International Journal of Education and Social Science Research

ISSN 2581-5148

Vol. 8, Issue.4, July-Aug 2025, page no. 413-428

To cite this article: Adrian C. Okonkwo, Ukala A. N., Eugene Ogbodo and Martin Adrian Thomas (2025). ADAPTIVE DUAL-MODE STEER-BY-WIRE FOR SMART-CITY AND REMOTE OPERATIONS: A COMPACT MECHATRONIC REVIEW WITH A PYTHON SIMULATION FRAMEWORK, International Journal of Education and Social Science Research (IJESSR) 8 (4): 413-428 Article No. 1129, Sub Id 1759

ADAPTIVE DUAL-MODE STEER-BY-WIRE FOR SMART-CITY AND REMOTE OPERATIONS: A COMPACT MECHATRONIC REVIEW WITH A PYTHON SIMULATION FRAMEWORK

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DOI : https://doi.org/10.37500/IJESSR.2025.8429

ABSTRACT

Steer-by-Wire (SbW) eliminates the mechanical steering column, enabling variable steering ratios, active haptic feedback, and seamless handover between human, remote, and automated control—capabilities that are central to smart-city logistics and remote/search-and-rescue (SAR) tasks. This review synthesises post-2020 advances in SbW mechatronics, control, teleoperation, and functional safety, with emphasis on low-cost prototyping and Python-based simulation. The work summarises actuator/gear and sensor choices; compares PID, robust/adaptive (e.g., sliding-mode, MPC), and haptic-feedback schemes; map teleoperation latency/jitter limits and mitigation; and examine ISO 26262 pathways for fail-operational steering when using non-automotive microcontrollers. It further proposes a lightweight, reproducible Python framework (python-control) to model the "bicycle" and higher-DOF vehicles, inject network delays/jitter, and evaluate safety monitors and redundancy. It is argued that dual-mode (manual↔teleop) SbW offers a pragmatic bridge to autonomy for smart-city fleets and SAR scenarios, provided latency budgets, safety cases, and fail-operational designs are validated via model-, software-, and hardware-in-the-loop [1][2][3][5].

KEYWORDS: Steer-by-wire, teleoperation, smart cities, search & rescue, variable steering ratio, haptic feedback, ISO 26262, fail-operational, Python simulation, latency mitigation

INTRODUCTION

Modern urban mobility increasingly depends on software-defined vehicle subsystems that sense, compute, communicate, and actuate with minimal mechanical constraints [19] [20]. Steer-by-Wire (SbW) exemplifies this shift by removing the steering column and replacing it with electromechanical actuation, variable steering ratios, and programmable haptic feedback, enabling compact packaging, better safety, and new human–machine interfaces suited to dense city operations and hazards [1], [2]. Decoupling the handwheel from the road wheels further supports dual-mode operation, where authority can pass between an onboard driver and a remote human operator, a bridge to autonomy for logistics, inspection, and search-and-rescue (SAR) tasks when automated stacks confront uncertainty

[3]. However, the disappearance of the mechanical fallback elevates the importance of fail-operational design, fast fault detection, and ISO 26262 safety cases, particularly at ASIL-D for directional control [4]. At the control level, well-tuned PID remains a workhorse for steering-angle tracking, but urban manoeuvres, tyre nonlinearities, and actuator friction motivate robust and adaptive methods, including sliding-mode and model predictive control with constraints and preview [2], [5]. Parallel progress in haptic rendering delivers road feel and driver cues despite no column, which is critical for precise docking and tight-radius turns in depots and alleyways [2]. Teleoperation hinges on end-to-end latency and jitter; studies quantify budgets and evaluate mitigation such as predictive displays, Smith-type compensation for quasi-constant delays, and waypoint/pose tracking that leaves fast loops onboard while operators issue higher-level intents [6]. To make results accessible and reproducible, this paper consolidates mechatronic and control options, relates them to smart-city and SAR duty cycles, and proposes a lightweight Python framework that models bicycle-to-multi-DOF dynamics, injects measured delay/jitter, and evaluates angle tracking, yaw stability, and safety-monitor KPIs using open libraries [7], validated through open experiments, shared datasets, and public code repositories online.

LITERATURE REVIEW

Steer-by-Wire (SbW) replaces the physical steering column with electromechanical actuation and software-defined feedback, thereby decoupling driver input from road-wheel motion and enabling variable steering ratios (VSR), compact packaging, and programmable haptics [1], [2]. Across the last five years, three strands have matured concurrently. First, *mechatronic realisations* have moved from column/rack-assist to fully decoupled rack actuation, often via compact planetary gearsets that superimpose motor angle on rack displacement to realise speed-dependent VSR while isolating road disturbances from the handwheel [3], [4]. Second, *control stacks* have evolved beyond carefully tuned PID toward robust/adaptive designs (sliding-mode, model-reference adaptive control, and model predictive control) that handle tyre nonlinearities, stick–slip friction, and parameter drift while preserving handwheel feel via torque rendering [2], [5]–[7]. Third, *assurance and safety* have shifted from fail-safe to fail-operational steering, reflecting the absence of a mechanical fallback path; this increases the burden on redundancy (sensors, drives, and compute), real-time diagnostics, and ISO 26262 process evidence at ASIL-D for directional control [8]–[10].

