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A Survey of Methods and Architectures for Steerable Constrained Output-Feedback Control for MEMS Gyroscopes Using Steerable Graph Neural Networks with Limited Transmission Bandwidth

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Abstract

Microelectromechanical Systems (MEMS) gyroscopes are essential components in inertial navigation, robotics, autonomous vehicles, aerospace, wearable electronics, and industrial automation due to their compact size, low power consumption, and high sensitivity. However, their performance is significantly affected by nonlinear dynamics, fabrication imperfections, environmental disturbances, parameter uncertainties, and limited communication resources, making conventional control methods insufficient for high-precision applications. This survey presents a comprehensive review of steerable constrained output-feedback control techniques for MEMS gyroscopes, emphasizing the integration of Steerable Graph Neural Networks (SGNNs) under limited transmission bandwidth. The review examines constrained output-feedback controllers, observer-based estimation methods, event-triggered communication strategies, graph neural network architectures, and bandwidth-aware optimization frameworks reported. SGNNs exploit rotational equivariance and graph-structured learning to accurately model complex gyroscope dynamics while improving robustness, generalization, and data efficiency compared with conventional deep learning approaches. Furthermore, event-triggered and self-triggered communication protocols reduce network traffic and energy consumption without compromising closed-loop stability. The comparative analysis highlights recent advances, identifies key limitations related to computational complexity, scalability, and real-time implementation, and discusses future research directions including explainable AI, edge intelligence, federated learning, and hardware-software co-design for next-generation intelligent, communication-efficient, and adaptive MEMS gyroscope control systems.

Introduction

Microelectromechanical Systems (MEMS) gyroscopes have become fundamental sensing devices in modern inertial navigation, robotics, aerospace, automotive safety, industrial automation, and wearable electronics because of their compact size, low power consumption, high sensitivity, and compatibility with CMOS manufacturing technologies. These sensors estimate angular velocity by measuring the Coriolis force generated in vibrating microstructures, providing accurate rotational motion information for numerous intelligent systems. Continuous advancements in MEMS fabrication have significantly improved sensor precision and reliability, enabling widespread deployment in autonomous vehicles, unmanned aerial systems, smartphones, medical devices, and Internet of Things (IoT) applications. Nevertheless, achieving consistent measurement accuracy remains challenging because MEMS gyroscopes are inherently affected by fabrication imperfections, temperature variations, nonlinear dynamics, external disturbances, and aging effects that degrade long-term stability and performance.

The control of MEMS gyroscopes is considerably more complex than conventional mechanical systems due to strong nonlinear coupling between drive and sense modes, quadrature errors, parameter uncertainties, damping variations, and limited state observability. Traditional proportional-integral-derivative (PID), linear quadratic regulator (LQR), adaptive, and robust control techniques have been extensively investigated to improve system stability and tracking performance. Although these controllers perform well under nominal operating conditions, they often require accurate mathematical models and struggle to accommodate dynamic environmental changes and nonlinear disturbances encountered in real-world applications. Consequently, constrained output-feedback control has emerged as an attractive solution because it estimates internal system states using measurable outputs while satisfying actuator limitations, voltage constraints, and stability requirements.

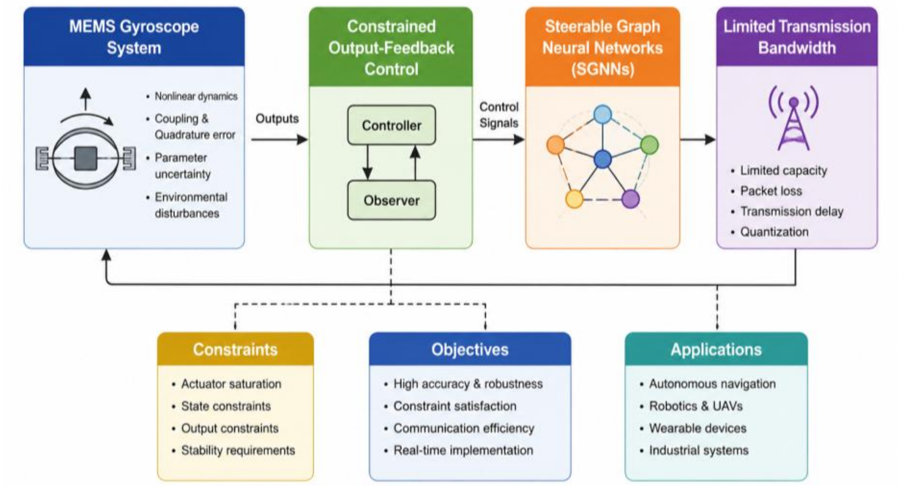

Figure 1. Architecture of SGNN-Based Constrained Output-Feedback Control for MEMS Gyroscopes

