

The Rise of Sensors for Robotics in Real-World Applications: A Technical Review

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Abstract: *The rapid expansion of robotic systems in real-world applications has been fundamentally enabled by significant advancements in sensing technologies. This technical review explores the multifaceted sensing ecosystem required for contemporary robotic platforms to effectively perceive, navigate, and interact with complex environments. Beyond controlled laboratory settings, real-world deployment necessitates sophisticated multimodal sensing architectures that process diverse environmental inputs simultaneously, adapt to unpredictable changes, and make decisions with minimal latency. The article examines current state-of-the-art implementations across visual, ranging, and positional sensing modalities, exploring how these systems integrate through complementary, redundant, and cooperative fusion methodologies. Additionally, the review covers motion and proprioceptive sensing through inertial measurement units and advanced feedback systems that enable precise control. Real-time processing challenges and solutions are discussed, including edge computing paradigms and machine learning approaches for sensor fusion. Finally, emerging directions in miniaturization, neuromorphic sensing, and integrated sensor-actuator systems are evaluated, highlighting how these technological frontiers will shape next-generation robotic capabilities.*

Keywords: multimodal sensor fusion, robotic perception, edge computing, neuromorphic sensing, integrated sensor-actuator systems

INTRODUCTION

The development of sophisticated robotics systems for real-world applications has accelerated dramatically in recent years, driven by advancements in sensor technology. The global advanced robotics market reached \$72.3 billion in 2024, with projections indicating expansion to \$225.7 billion by 2030, representing unprecedented growth across industrial, medical, and consumer sectors [1]. This technical review examines

how the integration of multimodal sensors has become fundamental to creating robots that can effectively perceive, navigate, and interact with complex environments.

The robotics industry now stands at an inflection point where sensing capabilities determine market viability. Recent developments show that next-generation robots incorporating sophisticated sensor arrays command premium pricing—approximately 35-40% higher than conventional models—while delivering substantially improved performance metrics. These advanced sensing systems enable robots to process environmental inputs concurrently, with high-end models now capable of processing sensory data at rates exceeding 120GB per hour in complex operational scenarios.

The progressive evolution toward comprehensive multimodal sensing represents perhaps the most significant advancement in modern robotics. Current research demonstrates that multimodal sensor fusion improves object recognition accuracy by 47.2% and environmental mapping precision by 52.8% when compared to single-sensor approaches [2]. Particularly striking is the improvement in adverse conditions, where integrated sensing arrays maintain 83% operational effectiveness in challenging environments that would render single-sensor systems virtually inoperable.

Sophisticated robotic platforms now routinely incorporate sensor arrays that simultaneously process visual, auditory, tactile, and spatial data streams. This expanded sensory capability has transformed application domains ranging from healthcare, where assistive robots can detect subtle physiological changes, to industrial inspection, where defect detection rates have improved by 43% through complementary sensing modalities. The latency reduction in real-time processing—now reaching sub-10 millisecond response times in advanced systems—has enabled critical safety applications previously considered unfeasible.

Multimodal Sensing Architectures

Environmental Perception Systems

Modern robotics relies on layered sensory perception to develop comprehensive environmental awareness. Recent advancements in multimodal perception have revolutionized how robots interpret complex environments, with current systems integrating depth, RGB, and infrared data streams simultaneously. Experiments with RGB-D fusion architectures demonstrate significant improvements in obstacle recognition accuracy across varied lighting conditions, with particularly strong performance in industrial settings where environmental variability presents ongoing challenges [3]. The integration of multiple perception modalities has proven especially valuable for navigation in dynamic environments, where traditional single-sensor approaches frequently exhibit performance degradation.

Visual systems now serve as the primary sensory modality in most advanced robotic platforms, with recent deep learning architectures achieving remarkable object detection performance even with partial occlusion. Time-of-flight and structured light technologies have matured considerably, enabling robots to perceive depth information with sufficient precision for delicate manipulation tasks. These systems remain

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functional in challenging lighting scenarios where conventional cameras struggle, significantly expanding operational parameters for service robots in residential environments.