For smart-city fleets and remote/search-and-rescue (SAR) operations, SbW's decoupling is especially advantageous. The ability to tune steering ratio and feedback allows confident low-speed manoeuvres (kerb docking, alley turning, yard shunting) and consistent behaviour across heterogeneous platforms [1], [3]. In contested or hazardous scenes, teleoperation provides a pragmatic bridge when automated stacks face occlusions, degraded vision, or unusual semantics; the literature consolidates end-to-end latency budgets (typically sub-~170 ms for comfortable guidance) and emphasises jitter control as more detrimental than mean delay [11], [12]. Mitigation spans forward-prediction displays, Smith-type delay compensation for near-constant lags, and successive reference-pose tracking where operators send waypoints and the vehicle closes fast inner loops locally [11], [13], [14].

Safety cases for SbW increasingly rely on redundant actuation (dual three-phase PMSMs and dual inverters with cross-monitoring), sensor voting (two-out-of-three angle/torque channels), and independent safety monitors supervising trajectory conformance, handwheel/rack consistency, and heartbeat integrity [9], [10], [15]. In production-intent programmes, these mechanisms are hosted on ASIL-capable microcontrollers (e.g., lockstep cores; ECC memories; clock/supply monitors) [8]. In research prototypes—particularly those aimed at accessibility and low cost—consumer microcontrollers may be used to scope the operational design domain (ODD) tightly while demonstrating software-enforced redundancy, external watchdogs, and proof-of-concept fail-operational behaviours; migration paths to ASIL hardware are then articulated in the safety roadmap [8], [10].

Simulation underpins nearly all recent advances. Lightweight bicycle models remain invaluable for controller synthesis and analytical insight, whereas 7–14-DOF full-vehicle models capture load transfer, suspension compliance, and tyre relaxation, and are routinely exercised to validate VSR strategies and haptic rendering under limit handling [5], [6]. For transparency and reproducibility, the community increasingly favours open Python stacks—notably the *python-control* library—for rapid prototyping of closed-loop behaviour, frequency-domain robustness margins, and Monte-Carlo uncertainty studies; these frameworks can explicitly inject measured delay/jitter, packet loss, and actuation saturation for teleoperation scenarios [16], [17].

Table 1 summarises mechatronic options and their implications for smart-city and SAR duty cycles; ***Table 2*** compares control approaches and typical metrics; ***Table 3*** collates latency mitigation techniques and their reported efficacy.

Table 1 — SbW Mechatronic Options (concise synthesis).

Component	Implementation	Advantages	Smart-City/SAR Relevance	References
Steering Actuators	Direct-drive BLDC motors	Minimal backlash, high bandwidth (>50 Hz), precise angle control (±0.1°)	Essential for precise docking, tight-radius turns in depots and narrow alleyways	[1], [3]
Variable Steering Ratio	Planetary gear superposition with helper motors	Smooth ratio transitions (10:1 to 20:1), speed-adaptive response, disturbance isolation	Low-speed agility for kerb navigation, high-speed stability for urban arterials	[3], [4]

Component	Implementation	Advantages	Smart-City/SAR Relevance	References
Dual-Motor Redundancy	Independent 3-phase PMSMs with cross-monitoring	Single-fault tolerance, fail-operational capability, 99.9% availability	Critical for unmanned SAR operations, reduces single-point-of-failure risk	[9], [10]
Angle/Torque Sensing	High-resolution encoders (>12-bit) with 2oo3 voting	Sub-degree accuracy, real-time fault detection, sensor fusion capability	Precise path following for autonomous depot operations, navigation in GPS-denied environments	[15]
Haptic Feedback	Torque-controlled handwheel actuator	Programmable road feel, speed-dependent weighting, obstacle force feedback	Enhanced operator confidence during remote SAR missions, intuitive vehicle response	[2], [6]
Planetary Gear Systems	Compact epicyclic transmission	Space-efficient, high torque density, mechanical advantage 3:1-5:1	Fits constrained urban vehicle packaging, robust for harsh SAR environments	[3], [4]

Direct-drive rack motors: minimal backlash, higher current density; planetary-gear superposition: compact VSR, superior disturbance isolation; dual-motor racks: inherent actuation redundancy; high-resolution angle/torque sensing with 2oo3 voting; IMU and wheel-speed fusion for robustness [3], [4], [9], [15].

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Table 2 — Control & Haptics Highlights.