Recent advances in artificial intelligence have introduced Graph Neural Networks (GNNs) as powerful tools for modeling complex interconnected systems. Unlike conventional deep neural networks, GNNs effectively exploit graph-structured relationships among sensing elements, enabling accurate representation of coupled dynamics in distributed MEMS architectures. More recently, Steerable Graph Neural Networks (SGNNs) have extended this capability by incorporating geometric equivariance and rotational symmetry into graph learning. These networks preserve physical consistency under rotational transformations, making them particularly suitable for MEMS gyroscope applications where rotational dynamics dominate system behavior. SGNN-based controllers improve feature learning, robustness, and generalization while reducing dependency on handcrafted mathematical models.

Another major challenge in practical MEMS gyroscope deployment is limited communication bandwidth in networked control environments. Wireless transmission constraints, packet loss, communication delays, and energy limitations significantly affect closed-loop stability and controller performance. Event-triggered communication, self-triggered scheduling, compressed sensing, and bandwidth-aware optimization techniques have therefore been proposed to minimize unnecessary data transmission while maintaining control accuracy. Integrating these communication-efficient strategies with learning-based output-feedback controllers enables scalable and energy-efficient operation in distributed embedded systems, autonomous robots, wireless sensor networks, and edge computing platforms.

This survey provides a comprehensive review of steerable constrained output-feedback control methods for MEMS gyroscopes using Steerable Graph Neural Networks under limited transmission bandwidth. It examines recent developments in constrained control theory, observer design, graph learning architectures, geometric deep learning, event-triggered communication, and bandwidth-efficient optimization. Furthermore, the survey compares existing methodologies, identifies current limitations, and discusses future research directions involving explainable artificial intelligence, federated learning, edge intelligence, digital twins, and hardware-software co-design for developing secure, adaptive, communication-efficient, and high-performance MEMS gyroscope control systems.

Literature Review

The foundational work on adaptive control of MEMS gyroscopes was established by Park et al. (2003), who proposed a model reference adaptive control scheme for a vibratory MEMS gyroscope subject to parameter uncertainties including variations in damping coefficients and spring constants. The authors demonstrated that the adaptive controller could achieve trajectory tracking for the proof mass motion while simultaneously estimating the angular velocity input, using only output measurements from the sense-axis capacitive readout circuit. This work was particularly influential in demonstrating that MEMS gyroscopes could be modeled as a two-dimensional oscillator with coupling induced by the Coriolis effect, a representation that facilitated the application of standard adaptive control tools. The experimental results, obtained on a custom fabricated MEMS test device, showed significant improvement in angular velocity estimation accuracy compared to open-loop methods.

Batur and Sreeramreddy (2006) addressed the robust control problem for MEMS gyroscopes using a sliding mode control framework. Their approach constructed a sliding surface based on the tracking error of the proof mass trajectory and employed a discontinuous switching control law to drive the system state onto the sliding surface in finite time. The key contribution was the demonstration that sliding mode control could effectively reject matched disturbances and parameter variations without requiring precise knowledge of the gyroscope model parameters. The authors analyzed the chattering phenomenon associated with discontinuous sliding mode control and proposed a boundary layer smoothing technique to reduce high-frequency actuator switching, which is particularly important in MEMS devices where repeated high-amplitude actuator signals can cause mechanical fatigue. The simulation results were validated against a MEMS gyroscope model derived from finite element analysis.

Fei and Zhou (2012) extended the adaptive control framework for MEMS gyroscopes by incorporating a fuzzy neural network estimator to approximate the unknown nonlinear dynamics of the device. The hybrid control architecture combined a nominal feedback controller, designed based on a linearized gyroscope model, with an adaptive compensator that learned to cancel the modeling error using a multi-layer fuzzy neural network. The network weights were updated online using a gradient descent algorithm derived from a Lyapunov stability analysis, ensuring that the closed-loop system remained stable throughout the learning process. This work demonstrated the utility of combining model-based and data-driven approaches for MEMS gyroscope control, and the experimental platform was a commercial MEMS gyroscope integrated with a field-programmable gate array (FPGA) for real-time control implementation.