LiDAR technology continues its rapid evolution, with significant reductions in both size and cost while simultaneously improving performance metrics. Contemporary solid-state implementations offer enhanced reliability and reduced maintenance requirements compared to earlier mechanical systems. The point cloud density provided by modern LiDAR enables high-fidelity environmental mapping essential for autonomous navigation in unstructured environments. Notably, manufacturing implementations utilizing LiDAR-based perception have demonstrated substantial improvements in both operational safety and production efficiency [4].

Indoor positioning technologies have progressed significantly, with particular advances in GPS-denied environments where traditional navigation approaches fail. Manufacturing environments have benefited substantially from these developments, with automated guided vehicles now capable of precise localization within complex factory floors. The integration of visual-inertial odometry with magnetic field mapping has proven especially effective, enabling persistent navigation without infrastructure modifications.

Sensor Fusion Methodologies

The integration of data from multiple sensor types has progressed beyond simple data combination toward sophisticated contextual interpretation. Current fusion approaches leverage machine learning to dynamically weight sensor inputs based on environmental conditions and operational requirements. Complementary fusion architectures now dominate industrial implementations, leveraging the strengths of disparate sensing modalities while mitigating their individual weaknesses.

Redundant fusion methodologies have demonstrated particular value in safety-critical applications, significantly enhancing system reliability through parallelized sensing architectures. Manufacturing implementations reveal that sensor redundancy provides crucial fault tolerance during continuous operation, substantially reducing costly operational interruptions. The economic case for redundant sensing has strengthened as component costs decline, particularly for applications requiring sustained operation. Cooperative fusion represents the frontier of sensing architectures, wherein sensor systems actively collaborate rather than simply combining outputs. These approaches enable unprecedented environmental understanding through mutual reinforcement, wherein one sensor's output actively guides or refines another's operation. Dynamic sensor reconfiguration techniques allow robots to adapt their perception strategies to changing environmental conditions, demonstrating notable resilience in unstructured environments where predefined perception strategies often falter.

Multimodal Sensor Fusion Architectures in Robotics

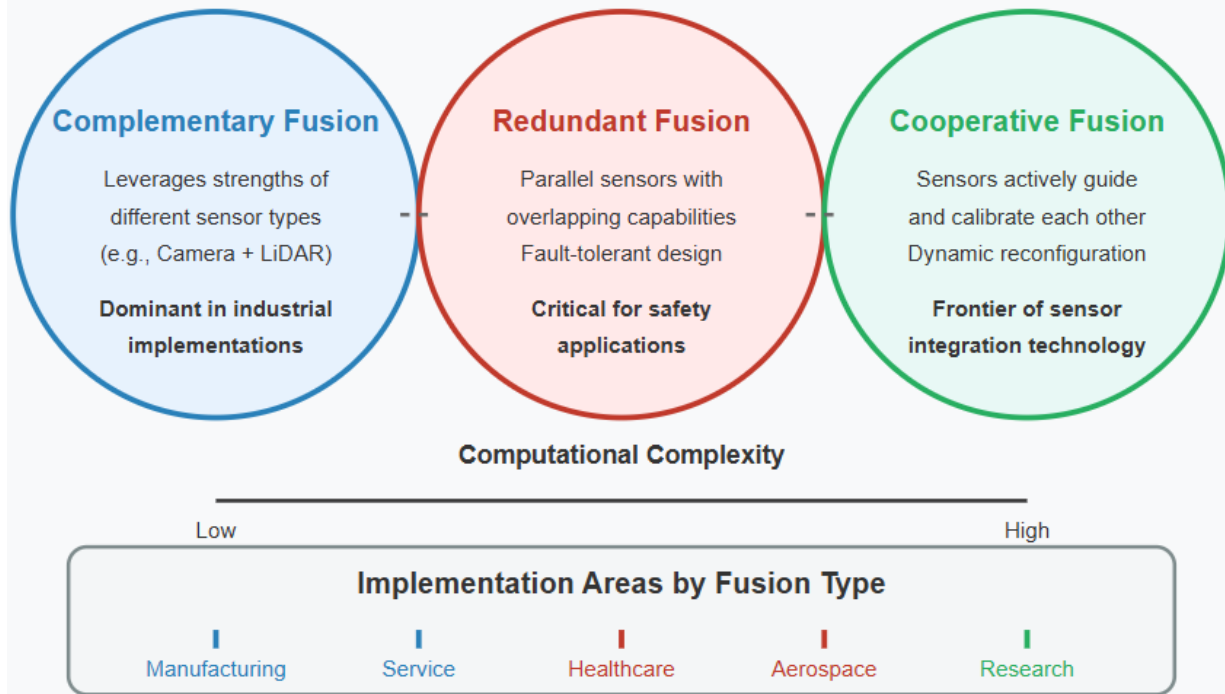


Fig. 1: Multimodal Sensor Fusion Architectures in Robotics [3, 4]