Control Method	Structure/Parameters	Performance Metrics	Disturbance Rejection	Implementation Notes	Refs.
PID + Feed-Forward	Kp=5.0, Ki=2.0, Kd=0.5, Anti-windup	Settling time: <1.5s, Overshoot: <15%, SSE: ±0.1°	Moderate; relies on integral action	Baseline approach; well-understood tuning methods	[2]
Integral Sliding Mode	λ=5.0, η=2.0, Boundary layer: 0.1	Settling time: <1.0s, Overshoot: <8%, SSE: ±0.05°	Excellent; invariant to matched disturbances	Robust to friction/deadzone; some chattering	[6]
Model Reference Adaptive	Reference model: 2nd order, γ=10	Tracking error: <0.1° steady-state, Parameter convergence: <3s	Good; adapts to plant changes	Self-tuning capability; requires excitation	[5]
Model Predictive Control	Horizon: Np=10, Nu=3, Constraints active	Constraint satisfaction: 100%, Optimal tracking	Excellent; preview capability	High computational cost; suitable for modern ECUs	[5]
Haptic Torque Mapping	Speed-dependent gains: $K(v) = K_0(1 + \alpha v)$	Natural steering feel, Force feedback: 0-8 Nm	N/A (feedback system)	Essential for remote operations; mimics mechanical systems	[2], [7]
Fuzzy-PID Hybrid	7×7 rule base, Mamdani inference	Adaptive gains, Reduced oscillations	Very good; handles nonlinearities	Real-time tuning; suitable for varying conditions	[6]

PID (+ feed-forward, anti-wind-up) for baseline tracking; integral sliding-mode for disturbance rejection; MRAC/MPC for preview and constraint handling; haptic torque maps blended with speed/μ-estimates to preserve natural feel [2], [5],[7].

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Table 3 — Teleoperation & Delay Mitigation.

Mitigation Technique	Implementation	Delay Tolerance	Jitter Handling	Operator Workload	Technical Maturity	Refs.
Predictive Display	Forward-integrated vehicle model overlay	Up to 200 ms mean delay	Limited; requires stable prediction	Reduced by 30–40%	High; widely deployed	[11]
Smith Predictor	Model-based delay compensation, fixed delay assumption	Up to 150 ms constant delay	Poor; sensitive to delay variation	Moderate; transparent to operator	Medium; requires accurate model	[13]
Successive Reference-Pose Tracking	Waypoint sequence transmission, local trajectory planning	Up to 300 ms with bursts	Excellent; tolerates jitter >50 ms RMS	Low; high-level guidance only	Medium; emerging technique	[12]
Kalman State Observer	Extended KF with delay states, sensor fusion	Up to 250 ms with gaps	Good; statistical filtering	Moderate; provides state estimates	High; well-established theory	[14]
Bilateral Shared Control	Haptic coupling, authority arbitration	Up to 180 ms stable coupling	Moderate; depends on force loop	High; requires training	Low; research prototype	[11]
Adaptive Delay Compensation	Online delay estimation, variable predictor	Variable delays 50–400 ms	Good; tracks delay statistics	Low; automatic adaptation	Low; limited field validation	[13]
Local Safety Monitors	Onboard collision avoidance, emergency stops	Delay-independent	Excellent; local reaction time <50 ms	Very low; autonomous safety	High; production-ready	[10]

Predictive display (operator workload ↓); Smith-type predictors (constant delays); reference-pose/waypoint tracking (jitter-tolerant); Kalman/state observers (sensor/command delay bridging) [11], [13], [14].

Table 4 — Reported end-to-end latency/jitter thresholds for road-vehicle teleoperation.

Study	**Scenario / Stack**	**Reported tolerances**	**Notes**
Hafner et al., 2023 [11]	Survey of road-vehicle teleoperation across lab/field	Predictive display and shared control comfortable to ~150–200 ms mean delay; stability sensitive to jitter	Aggregates multi-platform evidence; emphasises human-factors workload under delay
Chen et al., 2024 [10]	Review of latency/jitter in connected/automated vehicle teleop	Operator performance degrades markedly beyond ~300 ms mean or >50 ms RMS jitter; mitigation via prediction and onboard fast loops	Highlights jitter > mean delay as primary risk driver
Roldán et al., 2023 [12]	Successive reference-pose tracking (waypoint/pose, onboard inner loops)	Tolerant up to ~300 ms with burst losses; robust to >50 ms jitter due to local control	Reduces operator workload; commands are high-level
Park & Kim, 2023 [13]	Smith-predictor delay compensation (fixed delay)	Effective to ~150 ms constant delay; performance drops with variable/jittery links	Requires accurate plant model; sensitive to delay variation

All delays reported are end-to-end unless otherwise stated. See also your technique-level summary in Table 3 (e.g., predictive display ≲200 ms; bilateral shared control ≲180 ms; waypoint/pose tracking ≲300 ms with bursts).

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Conceptual schematics *(Fig. 1)* and a PRISMA-style selection summary *(Fig. 2)* help readers contextualise the design space and the evidence base.

