Tech & AI Systems | Jan 14, 2026 | 9 min read | By Bryan White

Thinking Robots: The Rise of Cognitive Intelligence in the Operating Room

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Introduction: The Fourth Era of Cognitive and Autonomous Surgery

Surgical science has evolved through three historical epochs: open surgery defined by direct manual intervention; late-20th-century laparoscopy mediated through rigid instruments and 2D video; and first-generation "master-slave" robotic teleoperation inaugurated by the da Vinci system.[1] By 2024-2025, clinical engineering has entered Surgery 4.0 -- defined by supervised task autonomy, transcontinental 5G and satellite teleoperation, compliant continuum mechanics, and untethered micro- and nanoscale therapeutic agents.

Rather than acting solely as passive mechanical extensions of human hands, modern surgical platforms integrate tip force sensors, reinforcement learning policies, vision transformers, and low-Earth-orbit (LEO) connectivity. Synthesizing 2024-2025 clinical and engineering advances, this report examines the global proliferation of surgical platforms, cognitive autonomy in deformable soft tissue, and continuum and molecular machines operating down to the cellular scale.

Global Platform Proliferation and the Restoration of Haptics

Following key patent expirations, the two-decade Western monopoly over multi-arm surgical robotics has diversified into a global ecosystem (Table 1). Intuitive Surgical's da Vinci 5 resolves a foundational deficit of robotic surgery -- reliance on "visual haptics" inferred from tissue deformation -- by integrating tri-axial tip force sensors.[2] Translating tissue resistance directly to the console hand controllers reduces peak traction forces and postoperative inflammation while recording kinematic and kinetic telemetry ("digital exhaust") to train surgical AI models.[3] Concurrently, UC San Diego researchers have developed wearable fingertip polymer actuators that deliver electrical cutaneous haptics to simulate tumor vs. cyst texture.[3]

Across Asia, domestic manufacturers are expanding access and pioneering telesurgery. Japan's compact Hinotori system (Medicaroid) completed five-year 5G validation under Japanese Remote Surgery Guidelines and expanded into Singapore and Malaysia.[4][6] China's Toumai robot (MicroPort MedBot) earned EU CE Mark certification while setting ultra-long-distance 5G/satellite telesurgery records.[5][7] South Korea's Revo-i (approved in Uzbekistan, Morocco, and Russia) and India's Mantra (deployed in India, Indonesia, and the UAE) deliver multi-arm capabilities at substantially lower capital cost.[5] Meanwhile, modular single-arm carts (CMR Versius, Medtronic Hugo) and specialized systems like Moon Surgical's Maestro (an automated laparoscopy "third hand") and Distal Motion's Dexter (toggling between sterile bedside laparoscopy and console control) target intermediate workflows.[4]

| System | | Manufacturer | | Origin | | Key Capabilities | | Markets / Approvals |

| da Vinci 5 | | Intuitive | | USA | | Tip force feedback, 10,000x compute | | Global (FDA, CE)[2] |

| Hinotori | | Medicaroid | | Japan | | Compact footprint, 5G telesurgery | | Japan, Singapore, Malaysia[4][6] |

| Toumai | | MicroPort | | China | | 5G & LEO satellite telesurgery | | China, EU (CE Mark)[5][7] |

| Revo-i | | Meerecompany | | S. Korea | | Cost-effective open console | | Korea, Russia, Uzbekistan[5] |

| Mantra | | SS Innovations | | India | | Affordable modular multi-arm | | India, UAE, Indonesia[5] |

| Ottava | | J&J | | USA | | Table-integrated zero-footprint | | FDA De Novo cleared (Jul 2026); 1st U.S. install (Nov 2026)[4][31] |

Cognitive Autonomy, Reinforcement Learning, and Transcontinental Telesurgery

The defining shift of 2024-2025 is the progression from Level 0 teleoperation to Level 2-3 conditional autonomy in deformable soft tissue. At Johns Hopkins University, the Smart Tissue Autonomous Robot (STAR) performed autonomous intestinal anastomosis -- suturing bowel segments without human hands -- by pairing a plenoptic 3D endoscope with machine-learning tracking of near-infrared fluorescence (NIRF) markers across breathing and peristaltic motion.[8][8] For sub-millimetric vessels, researchers coupled optical coherence tomography (OCT) with the Microvascular Anastomosis Positioning System (MAPS), a smart clamp that rotates vessels dynamically for optimal needle entry.[9]

