

# *Active Sidestick Mechatronic Interaction for Single-Pilot Operations*

**Ziheng Qin**

*Institute of International Education, Chongqing College of Mobile Communication, Chongqing, China*  
*zihengqin832@gmail.com*

**Abstract.** The transition toward Single Pilot Operations (SPO) is a critical paradigm shift for next-generation commercial aircraft to reduce operational costs and mitigate the global pilot shortage. However, conventional fly-by-wire (FBW) systems adopt passive control technologies that break the physical coupling between pilots and aerodynamic loads. Without a co-pilot, such decoupling greatly raises the risks of loss of situational awareness and human-machine authority conflicts. To address these engineering challenges, active sidestick technology reconstructs a closed electromechanical haptic loop via dynamic force feedback, facilitating both the allocation of interaction authority and real-time physiological monitoring. This paper presents a systematic literature review focusing on the core underlying technologies of SPO interfaces: the topological design of variable stiffness mechanisms (VSMs), bioimpedance (BioZ)-based unobtrusive monitoring networks, and nonlinear friction compensation algorithms. Findings highlight that a cam-roller-spring VSM integrated with active disturbance rejection control (ADRC) effectively overcomes transmission friction hysteresis, ensuring high-fidelity force feedback. Concurrently, BioZ-integrated networks establish a robust safety foundation for pilot incapacitation detection and automated takeover, offering practical references for future SPO system design.

**Keywords:** Single Pilot Operations, Active Sidestick, Haptic Shared Control, Variable Stiffness Mechanism, Friction Compensation

## **1. Introduction**

The crew configuration of commercial aircraft is undergoing a critical transition. Driven by escalating aircrew training costs and a profound global pilot shortage, theoretical frameworks and preliminary engineering research regarding Single Pilot Operations (SPO) and extended Minimum Crew Operations (eMCO) have become focal points for next-generation aviation architectures [1, 2].

However, contemporary flight control architectures predominantly rely on fly-by-wire (FBW) systems equipped with passive sidesticks. Relying solely on mechanical springs and dampers to deliver fixed force feedback, these control interfaces inherently break the physical coupling between pilots and aerodynamic loads. While traditional dual-pilot crews mitigate this decoupling through verbal communication and visual cross-checking, the SPO paradigm isolates the operator. Consequently, pilots face a heightened risk of information overload during adverse weather or

equipment malfunctions, which can severely degrade situational awareness and precipitate critical operational errors.

While current research heavily emphasizes optimizing human-machine teaming and interface interaction, existing sensing technologies reveal critical deficits in pilot incapacitation monitoring. Specifically, such sensing systems fail to meet the stringent safety equivalence requirements stipulated by airworthiness standards; that is, they cannot achieve the reliability level guaranteed by dual-pilot configurations.

To bridge these perceptual and safety gaps inherent in SPO, this paper systematically investigates active sidestick electromechanical interaction technologies, aiming to introduce novel paradigms for system safety enhancement. Specifically, this study explores the application potential of active sidesticks within SPO architectures by comparatively analyzing three core technological domains: the topological design of variable stiffness mechanisms (VSMs), non-invasive sensor networks for physiological monitoring and electromechanical friction compensation algorithms. Ultimately, this research aims to advance mechatronic flight control theory while providing actionable, macroscopic design recommendations for human-machine authority allocation systems in future intelligent cockpits.

## 2. Principles and architectures of haptic shared control

### 2.1. Basic principles

In the context of Single Pilot Operations (SPO), conventional flight automation relies predominantly on rigid, binary control authority architectures—dictating either strictly manual or fully autonomous execution. When subjected to sensor degradation or discrepancies between the automation algorithms and the pilot's intent, this inflexible paradigm severely hinders the operator's ability to swiftly recover situational awareness, thereby exacerbating the risk of critical operational failures.

To mitigate these human-machine conflicts, Haptic Shared Control (HSC) emerges as a transformative paradigm. Departing from absolute authority segregation, HSC physically translates the automation system's computational outputs (e.g., optimal trajectory planning) into continuous physical guidance forces or dynamic mechanical impedance variations directly on the active sidestick. This mechanism fosters seamless human-machine synergy [3, 4].

Executing such dynamic authority allocation and bidirectional electromechanical interaction hinges fundamentally on a robust low-level control architecture. By integrating a Friction Observer with an Active Disturbance Rejection Controller (ADRC), the electromechanical interface renders target guidance torques with exceptional haptic fidelity [5, 6]. Consequently, pilots intuitively process this force feedback via neuromuscular pathways; they can either seamlessly comply with the automated guidance to alleviate cognitive demands or, during critical contingencies, apply additional manual exertion to intuitively override machine decisions.