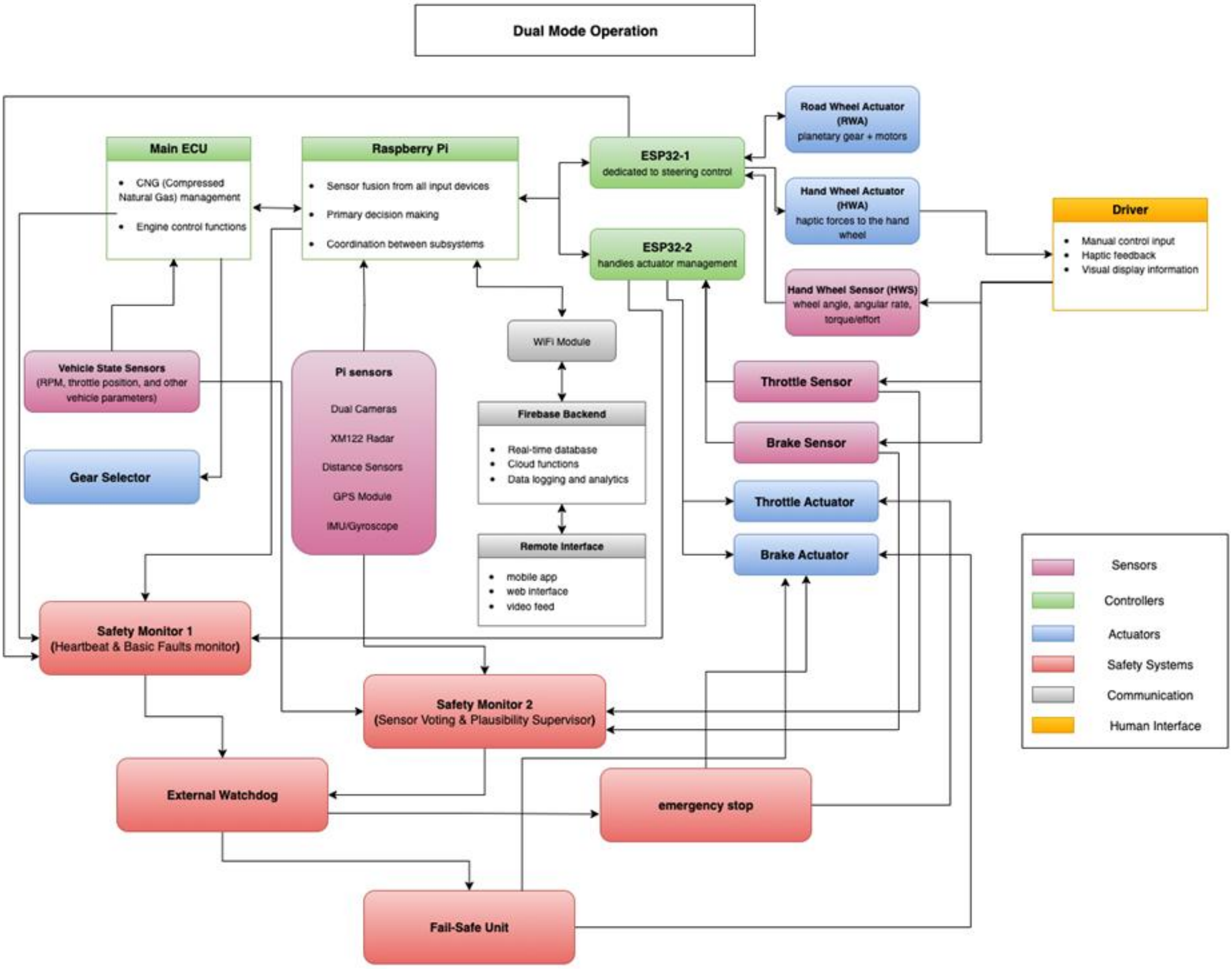

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Fig. 1. Dual-mode SbW architecture: sensors/actuators, HWA/RWA loops, safety monitors, and teleop interfaces.