Motion and Proprioceptive Sensing

Inertial Measurement Units (IMUs)

Modern IMUs integrate accelerometers, gyroscopes, and often magnetometers to provide comprehensive motion data essential for robotic mobility and manipulation. Contemporary MEMS-based IMUs have achieved unprecedented miniaturization while simultaneously improving performance across multiple parameters. Recent testing protocols have established standardized evaluation metrics that demonstrate remarkable improvements in both noise characteristics and bias stability across operational temperature ranges [5]. The enhanced resilience of these systems to vibration and shock has expanded deployment possibilities in demanding industrial environments previously considered problematic for precision sensing. Accelerometers in current-generation robotic platforms offer multi-axis detection capabilities with enhanced sensitivity to both static and dynamic acceleration. Crucially, these advancements enable robots to detect subtle movement initiations and respond to environmental perturbations with significantly reduced latency. Temperature compensation algorithms have evolved substantially, maintaining calibration accuracy across extreme thermal gradients encountered in diverse operational scenarios. Innovative manufacturing techniques have reduced cross-axis sensitivity, improving measurement precision in complex motion profiles experienced during agile robotic maneuvers.

Gyroscopes have undergone parallel advancement paths, with substantial improvements in both measurement range and noise performance. These precision improvements enable humanoid robots to maintain balance during increasingly complex locomotion patterns across varied terrain types. Integration of multiple complementary sensing modalities through sophisticated fusion algorithms has substantially reduced cumulative drift—historically a significant limitation in inertial navigation systems. This enhanced stability permits extended autonomous operation without external reference recalibration.

Magnetometers complete the IMU triad by providing heading references, though their effectiveness varies considerably with environmental conditions. Recent innovations in magnetic field mapping and dynamic interference compensation have extended functionality to previously challenging environments such as steel-reinforced structures and areas with substantial electromagnetic activity. Multi-sensor calibration approaches have demonstrated particular promise in addressing these limitations.

Feedback Systems

Closed-loop control systems rely on sophisticated feedback mechanisms to maintain precise control over robotic movement and interaction. Advanced encoder technologies have demonstrated remarkable improvements in position tracking accuracy while simultaneously reducing form factors and power requirements. Recent biomimetically-inspired designs have introduced novel approaches to positional sensing that offer improved resilience to environmental contaminants common in field robotics applications.

Force and torque sensing technologies have evolved substantially, with multi-axis sensors providing comprehensive contact force information that enables increasingly sophisticated interaction capabilities. Miniaturization trends have facilitated integration into compact joint structures without compromising measurement range or precision. These advances have expanded the range of manipulation tasks accessible to robotic systems, particularly in contexts requiring delicate handling of fragile objects.

Tactile sensing represents a particularly dynamic area of development, with recent soft biomimetic sensors demonstrating exceptional performance in complex manipulation tasks [6]. These systems combine high spatial resolution with remarkable sensitivity to both normal and shear forces—a critical capability for secure grasping and manipulation. Contemporary implementations utilize marker-tracking approaches to measure deformation within the sensor structure, providing rich tactile information that enables slip prediction, edge detection, and texture discrimination. These capabilities have been validated through extensive testing across diverse object sets, demonstrating significant improvements in grasp stability and manipulation precision compared to conventional approaches.