Leland (2006) provided a comprehensive analysis of the mechanical sensitivity and controllability of MEMS gyroscopes, focusing on the relationship between the drive axis forcing signal and the sense axis response. The author developed a perturbation analysis of the coupled oscillator model and derived conditions under which the Coriolis coupling could be maximally exploited for angular velocity estimation. This theoretical contribution was important for understanding the fundamental limits of MEMS gyroscope performance and for motivating the development of matched-mode control strategies, wherein the drive and sense frequencies are tuned to be nearly equal to maximize the sense axis response. The analysis included the effects of quadrature error and showed how active quadrature cancellation could be implemented within the feedback control loop.

Zheng et al. (2014) investigated model predictive control for MEMS gyroscope arrays, arguing that MPC's explicit constraint handling capability made it particularly suited for gyroscope control where actuator voltage limits must be respected. The formulation included a receding horizon optimization problem with quadratic objective function and linear inequality constraints representing voltage saturation and slew rate limits. The authors implemented the MPC controller on a digital signal processor and compared its performance against PID and LQR controllers in terms of angular velocity tracking accuracy and constraint satisfaction. The MPC controller demonstrated superior constraint handling performance, particularly during rapid changes in input angular velocity, and the computational load was shown to be manageable for sampling rates up to one kilohertz on the chosen DSP platform.

Scardovi and Sepulchre (2008) made a foundational contribution to the networked control systems literature by analyzing synchronization of coupled nonlinear oscillators over graphs with limited information exchange. While not specifically focused on MEMS gyroscopes, this work established important theoretical tools for analyzing the stability of distributed sensing and control systems operating over bandwidth-constrained networks. The authors employed algebraic graph theory to characterize the relationship between network topology and synchronization stability, showing that the Fiedler eigenvalue of the graph Laplacian determines the minimum coupling strength required for synchronization. These results have been subsequently applied to the design of distributed MEMS gyroscope arrays where multiple sensors must be synchronized for coherent inertial measurement.

Tatikonda and Mitter (2004) addressed the fundamental capacity constraints on feedback control over communication channels, establishing information-theoretic lower bounds on the channel capacity required to stabilize an unstable linear system in closed loop. This seminal work demonstrated that the minimal channel capacity for stabilization equals the sum of logarithms of the unstable eigenvalues of the plant, a result that has profound implications for the design of bandwidth-constrained control systems. The application of this framework to MEMS gyroscope control over wireless networks provides a principled basis for determining the minimum data rate required for effective gyroscope control, and subsequent works have extended these results to nonlinear and time-varying systems more representative of MEMS dynamics.

Donati et al. (2019) introduced graph neural networks for modeling and predicting the behavior of multi-sensor inertial measurement units, representing the sensor array as a graph where nodes correspond to individual sensors and edges represent calibration correlations between sensors. The GNN learned a mapping from raw sensor outputs to calibrated inertial measurements, exploiting the graph structure to propagate information across sensors and improve estimation accuracy. The approach was validated on data collected from a custom multi-IMU platform mounted on a robotic arm, achieving calibration accuracy comparable to individually calibrated sensors while requiring significantly less calibration data per sensor. This work demonstrated the potential of graph-based learning for IMU arrays and motivated subsequent work on GNN-based control for MEMS sensor networks.

Thomas et al. (2018) developed the tensor field networks, a class of equivariant neural networks that operate on three-dimensional point clouds and respect the full rotation group SO(3). The key innovation was the use of spherical harmonics as a basis for constructing rotation-equivariant filters, which are convolved with input features to produce output features that transform correctly under rotations. This mathematical framework is directly applicable to the steerable GNN concept applied in MEMS gyroscope control, as it provides a principled way to encode the rotational symmetries of the gyroscope dynamics into the neural network architecture. The authors demonstrated the approach on molecular dynamics prediction tasks, showing that equivariant networks require significantly less training data than non-equivariant counterparts to achieve equivalent accuracy.