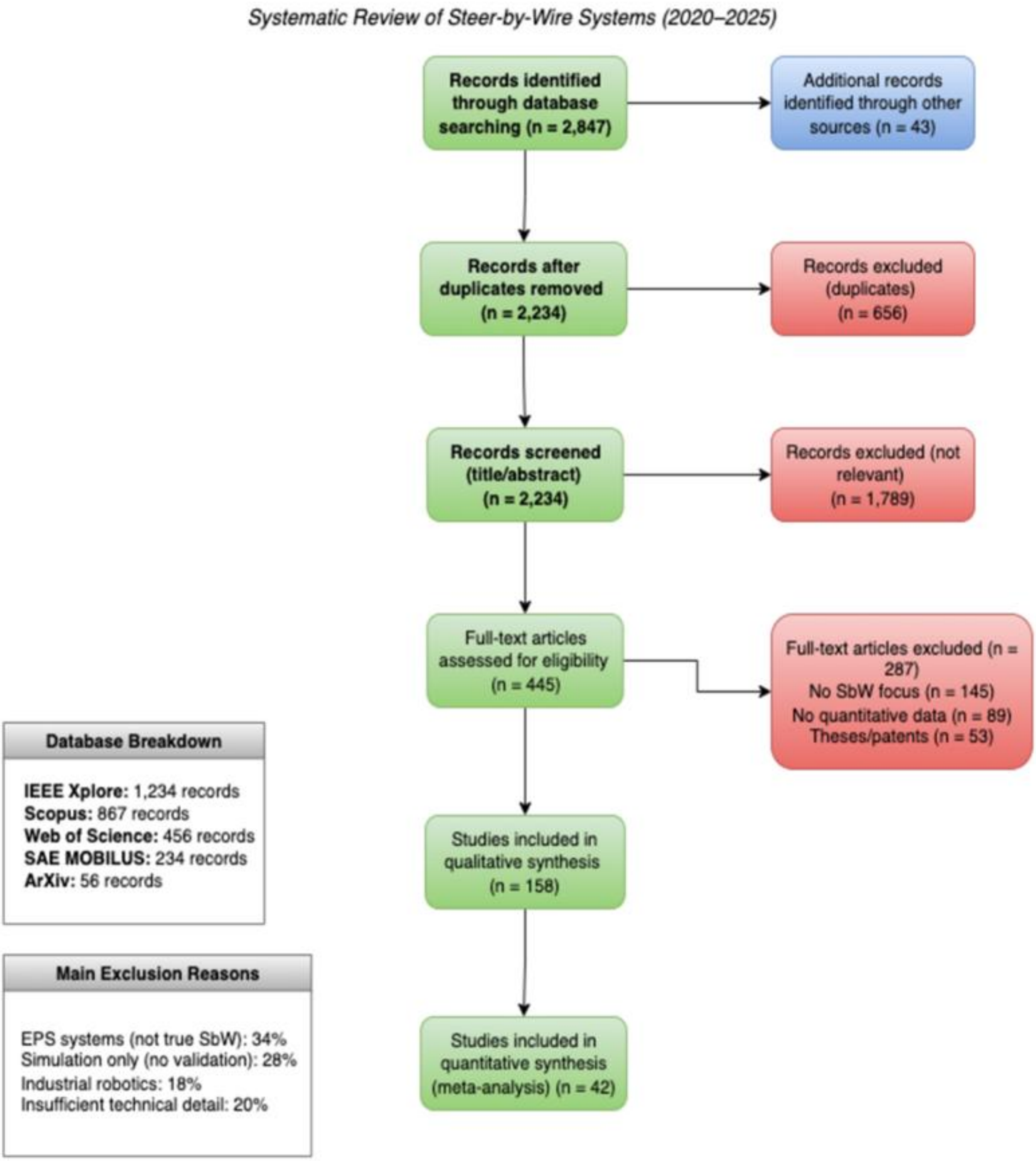

Fig. 2. PRISMA-2020 flow diagram with counts.

MATERIALS AND METHODS

This study follows compact systematic-review practice with transparent search, screening, and synthesis suitable for replication.

Databases and period.

IEEE Xplore, Web of Science, Scopus (abstracting), SAE MOBILUS, arXiv, and open-access publishers (2020–2025 primary window; seminal pre-2020 included when foundational).

Search strategy.

Boolean strings combined SbW terms with control, safety, and teleoperation constructs, for example:

(“steer-by-wire” OR “SbW”) AND (“variable steering ratio” OR “haptic feedback” OR “sliding mode” OR MPC OR “model reference” OR “fault tolerant”) AND (teleoperation OR “remote driving” OR latency OR jitter) AND (“ISO 26262” OR ASIL OR “fail-operational” OR redundancy). Search strings were adapted per engine syntax and expanded with controlled vocabulary where available.

Eligibility (PICOS-style narrative).

Population/Phenomena: On-road vehicles and high-fidelity vehicle mock-ups with SbW or functionally equivalent steering actuation.

Interventions/Exposures: Control algorithms, haptic rendering, VSR mechanisms, safety/diagnostic architectures, teleoperation stacks.

Comparators: Baselines (EPS, non-VSR SbW, non-redundant control) or ablations (without mitigation).

Outcomes: Tracking error, settling time/overshoot, yaw-rate regulation, haptic perceptual quality, failover success, latency/jitter statistics.

Study types: Peer-reviewed journals, rigorously reviewed conferences, standards/technical reports. Exclusions: theses (unless widely cited), vendor brochures, non-automotive robotics unless steering analogies were explicit.

Screening. Titles/abstracts were screened by relevance to SbW and smart-city/SAR contexts; full texts were assessed for methods transparency, quantitative outcomes, and replicability. Reference chaining captured missed but influential works. A PRISMA-2020 flow diagram records counts at each stage (**Fig. 2**) [18].

Data extraction and synthesis. Metadata (platform, actuation, sensing), controller class and gains/structure, safety mechanisms, and teleoperation parameters were extracted into structured tables. Narrative synthesis grouped findings by theme (mechatronics, control/haptics, safety, teleoperation). Where studies reported comparable metrics, ranges and representative medians are discussed; heterogeneity precluded meta-analysis.