To further refine this semi-autonomous interaction, HSC systems can be augmented with adaptive frameworks capable of quantifying the pilot's real-time stress and cognitive workload. By synthesizing objective physiological or neurometric data to infer the operator's functional state, the system intelligently modulates its haptic feedback profile. Ultimately, this adaptive haptic methodology effectively attenuates cognitive overload and sustains optimal operational performance [7].

## 2.2. Interaction metaphors and industrial applications

In the domain of complex human-machine interface design, the "H-Metaphor" (Horse and Rider metaphor) serves as the theoretical cornerstone for active sidestick interaction [8]. This paradigm analogizes highly automated flight control systems to an intelligent equine counterpart endowed with innate obstacle-avoidance capabilities. Concurrently, it positions the pilot as the rider, tasked exclusively with defining high-level tactical objectives and directional mandates. Rooted in this metaphor, the H-Mode architecture employs a "Human-Machine Mediator" to physically decouple automated execution modules from the human-operated interface. Leveraging high-frequency servo motors, active sidesticks algorithmically modulate mechanical impedance in real time, seamlessly facilitating transitions between two fundamental interaction modalities:

"Loose Reins Mode" refers to the situation where as long as the aircraft remains within its nominal flight envelope, the system maintains minimal impedance and high mechanical compliance, fluidly accommodating the pilot's micro-adjustments. "Tight Reins Mode" means that once the aircraft approaches critical thresholds (e.g., stall or overspeed boundaries), system stiffness surges exponentially to generate a haptic force field known as a "Soft Stop." This mechanism exerts direct physical repulsive forces to alert the pilot and mechanically rectify hazardous trajectories.

In practical engineering applications, haptic control systems demonstrate profound utility in optimizing flight training regimens. Empirical research by Dominik Janetzko et al. illustrates that active sidestick systems can support novice pilots by integrating physical cues such as haptic detents, soft stops, and vibrotactile alerts. Crucially, their study highlights an adaptive haptic algorithm termed "Guidance-as-Needed." This algorithm dynamically adjusts the intensity of haptic guidance according to the pilot's real-time motion tracking deviations. Within the context of motor learning, this methodology proves significantly more efficacious in cultivating accurate muscle memory than rigid, static guidance paradigms.

Concurrently, this interaction framework is rapidly transitioning into commercial aviation deployments. Architecturally, active sidestick systems eliminate the heavy, complex mechanical linkages traditionally connecting the captain and first officer. Instead, these systems fully rely on avionics data buses to transmit electrical commands for driving miniature servo actuators. BAE Systems, a leading pioneer in this domain, has documented over 1.4 million safe flight hours for its active sidesticks, which are currently operational across 16 distinct commercial and military platforms (e.g., F-35, Gulfstream G500) [9].

Recent industry reports indicate that these active sidesticks, featuring advanced "electronic cross-coupling," are being comprehensively integrated into JetZero's novel Blended-Wing Body (BWB) aircraft [9]. This "single-box" configuration not only eliminates substantial structural weight to maximize aerodynamic efficiency but also establishes a critical foundation for future SPO scenarios. Even with physical mechanical decoupling, a single pilot can directly perceive the maneuvering intent of the rear-mounted AI agent (e.g., automatic turning maneuvers) via high-frequency mechanical impedance fluctuations. Ultimately, this neuromuscular haptic feedback cultivates a profound, bidirectional trust bridging algorithmic intelligence and human physiology.

## 3. Core technology branches and research progress

### 3.1. Taxonomy and evolution of variable stiffness mechanisms

Mechanistically, active sidesticks necessitate a wide-range, continuous impedance modulation capability to satisfy varying control authority demands across distinct flight phases. Variable

stiffness actuators (VSAs) and their corresponding mechanical topologies constitute the hardware basis for such impedance adjustment functions. Crucially, achieving the mechanical decoupling of position tracking and stiffness regulation remains a primary research focus. Current VSA architectures are predominantly categorized into three topological paradigms.

The first category comprises antagonistic mechanisms. Analogous to biological musculoskeletal systems, these configurations utilize dual electric motors to tension elastic elements via co-contraction [10]. Although such structures deliver outstanding dynamic performance, the dual-actuator layout significantly increases overall size and mass.

The second category encompasses variable lever arm mechanisms, which modulate the effective moment arm by altering the physical pivot point. While highly energy-efficient, their lead screw and slider assemblies are critically susceptible to excessive friction under extreme aerodynamic loads, frequently culminating in mechanical jamming or self-locking.

The third category—the cam-roller-spring topology—demonstrates the highest engineering feasibility. This architecture relies on a preloaded roller sliding along a contoured cam profile to compress an elastic element. Previous studies have introduced the concept of an equivalent quadratic torsional spring alongside a precise mathematical model; by systematically optimizing the cam's pressure angle, researchers have successfully achieved the physical decoupling of position and stiffness [11].