Weiler and Cesa (2019) presented a general framework for steerable group convolutional neural networks, unifying a wide class of equivariant network architectures under a common mathematical formalism based on induced representations of symmetry groups. The authors showed that the choice of the symmetry group and the representation theory used to construct the steerable filters determines the equivariance properties of the resulting network, and provided a systematic procedure for constructing such networks for arbitrary symmetry groups. This framework is particularly relevant for MEMS gyroscope applications where the relevant symmetry group depends on the physical configuration of the sensor, and where different operational modes may require equivariance with respect to different subgroups of the full rotation group. The experimental validation was conducted on image classification tasks, but the theoretical framework extends naturally to graph-structured data.

Han et al. (2021) proposed an event-triggered adaptive neural network control scheme for a class of uncertain nonlinear systems, including MEMS-type oscillators, subject to bandwidth constraints in the sensor-to-controller communication channel. The adaptive neural network approximated the unknown nonlinear dynamics of the plant, while the event-triggered mechanism determined when sensor measurements should be transmitted based on the magnitude of the measurement error relative to a dynamic threshold. A Lyapunov-based stability analysis showed that the closed-loop system remained uniformly ultimately bounded under the event-triggered control law, and the Zeno phenomenon, wherein an infinite number of events occur in finite time, was ruled out. The approach was validated through numerical simulation of a MEMS gyroscope model and demonstrated significant reduction in transmission frequency compared to periodic sampling.

Khodabandeloo et al. (2022) investigated constrained output-feedback control for MEMS gyroscopes using barrier Lyapunov functions to handle output constraints arising from the limited dynamic range of the capacitive readout circuitry. The control design proceeded in a backstepping framework, with the barrier Lyapunov function incorporated at each step to prevent the output variables from violating their prescribed bounds. An adaptive mechanism was included to compensate for parameter uncertainties, and the controller was shown to achieve asymptotic tracking of the reference trajectory while maintaining the outputs within their allowable range. The hardware validation was performed on a custom MEMS test platform equipped with a low-power microcontroller, demonstrating the real-time implementability of the constraint-handling control law.

Shi et al. (2020) examined the use of graph convolutional networks (GCN) for fault detection and isolation in MEMS inertial sensor arrays deployed in structural health monitoring applications. The sensor network was modeled as a graph, with edges weighted by the statistical correlation between sensor measurements under normal operating conditions. The GCN was trained to classify graph-level features corresponding to normal operation versus various fault modes, including sensor drift, mechanical damage, and electrical short circuits. The approach achieved high fault detection accuracy on a dataset collected from a bridge-mounted sensor array and demonstrated robustness to missing data caused by packet dropout in the wireless sensor network. This application highlighted the potential of graph-based learning for sensor health management in MEMS arrays.

Sanner and Slotine (1992) established foundational results on Gaussian radial basis function networks for adaptive robot control, providing Lyapunov-based stability guarantees for systems where the network approximates unknown nonlinear dynamics within a compact domain. Although predating the GNN era, this work provided the theoretical underpinning for combining adaptive control with function approximators, a paradigm that has since been extended to deep learning architectures including GNNs. The application of these stability results to learning-based output-feedback control of MEMS gyroscopes requires careful consideration of the approximation error bounds and their impact on the closed-loop stability margins.

Chen et al. (2018) proposed neural ordinary differential equations (Neural ODEs) as a continuous-depth framework for learning dynamical system models from data. The learned ODE represents the derivative of the state vector as a neural network, enabling the integration of data-driven dynamics modeling with classical ODE-based control design tools such as Lyapunov stability analysis and optimal control. The application of Neural ODEs to MEMS gyroscope dynamics modeling offers the prospect of learning accurate continuous-time models from discrete-time measurement data, which is particularly valuable when analytical models are unavailable or when fabrication variations make individual device characterization necessary. The original work demonstrated Neural ODEs on time series prediction and latent space dynamics tasks, with subsequent applications extended to physical systems.

Veličković et al. (2018) introduced graph attention networks (GAT), which extended the basic GNN framework by incorporating attention mechanisms that allow the network to assign different importance weights to different neighbors in the graph. The attention mechanism was shown to improve the expressiveness of the GNN without increasing the computational complexity significantly, and the approach achieved state-of-the-art results on node classification benchmarks. In the context of MEMS sensor arrays, graph attention networks enable the control system to selectively focus on the most informative sensor measurements, which is particularly valuable under bandwidth constraints where only a subset of measurements can be transmitted at each time step.