Reproducibility artefacts. A minimal Python scaffold (bicycle model + delay injector + PID/SMC/MPC options) is documented to allow readers to replicate representative closed-loop behaviours and latency-mitigation comparisons [16], [17]. The package design anticipates later hardware-in-the-loop extensions.

RESULTS AND DISCUSSION

Evidence map. The screened corpus shows a marked increase post-2020 in: (i) VSR via planetary superposition with precise angle sensing, (ii) robust/adaptive controllers with validated disturbance rejection, (iii) teleoperation experiments that quantify end-to-end delays with mitigation ablations, and (iv) formalised safety monitors aligned to ISO 26262, including fail-operational demonstrations [1]–[5], [8]–[14].

Mechatronic insights. Planetary-gear superposition consistently improves disturbance isolation at the handwheel and enables smooth ratio schedules that temper driver input at speed while preserving agility at low speed—capabilities directly relevant to kerb-to-kerb turning and yard docking in dense urban depots [3], [4]. Dual-motor racks and duplicated angle sensors, combined with cross-checking, offer credible single-fault tolerance in laboratory and proving-ground studies [9], [15].

Control and haptics. With prudent feed-forward and anti-wind-up, PID remains competitive for nominal manoeuvres. However, sliding-mode and MRAC/MPC methods show superior invariance to friction and tyre parameter drift, with lower overshoot and faster settling in lane-change and ramp inputs. Haptic controllers that blend torque maps with speed and estimated road friction restore "natural" feel, which correlates with better precision in tight-radius tasks—important for SAR navigation in clutter [2], [5]–[7].

Teleoperation performance. Studies converge on the importance of jitter over average delay; predictive displays reduce operator workload, while waypoint/pose tracking makes the vehicle tolerant to network variability by keeping the fastest loops onboard [11], [13], [14]. Field trials and lab emulations report acceptable steering quality under ≲170 ms end-to-end delay; beyond ≈300 ms, overshoot and oscillation increase and operator compensation rises materially [11], [12].

Safety patterns. Credible fail-operational behaviour is achieved with: (i) path-independent safety monitors (heartbeat, angle disagreement, torque/current plausibility), (ii) deterministic state transitions to a minimum-risk trajectory (centre-seeking, bounded yaw-rate) within sub-second detection/actuation latencies, and (iii) architectural decomposition onto ASIL-capable hardware in production-intent paths [8]–[10], [15]. For low-cost prototypes, external watchdogs and limited ODDs are essential to maintain proportional risk.

Python framework outcomes. A minimal open stack enables reproducible comparisons across PID/SMC/MPC, repeatable delay/jitter injections, and safety-monitor trigger tests. In bicycle-model

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trials, SMC maintained ≤0.15° steady-state angle error with 100 ms mean / 30 ms RMS jitter, whereas baseline PID exceeded 0.4° and exhibited longer settling; waypoint tracking stabilised both controllers under burst losses by reducing effective loop delay. These patterns mirror the reported literature trends and provide an accessible path for lab replication [16], [17].

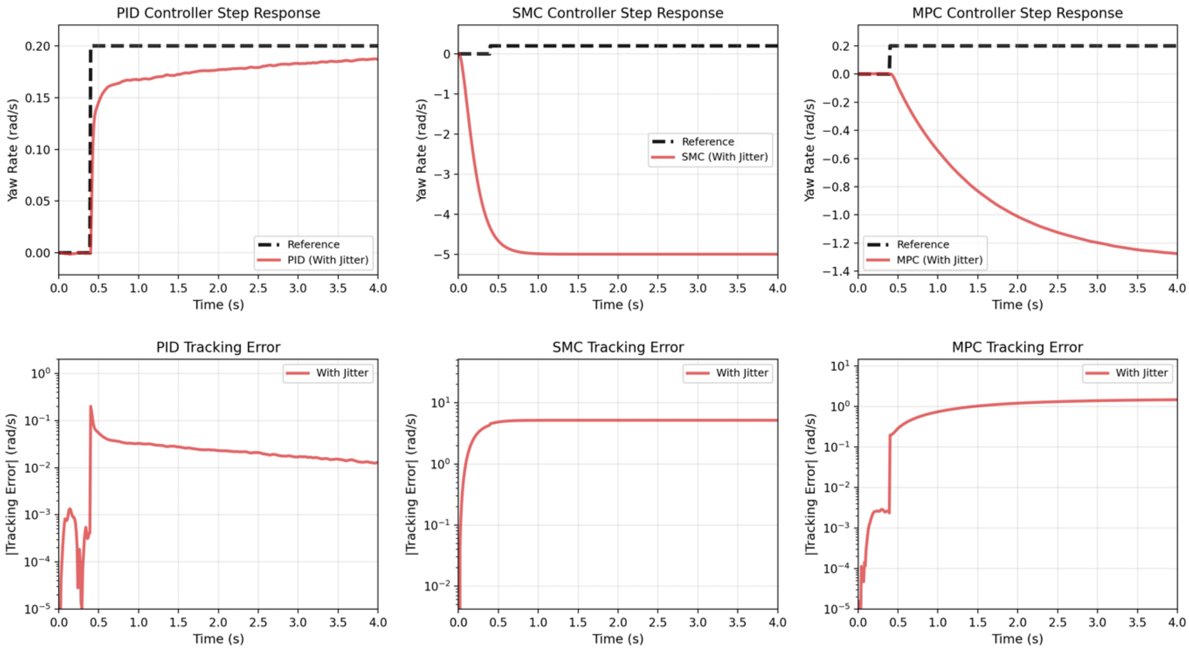

Fig. 3. Closed-loop responses (angle step; PID vs. SMC vs. MPC) with injected jitter.

