



NEXT-GENERATION SINGLE-PORT ROBOTIC CARDIAC SURGERY: BIOMECHANICAL PRINCIPLES, ADVANCED KINEMATICS, AND FUTURE PARADIGMS IN AUTONOMOUS INTRACARDIAC INTERVENTIONS

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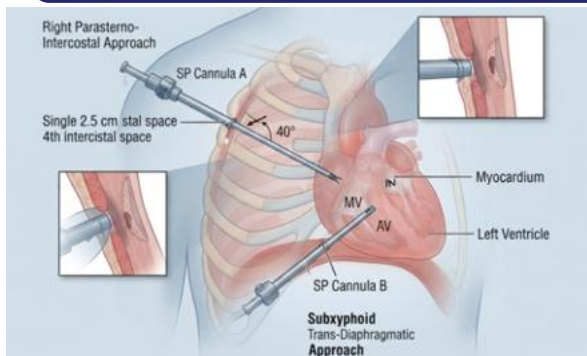
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ABSTRACT

Minimally invasive cardiac surgery has transitioned from conventional multi-port thoracoscopic and robotic platforms to single-port (SP) multi-articulated access paradigms. This evolution significantly minimizes surgical access trauma, eliminates multi-planar intercostal nerve compression, and markedly accelerates postoperative recovery. However, consolidating high-dexterity surgical instruments and high-definition stereoscopic cameras into a single, restrictive incision (~2.5 to 3.5 cm) introduces severe physical challenges, including instrument triangulation compromise, micro-space collisions, and altered force transmission dynamics. This comprehensive article analyses the technical, spatial, and mechanical methodologies underlying Single-Port Cardiac Surgery (SPCS). We define the exact anatomical and mathematical principles governing optimal subxiphoid and intercostal single-port placements. We detail the underlying engineering kinematics—specifically focusing on double-jointed, elbow-wrist multi-axial articulation and parallel-link instrument systems. Moving forward, we project next-generation innovations within this domain, highlighting the integration of continuum concentric-tube robotics, intraoperative shape-sensing fiber Bragg gratings (FBG), real-time augmented reality (AR) tissue overlay, and autonomous, AI-driven suture tracking.

KEYWORDS : Single-Port Surgery, Robotic Cardiac Surgery, Biomechanical Kinematics, Continuum Robotics, Intracardiac Navigation.



1. INTRODUCTION

Minimally invasive cardiac surgery (MICS) has historically relied on right mini-thoracotomies or multi-port robotic arrays (typically requiring 4 to 5 separate incisions across multiple intercostal spaces) to execute complex procedures like mitral valve repairs or coronary artery bypass grafting. While multi-port robotic platforms (such as the *da Vinci Xi/X*) successfully mitigate tremor and scale micro-movements, their multi-incision footprint exposes patients to cumulative intercostal nerve injuries, localized pleuritic pain, and the risk of device-to-device arm collisions outside the chest wall.

The introduction of single-port robotic configurations—most notably the *da Vinci SP* platform and specialized single-cannula designs—marks a major paradigm shift. By packaging a 3D-HD flexible stereoscopic endoscope and three independent, multi-jointed end-effectors inside a single 25 mm entry profile, single-port approaches completely redefine access engineering.

In mid-2026, pioneering procedures like the world's first single-port robotic mitral valve repair confirmed the clinical viability of this hyper-focused access approach. Yet, operating safely within the strict, deep spatial constraints of the

pericardial cavity requires deep comprehension of access vector mechanics and advanced instrumentation kinematics.

2. Anatomical Port Placement Methodology

Unlike multi-port setups that position instruments across a wide structural "baseball diamond" array to naturally create operational triangulation, single-port placement relies on an axial entry vector concept. The port site must be precisely mapped to align with target structures without requiring forced instrument deflection or risking collision with the right ventricular free wall or the phrenic nerve.

Approaches for Single Port Cardiac Access

Approach A: Peristernal/Intercostal

```
( Sternum )
  ||
[3rd/4th ICS]||
(0)====>|| => Mitral Valve / LA
Single Port ||
  ||
```

Approach B: Subxiphoid / Retro-Retrosternal

```
( Sternum )
  ||
  ||
  ||
  ||
  || \ Single Port
  || \ [Subxiphoid]
(X)====(0)
      => Trans-diaphragmatic
          Upward Vector (AV/Root)
```

2.1 The Right Parasterno-Intercostal Vector (Mitral & Tricuspid Target)

For procedures targeting the mitral valve, tricuspid valve, or

left atrium, the optimal single-port entry point is located through a 2.5 cm to 3.0 cm incision in the right 3rd or 4th intercostal space (ICS), positioned exactly along the anterior axillary line or slightly medial to it.