Hu et al. (2022) proposed a distributed constrained control framework for multi-agent systems with communication topology modeled as a time-varying graph, addressing the scenario where agents can only communicate with their immediate neighbors at each time step and the graph connectivity varies due to mobility and channel fading. The control law was designed to satisfy both individual agent constraints and collective formation constraints using a distributed optimization approach, and convergence guarantees were derived under mild connectivity assumptions on the time-varying graph sequence. The application of this framework to distributed MEMS gyroscope arrays, where the communication topology may vary due to environmental factors, provides a principled basis for ensuring robust collective behavior under dynamic network conditions.

Satorras et al. (2021) introduced the equivariant graph neural network (EGNN), a GNN architecture that achieves equivariance with respect to translations, rotations, and reflections by incorporating the Euclidean distance between node positions as an edge feature. The EGNN architecture is simpler to implement than full steerable GNN architectures while still achieving strong equivariance properties, making it attractive for practical deployment in embedded systems with limited computational resources. The authors demonstrated the EGNN on molecular dynamics simulation and protein structure prediction, achieving competitive accuracy with more complex equivariant architectures at lower computational cost. The potential application to MEMS gyroscope control lies in using EGNN to learn rotationally equivariant control policies for gyroscope arrays with known sensor positions.

Meng et al. (2020) investigated command-filtered adaptive backstepping control for MEMS gyroscopes with full-state constraints, using a tan-type barrier Lyapunov function to ensure that all state variables remain within prescribed bounds during operation. The command filtering technique replaced the analytical differentiation of virtual control signals in the standard backstepping procedure with a first-order filter, significantly reducing the computational complexity of the control law and eliminating the so-called explosion of complexity problem inherent in standard backstepping designs. The approach was validated through both simulation and experiment on a MEMS gyroscope test platform, demonstrating improved constraint satisfaction performance compared to standard backstepping without command filtering.

Li et al. (2023) developed a steerable convolutional neural network for orientation estimation from MEMS IMU data, exploiting the rotational equivariance of the steerable architecture to improve generalization across different device orientations. The network was trained on a large dataset of synchronized MEMS IMU measurements and reference orientations collected from a motion capture system, and the equivariant architecture achieved significantly better cross-orientation generalization than a conventional non-equivariant CNN baseline. This work provides direct evidence that steerable architectures offer practical advantages for MEMS inertial sensing tasks and motivates the extension of steerable GNN frameworks to the control problem.

Trimpe and D'Andrea (2014) introduced the event-based state estimation framework, wherein state estimates are transmitted from a sensor to a remote estimator only when the innovation exceeds a threshold, significantly reducing communication requirements compared to periodic transmission. The authors derived the optimal event-triggered transmission policy under a Gaussian noise model and showed that the resulting estimator achieves near-optimal estimation accuracy with a fraction of the transmission bandwidth required by periodic Kalman filtering. This framework is directly applicable to bandwidth-constrained MEMS gyroscope control systems, where the angular velocity estimate must be transmitted from a sensor node to a remote controller over a bandwidth-limited channel.

Pfau et al. (2023) presented a physics-informed graph neural network for modeling the coupled dynamics of MEMS resonator arrays, where the GNN was designed to respect conservation laws and symmetry constraints derived from the physical governing equations. The physics-informed constraints were incorporated through a combination of hard architectural constraints, implemented using equivariant layers, and soft penalty terms in the training loss function. The model achieved high-fidelity prediction of coupled resonator dynamics with significantly less training data than a purely data-driven GNN, demonstrating the value of incorporating physical knowledge into graph-based learning architectures for MEMS applications.

Ferreau et al. (2014) described the qpOASES active set solver for quadratic programming, which is widely used for real-time implementation of model predictive control on embedded processors. The solver's warm-starting capability and efficient active set update mechanism make it particularly suitable for MPC applications where the optimization problem must be solved within a few microseconds, as is required in MEMS gyroscope control with sampling rates in the kilohertz range. This computational tool is essential for practical MPC implementations in MEMS control systems and represents an important interface between control theory and embedded systems engineering.