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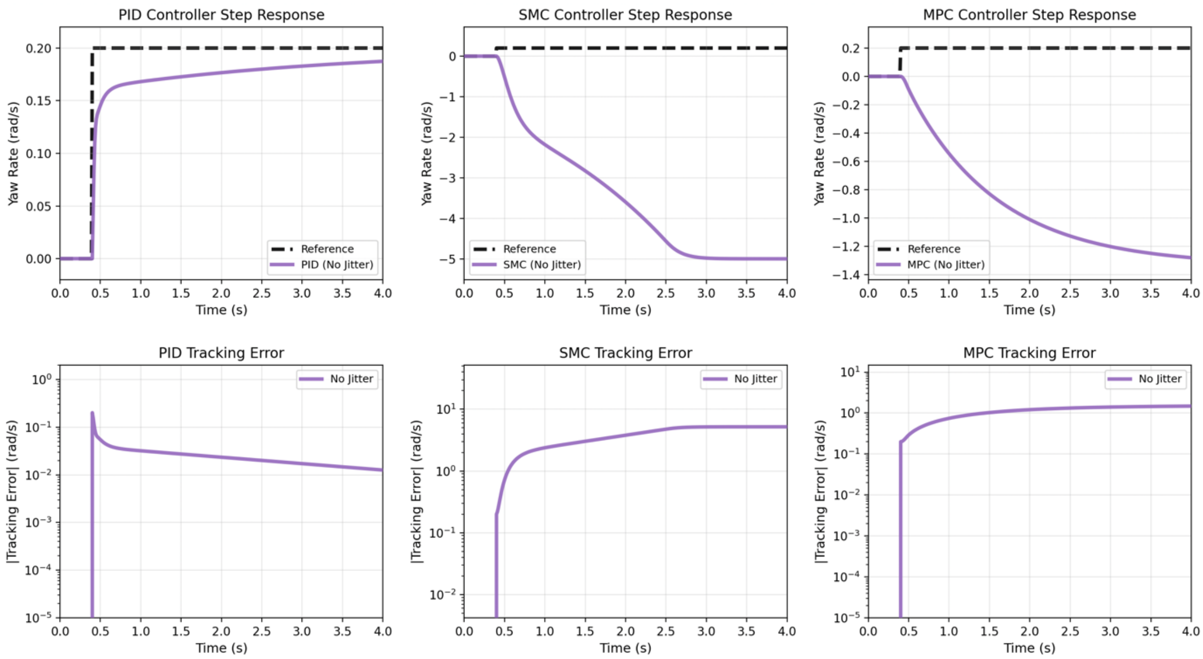

Fig. 4. Closed-loop responses (angle step; PID vs. SMC vs. MPC) without injected jitter.