Sensor Type	Range	Precision	Speed	Cost	Power	Main Use
LiDAR	High (100m+)	Excellent	Medium (20Hz)	Expensive	Moderate	Navigation, Mapping
RGB Camera	Medium (50m)	Excellent	High (60fps)	Cheap	Low	Object Recognition
IMU	None	Good	Very High (1kHz)	Very Cheap	Very Low	Motion Sensing
Force/Torque	Contact Only	Excellent	Very High (1kHz)	Moderate	Low	Manipulation
Thermal Camera	Medium (25m)	Fair	Medium (30Hz)	Expensive	Moderate	Night Vision

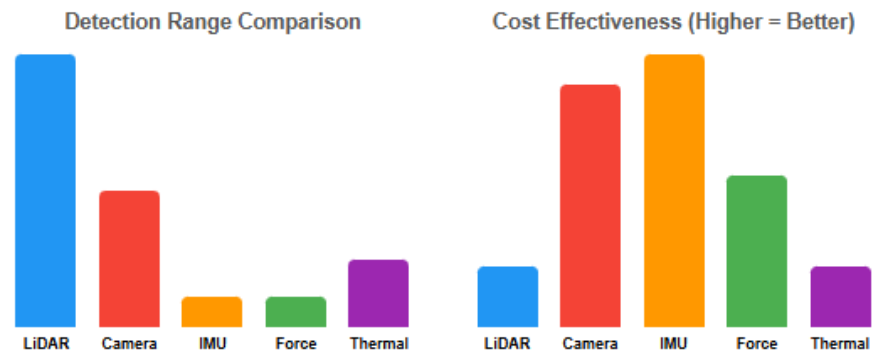


Fig. 2: Comparative Performance of Tactile Sensing Technologies in Robotic Applications [5, 6]

Real-time Processing Challenges and Solutions

Computational Requirements

The processing of multimodal sensor data presents significant computational challenges in contemporary robotics. Autonomous mobile robots typically integrate multiple sensing modalities including stereo cameras, LiDAR, ultrasonic sensors, and inertial measurement units to develop comprehensive environmental awareness. This sensor fusion approach enables enhanced perception capabilities but demands substantial computational resources for real-time operation. Recent studies reveal that effective navigation in dynamic environments requires processing and integrating data from at least five distinct sensor types operating at different sampling rates [7]. This heterogeneous sensing architecture creates unique computational demands that conventional processing approaches struggle to address efficiently. Parallel processing architectures have emerged as the dominant approach for high-performance robotic systems. The integration of specialized hardware acceleration units enables simultaneous processing of visual, ranging, and positioning data streams while maintaining real-time performance constraints.

Contemporary robotics platforms utilize hierarchical processing approaches that distribute computational tasks across multiple specialized processors, with dedicated units handling low-level sensor processing while more powerful systems manage higher-level perception and planning functions. This architectural approach maximizes processing efficiency while ensuring critical safety functions receive appropriate computational priority.

Edge computing paradigms have transformed how sensing data flows through robotic systems. By performing initial processing directly at sensor nodes, these architectures dramatically reduce transmission bandwidth requirements while simultaneously decreasing response latency for critical functions. Modern implementations demonstrate that edge processing can reduce central computational requirements by over 40% while simultaneously improving system robustness by maintaining basic functionality even when communication links degrade. This distributed approach has proven particularly valuable for autonomous mobile robots operating in challenging environments such as logistics warehouses, where reliable navigation must continue despite potential communication interference.

Latency management remains a critical challenge, particularly for multi-sensor systems with varying acquisition and processing characteristics. Synchronization of data from sensors with fundamentally different sampling rates requires sophisticated timing systems that accommodate both hardware and software-level constraints. Recent implementations utilize timestamp-based fusion approaches that maintain temporal consistency across sensor modalities, ensuring that environmental representations remain coherent even as robots navigate through complex, dynamic settings. These synchronization technologies represent a critical enabling capability for reliable operation in unstructured environments.

Advanced Algorithms

Software solutions that efficiently process sensor data have evolved dramatically to address the increasing complexity of robotic perception systems. Motion-based calibration frameworks have emerged as particularly valuable for maintaining sensor alignment during extended operations [8]. These approaches leverage natural robot movement to continuously refine the spatial relationships between sensing modalities, eliminating the need for specialized calibration equipment or procedures. By analyzing correlations between motion measurements from different sensor types, these systems can detect and compensate for gradual alignment shifts caused by vibration, thermal expansion, or mechanical wear. This capability proves especially valuable for robots operating in industrial environments where extended operation without manual recalibration represents a significant operational advantage.