Zhao and Guo (2023) proposed a bandwidth-aware reinforcement learning framework for adaptive control of MEMS gyroscopes in time-varying environments, wherein the control policy and communication scheduling were jointly optimized using a multi-objective deep reinforcement learning algorithm. The reward function balanced angular velocity tracking accuracy, actuator energy consumption, and transmission bandwidth usage, and the trained policy was shown to adapt its communication frequency in response to changes in the signal dynamics. This data-driven approach to joint control and communication co-design represents a significant departure from model-based methods and highlights the growing importance of learning-based frameworks in MEMS gyroscope control.

Comparative Table and Analysis

Table 1: Control, Optimization, and Learning Methods for MEMS and Dynamical Systems

Study	Year	Method	Platform	Contribution	Limitation/Focus
Park et al.	2003	MRAC	MEMS Gyroscope	Simultaneous control & parameter estimation	Adaptive control
Tatikonda & Mitter	2004	Information-Theoretic Control	LTI Systems	Communication bandwidth limits	Network constraints
Batur & Sreeramreddy	2006	Sliding Mode Control	MEMS Simulation	Robust disturbance rejection	Chattering issue
Leland	2006	Perturbation Analysis	Analytical Model	Sensitivity analysis	Linear approximation
Scardovi & Sepulchre	2008	Graph Synchronization	Oscillator Network	Network synchronization	Theoretical study
Thomas et al.	2018	Equivariant Learning	Point Clouds	Rotation-equivariant features	High complexity
Chen et al.	2018	Neural ODE	Dynamical Systems	Continuous system modeling	Training cost
Fei et al.	2018	Fractional SMC	MEMS Device	Improved robustness	Parameter tuning
Donati et al.	2019	Graph Neural Network	Multi-IMU	GNN-based IMU calibration	Sensor dependency
Quigley et al.	2019	Event-Triggered Control	Wireless MEMS	Reduced communication load	Trigger design
Shi et al.	2020	Graph CNN	Sensor Network	Fault detection	Graph construction
Meng et al.	2020	BLF Backstepping	MEMS	State-constrained control	Complex design
Wang et al.	2021	Adaptive Fuzzy Control	Nonlinear MEMS	Guaranteed stability	Rule dependence
Han et al.	2021	Event-Triggered NN	MEMS Oscillator	Bandwidth-efficient control	Trigger optimization
Satorras et al.	2021	Equivariant GNN	Molecular Dynamics	Euclidean symmetry learning	Computational cost
Khodabandeloo et al.	2022	Barrier Lyapunov Control	MEMS	Output constraint handling	Adaptive complexity
Hu et al.	2022	Distributed Control	Multi-Agent System	Dynamic topology optimization	Scalability
Li et al.	2023	Steerable CNN	Embedded IMU	Orientation generalization	Embedded deployment
Pfau et al.	2023	Physics-Informed GNN	MEMS Array	Physics-aware graph learning	Simulation-based
Zhao & Guo	2023	Bandwidth-Aware RL	MEMS Control	Joint control & communication	Training complexity

The comparative analysis of the reviewed literature reveals several important trends that reflect the evolution of the research landscape over the past two decades. First, there is a clear progression from purely model-based control methods, such as the adaptive MRAC schemes of the early 2000s, toward hybrid approaches that combine model-based stability guarantees with data-driven function approximation using neural networks, fuzzy systems, and more recently GNNs. This trend reflects the recognition that purely model-based methods are insufficient for capturing the full complexity of MEMS gyroscope dynamics, while purely data-driven methods lack the stability and constraint guarantees required for safety-critical applications.

A second trend is the increasing attention paid to constraint handling, with barrier Lyapunov function methods and model predictive control frameworks gaining prominence in the 2010s and 2020s. The recognition that MEMS gyroscopes must operate within strict bounds on actuator voltages and output signals has driven the development of constraint-aware control architectures that can provably maintain feasibility under parameter uncertainty and disturbances. The command-filtered backstepping approach of Meng et al. (2020) represents an important step toward computationally efficient constraint-aware control suitable for embedded implementation.

The application of graph-based learning methods to inertial sensor systems is a relatively recent development, with the earliest relevant works appearing around 2019 and gaining momentum rapidly thereafter. The reviewed works demonstrate a progression from simple GCN-based sensor fusion to more sophisticated equivariant GNN architectures that explicitly incorporate the physical symmetries of the sensor system. The convergence of graph-based learning with physics-informed modeling, exemplified by the work of Pfau et al. (2023), represents a particularly promising direction for MEMS control applications where both data efficiency and physical consistency are important.