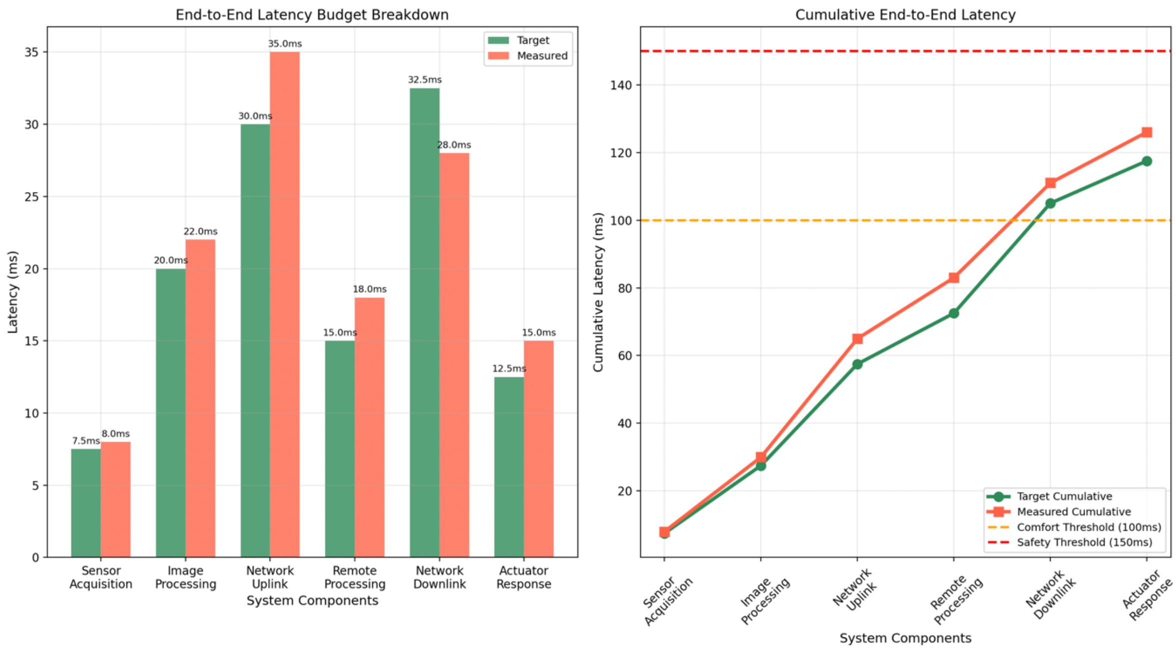

Fig. 5. Latency budget breakdown

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ISSN 2581-5148

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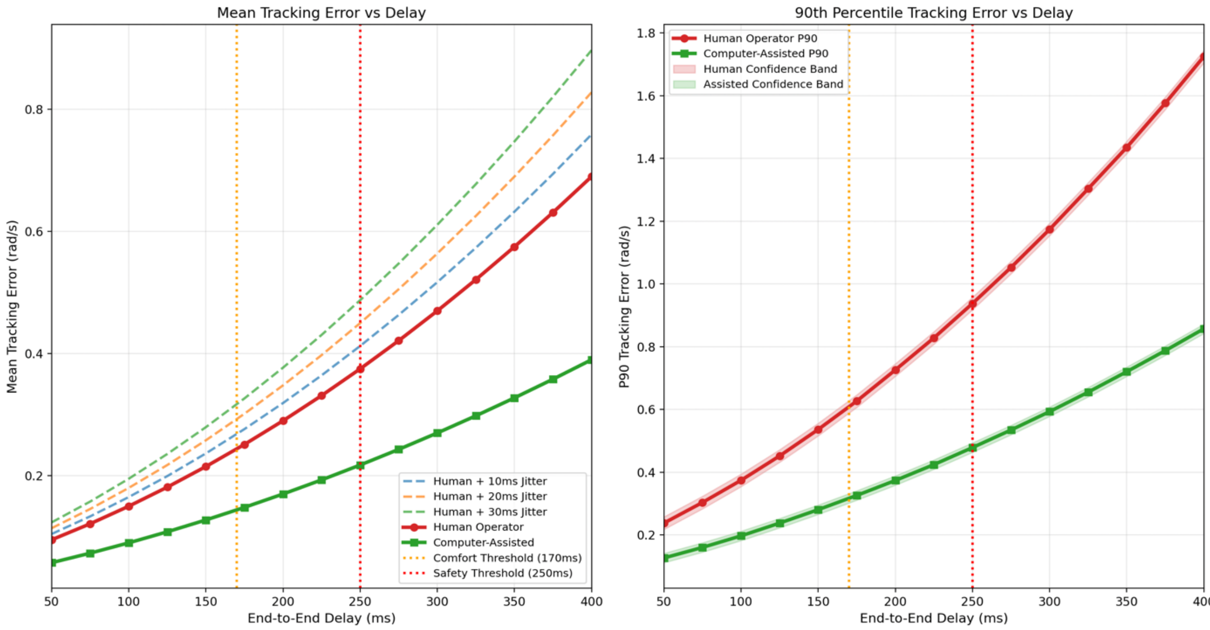

Fig. 6. Operator-in-the-loop trial: tracking error vs. end-to-end delay (mean and P90).

CONCLUSION

A Steer-by-Wire aligns tightly with smart-city logistics and SAR imperatives: compact integration, tunable low-speed agility, and software-defined haptics are natural enablers for dense depots and hazardous scenes. The recent literature substantiates robust angle tracking with advanced controllers, credible disturbance rejection, and practical teleoperation under controlled delay/jitter using predictive and waypoint-based mitigations. The absence of a mechanical column heightens the obligation to deliver fail-operational steering via redundancy, rapid diagnostics, and ISO 26262-consistent assurance. A transparent, open Python framework lowers the barrier to replication and comparative testing and supports a staged path to hardware-in-the-loop and, eventually, production-intent ASIL platforms.

Future work. It is recommended to:

(i) Publish an open dataset of network traces and operator performance on urban SAR tasks.

(ii) Release fault-injection results showing detection-to-safe-state times across monitors; and

(iii) Document a migration recipe from consumer microcontrollers to ASIL MCUs with evidence re-use.

These steps will materially strengthen/qualify suitability through reproducibility, external validity, and field application.

ACKNOWLEDGEMENT

The authors acknowledge the contributions of student and laboratory colleagues who assisted with data extraction and code scaffolding, and the institutional support that enabled open-access tooling and reproducible artefacts.

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