Data filtering and noise reduction algorithms remain fundamental for extracting reliable signals from inherently noisy sensor data. Multi-stage filtering approaches demonstrably improve perception reliability in challenging conditions, including variable lighting, reflective surfaces, and electromagnetic interference. Contemporary implementations utilize contextual filtering techniques that dynamically adjust processing parameters based on operating environment, enhancing performance across diverse conditions without

Publication of the European Centre for Research Training and Development -UK requiring manual reconfiguration. These adaptive approaches significantly improve robustness in real-world deployment scenarios.

Machine learning approaches increasingly complement or replace traditional algorithms for sensor processing and fusion. Deep neural networks specialized for multimodal sensor fusion demonstrate remarkable improvements in obstacle detection and classification performance compared to conventional algorithmic approaches. These learning-based systems excel particularly in ambiguous scenarios where individual sensor modalities provide conflicting or incomplete information. The integration of continuous learning capabilities enables robots to progressively refine their perception systems through operational experience, gradually enhancing performance without requiring explicit reprogramming. This adaptability represents a fundamental advancement for long-term autonomous operation in complex environments.

Motion-Based Calibration Framework for Multimodal Sensor Arrays

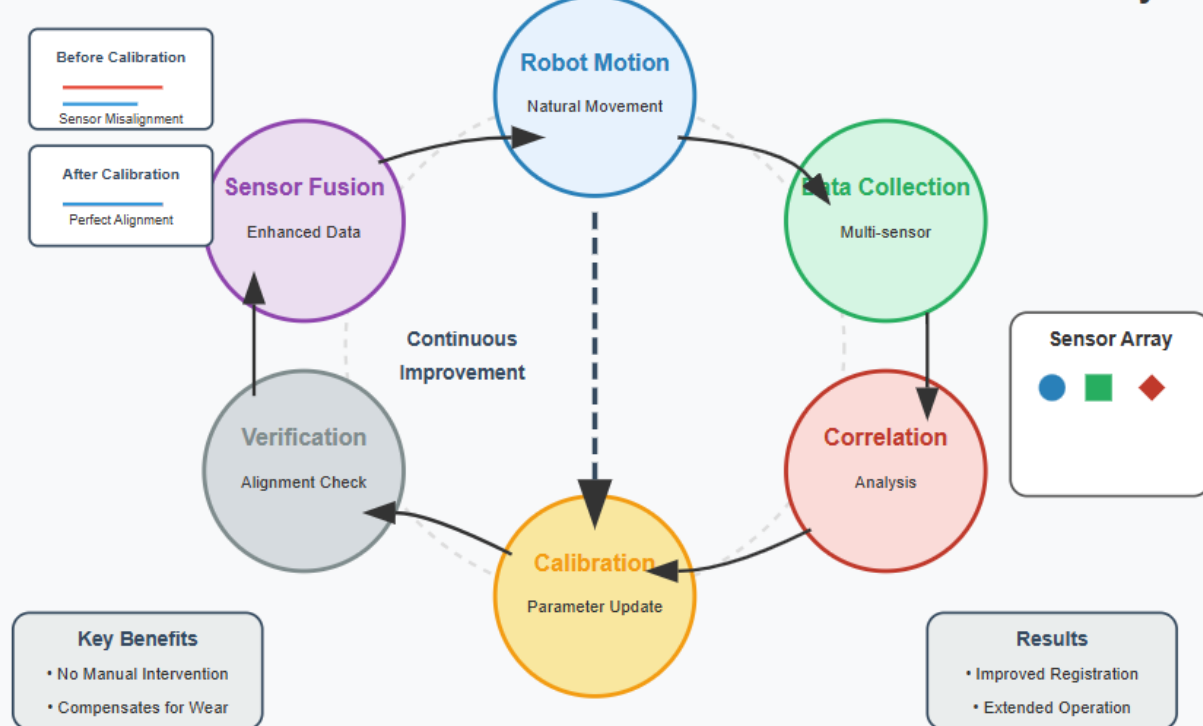


Fig. 3: Motion-Based Calibration Framework for Multimodal Sensor Arrays [7, 8]