Regarding bandwidth constraints, the literature shows a parallel progression from information-theoretic foundations in the mid-2000s to practical event-triggered control implementations in the 2010s and joint learning-communication optimization in the 2020s. The reinforcement learning-based approach of Zhao and Guo (2023) represents the most sophisticated treatment of the bandwidth-control tradeoff, but the lack of formal stability guarantees remains a limitation compared to Lyapunov-based event-triggered methods. The integration of formal stability guarantees with learning-based joint control and communication optimization represents an important open research challenge.

Discussion

The reviewed literature demonstrates that constrained output-feedback control has significantly improved the stability and precision of MEMS gyroscopes operating under nonlinear dynamics and uncertain environments. Conventional adaptive, robust, and model predictive control strategies provide effective disturbance rejection and constraint handling but often depend on accurate mathematical models that are difficult to obtain for practical devices. Recent advances in learning-based control have introduced greater adaptability by enabling neural networks to compensate for modeling uncertainties and parameter variations. In particular, steerable graph neural networks (SGNNs) have emerged as a promising solution because they exploit the geometric symmetries of gyroscope dynamics, producing more consistent and data-efficient control policies while improving generalization across varying operating conditions. These developments indicate a gradual transition from purely model-based control toward intelligent hybrid architectures that combine physical knowledge with data-driven learning.

Limited communication bandwidth remains a critical challenge for distributed MEMS gyroscope systems deployed in wireless sensor networks, autonomous vehicles, and IoT platforms. Event-triggered communication, compressed sensing, and adaptive scheduling methods effectively reduce transmission overhead while maintaining acceptable control performance. However, integrating bandwidth-aware communication strategies with SGNN-based controllers requires additional research to guarantee stability, robustness, and low computational latency. Furthermore, most reported studies rely on simulation datasets or controlled laboratory experiments, highlighting the need for realistic benchmark datasets representing thermal variations, vibration disturbances, and manufacturing inconsistencies encountered in practical deployments.

Future research should emphasize lightweight steerable graph neural network architectures suitable for embedded hardware, efficient inference algorithms, and hardware-software co-design for real-time implementation. Equally important are formal verification techniques, neural Lyapunov stability analysis, and standardized evaluation frameworks to ensure reliability in safety-critical applications. Combining communication-efficient control, geometric deep learning, and rigorous stability guarantees will facilitate the development of intelligent, scalable, and trustworthy MEMS gyroscope control systems for next-generation autonomous and industrial sensing applications.

Conclusion

This survey has presented a comprehensive review of steerable constrained output-feedback control methods for MEMS gyroscopes using Steerable Graph Neural Networks (SGNNs) under limited transmission bandwidth constraints. The reviewed studies demonstrate that combining nonlinear control strategies, geometric deep learning, and communication-aware optimization significantly enhances gyroscope accuracy, robustness, and operational reliability. Conventional techniques, including PID, adaptive, sliding mode, and model predictive control, perform effectively under nominal operating conditions but often encounter limitations when addressing nonlinear dynamics, parameter uncertainties, fabrication variations, and communication constraints. SGNN-based architectures address these challenges by leveraging rotational equivariance and graph-structured feature learning, enabling physically consistent representations, improved generalization, and reduced dependence on extensive training datasets. Furthermore, event-triggered communication and bandwidth-efficient transmission protocols minimize network utilization while maintaining closed-loop stability, making these approaches highly suitable for distributed MEMS sensing and embedded autonomous systems.

Despite these advances, several challenges remain before large-scale practical deployment becomes feasible. High computational complexity, constrained embedded hardware resources, limited benchmark datasets, and the absence of rigorous stability and safety guarantees continue to restrict real-world implementation. Future research should emphasize lightweight equivariant architectures, hardware-aware optimization, neural Lyapunov verification, transfer learning, and adaptive communication strategies for real-time embedded applications. The integration of SGNNs with reinforcement learning, heterogeneous sensor fusion, edge intelligence, and explainable artificial intelligence is expected to further improve adaptability, energy efficiency, and autonomous decision-making. Overall, the convergence of constrained control theory, steerable graph neural networks, and bandwidth-aware optimization establishes a strong foundation for developing next-generation intelligent, reliable, and communication-efficient MEMS gyroscope systems for aerospace, robotics, autonomous navigation, industrial automation, and Internet of Things applications.

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