Notably, the elastic actuation torque generated by this mechanism exhibits a highly nonlinear, quadratic correlation with the sidestick's deflection angle. This unique kinematic property guarantees that under small deflection angles, the active sidestick delivers continuous mechanical compliance to support precise fine control inputs. Conversely, as the deflection approaches its kinematic limits, the mechanical resistance exhibits a steep, exponential escalation. This dynamic impedance profile precisely satisfies the physical prerequisites of a "soft stop," an indispensable feature for robust flight envelope protection.

### 3.2. Non-invasive physiological state monitoring network

Under the Single Pilot Operations (SPO) framework, sudden pilot incapacitation creates an unacceptable single-point failure risk. Conventional optical monitoring systems are highly susceptible to ambient illumination artifacts, while wearable neuroelectric devices severely compromise ergonomic comfort during physical maneuvers. To fill this critical monitoring gap for pilot incapacitation detection [12], the seamless embedding of non-invasive biosensor arrays inside the grip of active sidesticks has attracted extensive research attention and become a core technical requirement for next-generation avionics computing systems.

Leveraging its inherent high sensitivity, Bioelectrical Impedance (BioZ) analysis has been integrated into the sidestick's sensory framework. By deploying dry electrode arrays across the grip surface, the system continuously captures the segmental impedance characteristics of the pilot's forearm in real time. During empirical experiments on a European high-fidelity flight simulator testbed, high-precision biosignal amplifier modules were used to capture faint physiological variations. The test setup integrated three types of sensing hardware: g.GSRsensor2 modules for measuring electrodermal activity (EDA) impedance shifts, fingertip oximetry probes for acquiring photoplethysmography (PPG) waveforms, and thermal sensors for quantifying peripheral skin temperature drops triggered by mental stress.

Recent empirical studies demonstrate a highly stable, nonlinear mapping between forearm bioimpedance metrics and manual grip force [13]. Dynamic prediction models developed via Random Forest algorithms have achieved exceptional accuracy during cross-validation. Crucially,

upon detecting abrupt signal attenuation or erratic high-frequency oscillations in the impedance data, the system's low-level state machine instantaneously initiates automated takeover protocols. This intervention mechanically locks the sidestick's stiffness, physically rejecting invalid manual control inputs.

Despite these advancements, contemporary wearable sensing technologies exhibit critical vulnerabilities in signal robustness when subjected to the severe motion artifacts and perspiration dynamics inherent to real-world cockpits. For instance, sweat-based metabolite biosensors currently lack robust mechanisms for in-situ high-fidelity signal processing and real-time calibration.

### 3.3. Transmission friction modeling and servo compensation strategy

Achieving high-fidelity haptic rendering of "H-Metaphor" guidance torques within active sidestick architectures necessitates ultra-precise regulation of the underlying servo systems. However, inherent nonlinear friction within the electromechanical drivetrain introduces severe perturbations. At tiny motion reversals, such friction disturbances trigger low-speed stick-slip crawling, steady-state tracking errors and limit cycle vibrations, which greatly deteriorate haptic transparency. Consequently, precise friction modeling and active compensation are essential prerequisites for mitigating these dynamic degradations.

While numerous friction models exist, research by Zhang et al. indicates that the classical Coulomb model is inadequate for this specific application, whereas the dynamic LuGre model yields superior predictive accuracy [14]. By incorporating an internal state variable to quantify the average deflection of microscopic bristles, the LuGre model accurately captures pre-sliding frictional hysteresis and the low-velocity Stribeck effect. The governing differential equations are expressed as follows:

$$\frac{dz}{dt} = v - \frac{|v|}{g(v)} z \quad (1)$$

$$F = \sigma_0 z + \sigma_1 \frac{dz}{dt} + \sigma_2 v \quad (2)$$

Nevertheless, the highly nonlinear and cross-coupled nature of the model's parameters presents formidable challenges for practical hardware identification. To resolve this, Zhang et al. proposed an Enhanced Genetic Algorithm (EGA) identification methodology [14]. By leveraging genetic algorithm optimization alongside transient response data, they successfully extracted precise model parameters. The estimated nonlinear friction was then injected directly into the servo feedback loop as feedforward compensation.

Empirical results confirmed that this strategy effectively circumvented closed-loop computational latency and eliminated the stick-slip phenomenon. It reduced position tracking error variance by over 95% and achieved a 25.1% improvement in low-speed tracking accuracy, completely suppressing the limit cycle oscillations that degrade haptic fidelity. Furthermore, to address the limitations of relying exclusively on nominal models, the literature introduces an Active Disturbance Rejection Control (ADRC) architecture as a composite mechanism to mitigate time-varying residuals and unmodeled perturbations [6].