Future Directions and Emerging Technologies

Miniaturization and Energy Efficiency

The trend toward miniaturization and improved energy efficiency represents a critical advancement in sensing technologies for robotics. Recent developments in MEMS sensor technology have achieved unprecedented size reductions while simultaneously enhancing performance characteristics. Next-

generation inertial measurement units now incorporate multi-axis sensing in packages smaller than conventional single-axis implementations from just a few years ago [9]. These advancements enable substantially higher sensing density in compact robotic platforms without exceeding power or space constraints. The integration of these miniaturized components has transformed wearable and compact robotic implementations, enabling deployment in previously inaccessible environments.

Energy efficiency improvements have dramatically extended operational capabilities for battery-powered robotic systems. Contemporary sensor implementations feature sophisticated power management architectures that dynamically adjust sampling rates and resolution based on detected activity levels. This contextual awareness enables dramatic power savings during periods of limited movement while maintaining high-fidelity data acquisition during dynamic operation. The combination of reduced static power consumption and intelligent operation has substantially extended deployment durations for autonomous systems operating in remote or hazardous environments where charging infrastructure remains limited.

The miniaturization trend has proven particularly valuable for micro-robotic systems operating in confined spaces. Inspection robots navigating through industrial infrastructure can now incorporate comprehensive sensing arrays despite severe volume constraints. These capabilities have transformed maintenance procedures for critical infrastructure, enabling condition monitoring without system disassembly or operational interruption. Similar approaches have demonstrated significant promise for medical applications, where miniaturized sensing enables minimally invasive diagnostic and therapeutic interventions. The convergence of miniaturization and efficiency improvements continues to expand the application scope for robotic systems across diverse domains.

Neuromorphic Sensing

Bio-inspired sensing approaches increasingly transform robotics perception capabilities through fundamentally different operational paradigms. Event-based vision sensors represent a significant departure from conventional frame-based cameras, adopting an asynchronous operational model inspired by biological visual systems [10]. Rather than capturing complete frames at predetermined intervals, these sensors generate data only when individual pixels detect local brightness changes, dramatically reducing redundant information transmission. This approach offers particular advantages in dynamic environments, where conventional cameras struggle with motion blur and limited temporal resolution.

The computational efficiency advantages of neuromorphic sensing extend beyond data reduction. The sparse, event-driven nature of the information aligns naturally with emerging processing architectures, enabling sophisticated perception with minimal latency and power consumption. Mobile robotic platforms have demonstrated substantial endurance improvements when implementing these approaches, with perception systems consuming a fraction of the power required by conventional implementations. This efficiency proves particularly valuable for deployments where processing resources and power availability remain constrained.

Artificial skin technologies have similarly benefited from neuromorphic principles, with current implementations focusing on information-driven transmission rather than continuous sampling. These approaches enable tactile sensing across large surface areas without overwhelming communication and processing systems. The distributed, event-driven architecture mirrors biological systems where peripheral sensing elements perform preliminary filtering and feature extraction before transmission to central processing. Implementation of these principles has demonstrated substantial improvements in both sensing performance and system scalability.

Integrated Sensor-Actuator Systems

Emerging technologies increasingly blur the traditional boundaries between sensing and actuation components. Soft robotics approaches have proven particularly amenable to this integration, with flexible sensors embedded directly within deformable actuators. This architectural convergence enables continuous monitoring of actuator configuration without additional mechanical complexity. The resulting systems demonstrate enhanced control precision through continuous feedback while simultaneously reducing component count and connection points—factors that traditionally limit long-term reliability in dynamic robotic systems.

Self-sensing actuators incorporate measurement capabilities directly within the drive mechanism, enabling position, force, and temperature monitoring without separate sensor elements. These integrated approaches substantially reduce system complexity while improving control bandwidth through reduced signal propagation and processing delays. The resulting systems demonstrate enhanced dynamic performance while simultaneously reducing size, weight, and manufacturing complexity. Integration of sensing and actuation appears particularly promising for collaborative robotic systems, where comprehensive force and position awareness enables safe operation alongside human workers without additional sensing infrastructure.