- **Mathematical Trajectory Determination:** The single port cannula is tilted at an entry pitch angle of 35 to 45 degrees relative to the coronal plane. This angle maximizes the direct line-of-sight toward the interatrial groove (Waterston's groove) while preventing the distal ends of the instruments from making restrictive contact with the ascending aorta.
- **Tissue Preservation:** Positioning all devices through a single intercostal space prevents structural distortion across multiple ribs, effectively isolating respiratory-induced chest wall torque to a single anatomical point.

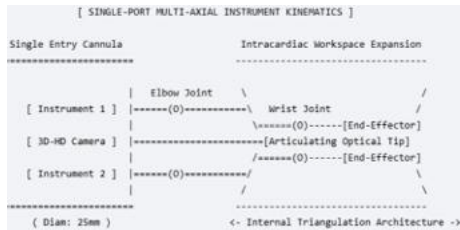
2.2 The Subxiphoid Trans-Diaphragmatic Vector (Aortic & Coronary Target)

For access to the aortic valve, ascending aorta, or anterior coronary arteries (such as LIMA-to-LAD grafting), an alternative subxiphoid trans-diaphragmatic approach is used.

- **Port Trajectory:** The single port enters just below the lower margin of the xyphoid process, tracking superiorly through the diaphragm's anterior avascular space into the lower pericardial recess.
- **Mechanical Benefit:** This path completely avoids the intercostal spaces, eliminating any risk of bone or nerve compression. It provides a straight, bottom-up path directly aligned with the long axis of the left ventricular outflow tract (LVOT).

3. Clear Kinematic Mechanics and Operational Dynamics

Operating multiple instruments through a single-entry lumen eliminates traditional, external physical triangulation. Standard robotic instruments require a clear external pivot point to function effectively; single-port engineering avoids this limitation by utilizing nested intra-luminal multi-axial joint articulation.



3.1 The "Elbow-and-Wrist" Double Articulation Matrix

To restore necessary working angles inside the cardiac chambers, single-port systems employ specialized, multi-jointed instruments:

1. **The Primary Cannula Core (Diameter 25 mm):** Holds up to three modular instruments alongside an articulating 3D-HD camera. All system elements exit parallel to one another.
2. **The Proximal "Elbow" Joint:** Upon exiting the main cannula inside the chest cavity, the instrument arms bend outward away from the central optical axis. This outward flare creates an artificial internal workspace, establishing a functional internal triangulation angle (θ_m) between 45 – 60 degrees.
3. **The Distal "Wrist" Joint:** Provides an additional 7 degrees of freedom directly at the tool head. This second joint allows the instrument tips to curve back inward toward the target tissue, restoring intuitive handling and precise control during complex maneuvers like patch grafting or annular suturing.

3.2 Dynamic Vector Forces and Tremor Filtering Control

Because all structural force lines converge back onto a single-entry point through the chest wall, the system experiences altered physical leverage:

$$\sum \mathbf{M}_{incision} = \mathbf{M}_{arm_1} + \mathbf{M}_{arm_2} + \mathbf{M}_{camera} + \mathbf{M}_{tissue}$$

To maintain perfect tip precision under varying tissue resistances, the control console uses advanced dynamic inverse kinematics algorithms. These software systems actively calculate real-time joint transformations, automatically compensating for any physical movement or flex within the primary delivery cannula.

Furthermore, the software scales down the surgeon's physical hand inputs while running a continuous 6-Hz low-pass filter to erase micro-tremors, ensuring rock-solid stability even within confined, fluid-filled cardiac spaces.

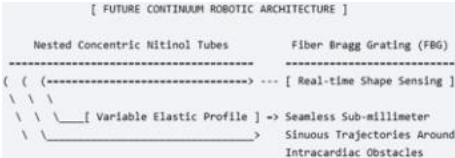
4. Advanced Engineering Concepts & Systems Integration

Executing complex open-heart procedures through a single narrow port requires a highly synchronized technical ecosystem to manage visualization, global myocardial protection, and precise tissue manipulation.

