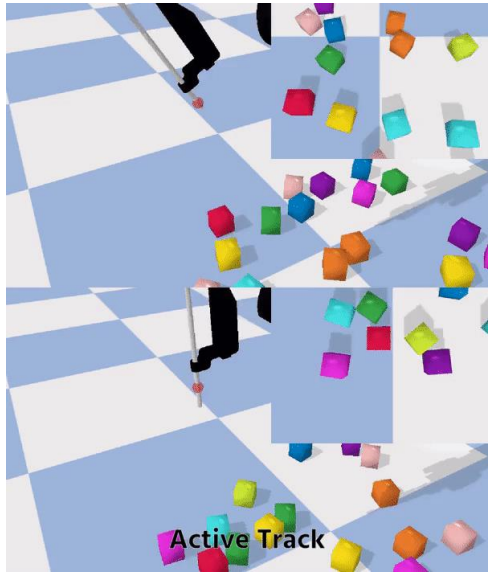
☐ Open-source platform for PCI robot learning

- **Highlights:** Reinforcement-learning-based design for PCI procedure skill learning.
- **Significance:** Low-cost data collection and accelerates the developments of learning-based robot-assisted PCI procedures.
- **Sim2Real skill acquisition:** Reducing the reliance on hardware platform when learning autonomous operation skills.

SurRoL: Online skill training platform based on the **dVRK** for the **Da Vinci Surgical System**.







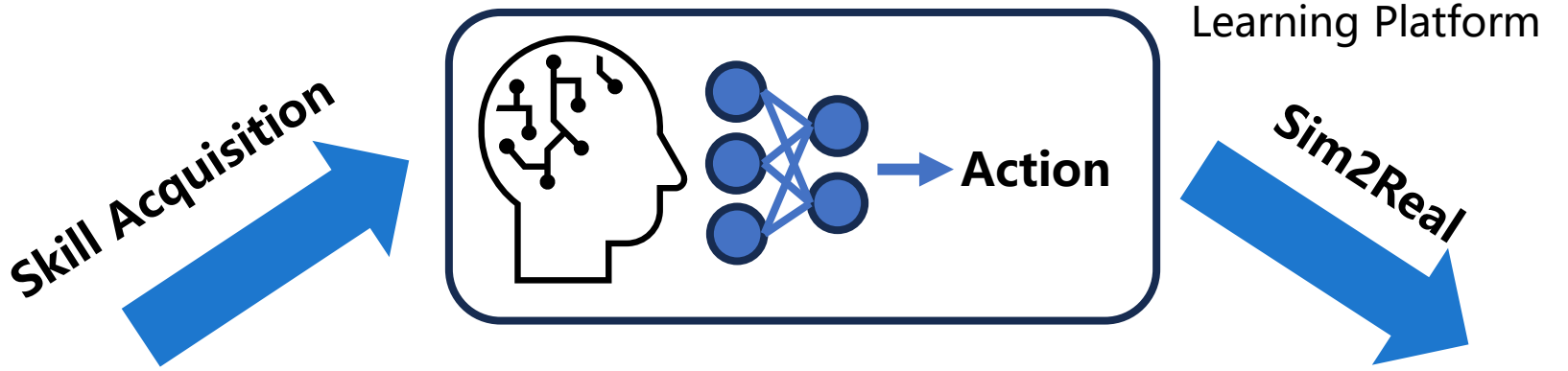
RL-driven robotic PCI procedure remains unexplored!

Ongoing Work

Robot-assisted PCI Procedure: RL-driven Robotics

☐ Sim2Real platform for PCI robot learning

- **Physical Engine and Model**: PCI procedure simulation platform.
- **PCI Robotic hardware platform**: PCI robotic system.
- **Reinforcement Algorithm and skill acquisition: To be developed.**



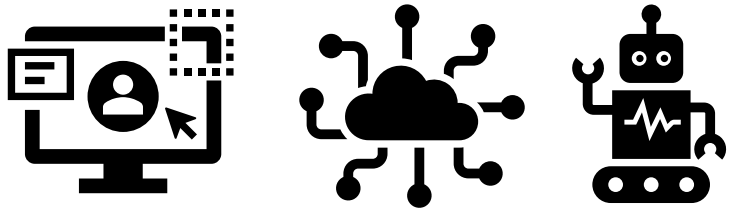
Real-world Learning and Feedback

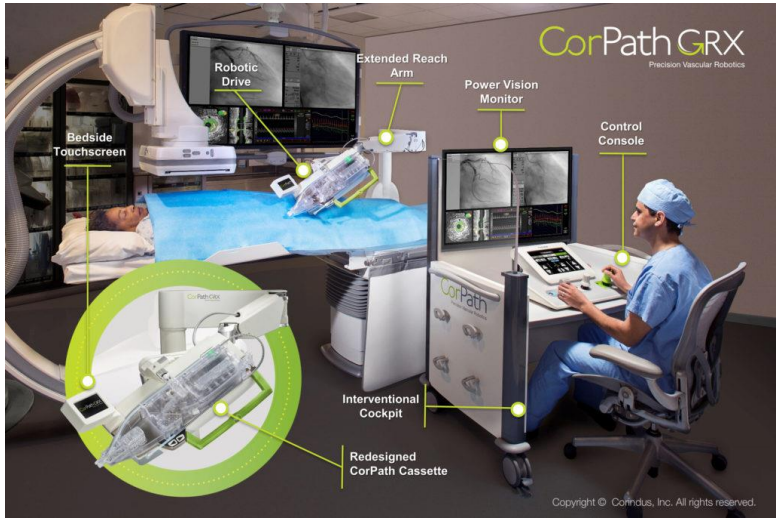
Simulation Platform

PCI Robotic System

Summary

EARTH (Embodied AI and Robotics for Healthcare) in PCI





AI-Powered PCI Robots: Redefining Precision and Autonomy in Cardiac Care

- Leveraging sophisticated AI algorithms to enable task-level-autonomous PCI procedure.
- Integrating data from multiple sources to adapt the actions of robots in real-time.
- Incorporating large language models, enabling seamless collaboration between interventional cardiologists and the robotic system.
- Mechanical structure should be flexible and adaptable to different environments and patient anatomies.

Embodied AI = Algorithmic Intelligence + Mechanical Intelligence

-- Jian S. Dai (FREng, MAE, Fellow of IEEE, ASME, Editor-in-Chief of Robotica)

Thanks!

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