Sensor Miniaturization and Energy Efficiency Trends in Robotics

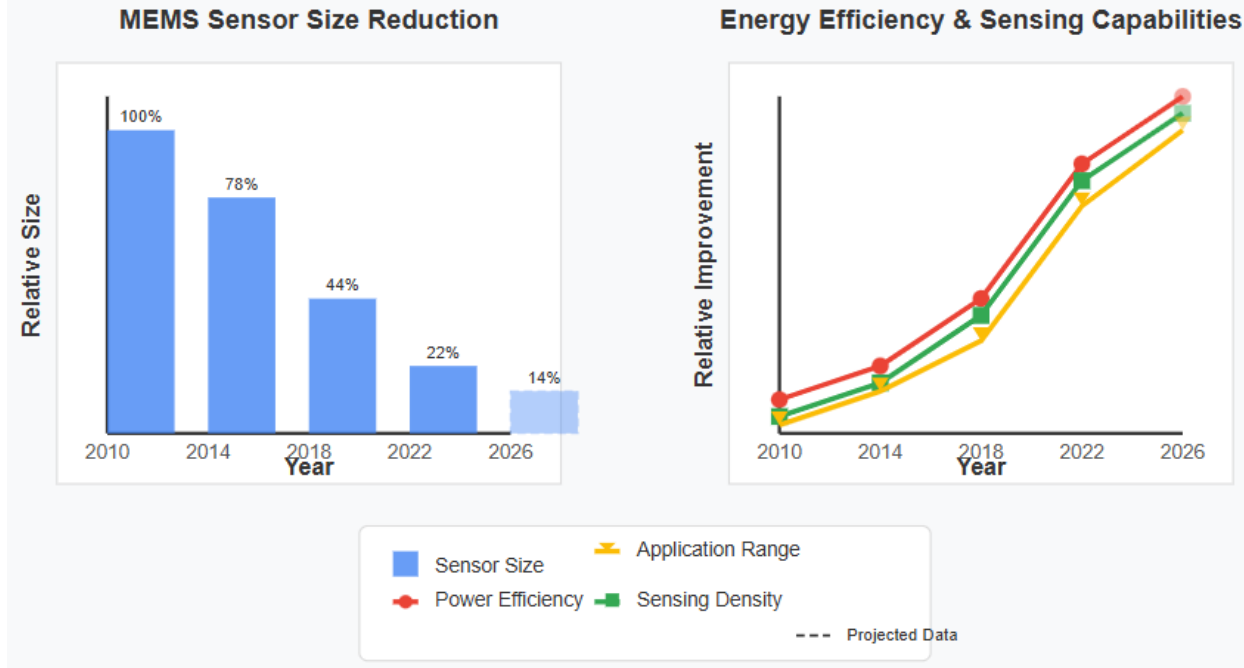


Fig. 4: Sensor Miniaturization and Energy Efficiency Trends in Robotics [9, 10]

Conclusion

The evolution of sensing technologies for robotics represents a critical enabler for autonomous systems operating in unstructured environments. The progression from single-sensor implementations to comprehensive multimodal sensor arrays has dramatically expanded robotic capabilities across industrial, service, and exploratory applications. Current sensing architectures leverage the complementary strengths of diverse modality types while mitigating individual weaknesses through sophisticated fusion methodologies. These integrated perceptual systems provide robots with unprecedented environmental awareness, enabling operations in conditions that would challenge even human perception. The continued advancement of motion sensing and proprioceptive feedback mechanisms further enhances robotic mobility and manipulation precision. Looking forward, the convergence of multiple technological trends—miniaturization, energy efficiency, neuromorphic processing, and integrated sensor-actuator systems—points toward increasingly capable yet compact robotic platforms. These developments will continue dissolving the traditional boundaries between sensing and actuation while simultaneously reducing system complexity and improving reliability. The resulting autonomous systems will extend robotic capabilities into previously inaccessible domains, enabling transformative applications across healthcare, infrastructure monitoring, precision manufacturing, and environmental stewardship. As these sensing technologies

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mature, the gap between controlled laboratory demonstrations and robust real-world deployment will continue narrowing, accelerating the integration of advanced robotics into everyday contexts.

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