Operational Challenge	Advanced Engineering Solution	Primary System Mechanism
System Overcrowding & Internal Tool Collisions	Non-parallel, joint-triangulating software control pathways.	Predictive collision monitoring models continuously track joint proximity, automatically restricting slave arm movements if instruments come within 1.5 mm of one another.
Complete Visualization Deprivation	0° → 90° Continuously steerable stereoscopic vision systems.	Dual-optical CMOS sensors mounted on a flexible, cable-driven neck can bend up, down, or around active instruments, maintaining clear line-of-sight without needing a separate camera incision.
Myocardial Preservation and Extracorporeal Support	Endovascular balloon occlusion & multi-stage peripheral cannulation.	Cardiopulmonary bypass (CPB) is established via femoral venous-arterial lines. Myocardial protection is maintained using an endoaortic balloon clamp (EndoClamp) positioned via the femoral artery, enabling targeted cardioplegia delivery directly into the aortic root without requiring transthoracic access clamps.

5. Future Innovations: Robotics and Autonomous Paradigms

The current generation of rigid-jointed single-port platforms represents only the baseline architecture. Over the next decade, the intersection of advanced continuum robotics, quantum-dot optics, and artificial intelligence will drive single-port cardiac surgery into an entirely autonomous, tissue-intelligent era.



5.1 Continuum Concentric-Tube Robotics

Future systems will replace rigid, jointed links with continuum concentric-tube robots. These mechanisms use nested, pre-curved tubes made of superelastic Shape Memory Alloys (SMA), such as Nitinol. By rotating and translating these tubes inside one another, the instrument can smoothly alter its structural curvature along its entire length. This snake-like agility allows the robot to follow complex, non-linear paths through the vascular system or around dense cardiac anatomy without needing clear internal straight-line spaces.

5.2 Fiber Bragg Grating (FBG) Shape-Sensing & Haptic Feedback

A major limitation of current robotic platforms is the lack of direct haptic force feedback. Future systems will embed multi-core optical fibers utilizing Fiber Bragg Grating (FBG) sensors directly along the flexible body of each instrument:

- **Mechanism:** As the instrument curves or encounters tissue resistance, the physical wavelength of light traveling through the fiber changes proportionally to the strain.
- **Result:** The system calculates sub-millimeter shape changes in real time and translates those structural

changes into direct haptic feedback at the surgeon's console, providing a safe, tactile sense of tissue resistance.

5.3 Real-Time AI Augmented Reality (AR) Tissue Overlays

Using deep neural networks trained on pre-operative 4D CT scans and intraoperative transesophageal echocardiography (TEE), the robotic display will dynamically superimpose anatomical structures directly onto the surgeon's live visual feed:

- **Dynamic Tracking:** The system projects hidden structures—such as the exact course of the circumflex coronary artery during a mitral annuloplasty—directly onto the live tissue view.
- **Safety Boundaries:** The software sets virtual, real-time "no-fly zones." If an instrument tip inadvertently approaches vulnerable structures (like the conduction bundle or aortic wall), the system automatically increases resistance or pauses movement to prevent tissue injury.

5.4 Autonomous Intracardiac Suture Navigation

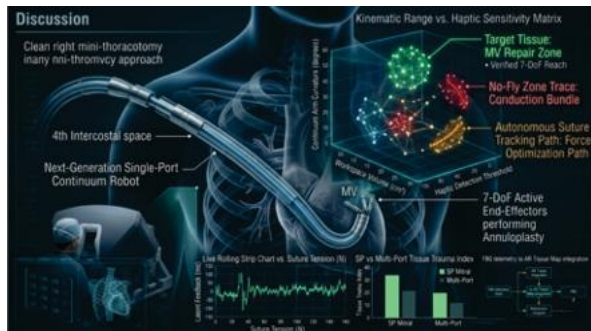
Routine, high-repetition tasks such as driving annuloplasty ring sutures or managing structural tissue closures will shift toward supervised autonomy:

- **Tracking Kinematics:** Computer vision models analyze tissue deformations in real time, automatically calculating optimal entry and exit points for each suture needle.
- **Execution:** Once approved by the surgeon, the robot autonomously drives the needle along a flawless arc, maintaining perfect tension control regardless of residual cardiac movement or baseline engine vibrations.

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6. DISCUSSION AND CONCLUSIONS



Single-Port Cardiac Surgery (SPCS) represents the current pinnacle of structural optimization within minimally invasive cardiothoracic interventions. By consolidating all necessary visual and mechanical inputs into a single, compact entry corridor, this methodology reduces patient trauma to a minimum while preserving full structural surgical capability.

While early applications required highly advanced, specialized surgical skillsets, ongoing engineering innovations in dynamic multi-axial kinematics and inverse control algorithms continue to lower the learning curve.

As the field integrates continuum robotics, real-time shape-sensing optical arrays, and autonomous vision guidance, the single-port paradigm will evolve from an expert-tier surgical option into a standardized, highly accessible gold standard for global cardiac care.