Autonomous suturing and knot-tying policies are trained via Reinforcement Learning (RL) and apprenticeship imitation learning.[10][12] To cross the "Sim-to-Real" gap safely, training pipelines employ Domain Randomization -- varying simulated tissue stiffness, friction, and lighting so policies generalize to living tissue.[10][11] Concurrently, surgical scene segmentation has shifted to Multi-Scale Transformers for Surgical Phase Recognition (MuST),[13] paired with a lightweight Overseer model (in SASVi) that detects tracking loss amidst electrocautery smoke and automatically re-prompts foundation segmentation models.[14]

In telesurgery, clinical safety requires a Round-Trip Latency (RTL) below 200 ms and minimal packet jitter.[15] Using AI jitter buffering and predictive trajectory control,[6][16] a surgeon in Shanghai used the Toumai robot in late 2024 to perform a radical prostatectomy on a patient in Casablanca, Morocco -- spanning 12,000 km (30,000 km fiber/5G path) at an average RTL of 181.4 ms.[7][17] Furthermore, whereas geostationary (GEO) satellites (36,000 km) impose ~500 ms latency, 2025 demonstrations over Low Earth Orbit (LEO) satellites (~550 km) completed liver resections with one-way latency under 60 ms.[18]

Continuum Soft Robotics, Microrobots, and Molecular Nanomedicine

Miniaturized platforms are simultaneously eliminating external footprints. Virtual Incision's two-pound MIRA inserts through a single umbilical incision to achieve

internal triangulation.[19] For transnasal skull-base or bronchial pathways, Concentric Tube Robots (CTRs) use nested, pre-curved tubes of super-elastic Nitinol (nickel-titanium) modeled via Cosserat rod theory.[20][21] Compliant pneumatic eversion ("vine") endoscopes grow from the tip with zero sliding colon-wall friction,[22] while UNSW's electricity-free hydraulic Soft Fibrous Syringe Architecture (SFSA) offers intrinsic obstacle pressure sensing inside MRI scanners.[23]

At the micro- and nanoscale, robotics converges with molecular biology:

* Magnetic Millirobots: External electromagnetic coils actuate shaftless propeller millirobots that switch between wall-rolling, turbine swimming, and tumbling to mechanically disrupt blood clots and deliver fibrinolytics.[24]

* DNA Origami Nanorobots: Karolinska Institutet researchers engineered hexagonal DNA origami cages concealing cytotoxic peptides that trigger apoptosis.[25] Latched at normal blood pH (~7.4), the cage unlocks specifically in the acidic microenvironment (pH ~6.5) produced by solid-tumor glycolysis -- the Warburg effect -- selectively killing cancer cells.[25][26]

Preoperative planning now leverages reimbursable patient-specific Digital Twins (HCPCS C8001) to simulate hepatic blood flow and cardiac electrophysiology.[27][27] While robotic cholecystectomy shows limited cost-effectiveness over laparoscopy,[28] complex robotic cervical oncology yields superior Quality-Adjusted Life Years (QALYs),[29] even as autonomous systems raise pressing legal liability and resident de-skilling questions.[30][30]

Conclusion: Orchestrating the Multi-Scale Operating Room

The breakthroughs of 2024-2025 have forged a new surgical ecosystem uniting force-feedback consoles, domain-randomized reinforcement learning, 12,000 km telesurgery, continuum endoscopes, and pH-gated DNA nanorobots -- transforming the surgeon into the orchestrator of a multi-scale clinical intervention.[1]

2026 Regulatory and Clinical Update: In July 2026, Johnson & Johnson's zero-footprint, table-integrated OTTAVA robotic surgical system received FDA De Novo authorization for upper-abdominal general surgery procedures, and on November 19, 2026, J&J announced Memorial Hermann-Texas Medical Center in Houston as the first U.S. hospital commercial installation.[31]

Updates... (Nov 23, 2026): Replaced all PubMed Central reCAPTCHA-gated URLs, PubMed 203 links, IEEE Xplore anti-bot URL, and SpringerMedizin client-challenge URL with CrossRef-verified primary DOIs carrying exact authors and publication dates. Previously (Nov 20, 2026) removed numbered section prefixes, replaced unreachable/403 URLs, enforced 1:1 inline parity, and added Johnson & Johnson's November 19, 2026 OTTAVA installation release.

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