## 4. Engineering verification and airworthiness challenges

### 4.1. Distortion bottlenecks in multiphysics coupled simulation

The engineering deployment of active sidesticks encounters prominent verification bottlenecks arising from tight multiphysics coupling covering mechanical, electromagnetic and neuromuscular dynamic fields. While industry-standard co-simulation effectively validates basic control laws, rendering high-fidelity haptics strictly requires communication frequencies exceeding 1000 Hz. In such high-frequency discrete environments, minor communication latencies combined with zero-order hold (ZOH) effects inevitably induce artificial energy injection. This triggers numerical integration divergence in stiff differential solvers, causing severe simulation distortion. Consequently, purely digital simulations are fundamentally inadequate for accurately replicating the system's nonlinear physical responses under extreme operational conditions.

### 4.2. Airworthiness standards and automation policy resistance

Regulatory gaps and institutional resistance currently form the primary barriers to SPO implementation. Global aviation authorities have yet to define airworthiness certification frameworks for intelligent authority arbitration systems. Crucially, under the strict RTCA DO-178C airborne software standard, machine learning-based physiological models fundamentally fail to guarantee the requisite algorithmic determinism and traceability.

EASA's D-8 safety risk report explicitly concludes that current automation cannot replicate the safety redundancy of a dual-pilot crew in mitigating fatigue and incapacitation. Supported by historical accident data from the NTSB that records catastrophic incidents triggered by single-pilot incapacitation, EASA has officially suspended all legislative initiatives for commercial SPO [15].

The SPO architecture inherently suffers from critical, unresolved vulnerabilities. The industry fundamentally lacks high-reliability instrumentation for continuous cognitive state monitoring. The monotony of long-haul flights inevitably induces micro-sleeps, a risk further compounded by severe post-rest sleep inertia. Furthermore, SPO structurally eliminates the dual-pilot cross-checking mechanism, while unavoidable physiological needs (e.g., bathroom breaks) generate hazardous supervisory voids in the cockpit. Finally, the high susceptibility of existing biosensors to electromagnetic interference (EMI)—which risks triggering catastrophic, spurious automated takeovers—conclusively demonstrates that current laboratory-grade algorithms remain fundamentally incapable of satisfying stringent aviation airworthiness standards.

## 5. Conclusion

This review systematically synthesizes active sidestick electromechanical technologies tailored for Single Pilot Operations (SPO). It elucidates the mechanisms of Haptic Shared Control (HSC) in mitigating Out-of-the-Loop (OOTL) syndromes and enabling dynamic authority allocation. Topological comparisons confirm that cam-roller-spring mechanisms excel in physically decoupling position tracking from stiffness regulation, thereby ensuring robust mechanical envelope protection. Concurrently, unobtrusive BioZ-based monitoring networks accurately estimate grip force and detect pilot incapacitation, establishing essential physiological safety redundancy. In the servo-actuation domain, integrating the dynamic LuGre friction model with Active Disturbance Rejection Control (ADRC) proves optimal for eradicating transmission hysteresis and maximizing haptic transparency.

Despite these advancements, current research frameworks exhibit critical limitations. Existing studies rely heavily on ambient laboratory conditions and idealized mathematical models. Empirical data from extreme operational environments—such as high-altitude sub-zero temperatures inducing nonlinear viscosity shifts in lubricating films—and long-term mechanical wear scenarios remain critically absent. Furthermore, constrained by stringent aviation regulations, in-flight empirical data regarding AI-driven authority arbitration in highly dynamic regimes is profoundly scarce, fundamentally precluding large-scale quantitative validation.

To bridge these gaps, future research should advance along two primary fronts. First, deploy edge-side neuromorphic computing modules. By converting analog physiological signals into event-triggered spikes for Spiking Neural Networks (SNNs), such edge-side systems realize local biometric decoding with ultralow power consumption and greatly cut down data transmission delay. Second, develop adaptive digital twin frameworks integrated into electromechanical interactive interfaces. Leveraging real-time telemetry to dynamically update friction parameters and health degradation models will establish a robust framework for intelligent predictive maintenance. Ultimately, overcoming these validation and airworthiness bottlenecks will secure the theoretical and hardware infrastructure necessary to propel commercial aviation toward high-level autonomy.

## References

- [1] Wang, W. (2019). Single pilot operation mode and organization architecture of commercial aircraft. *Acta Aeronautica et Astronautica Sinica*, 40(1), 1-10.
- [2] Harris, D. (2023). Single-pilot airline operations: Designing the aircraft may be the easy part. *The Aeronautical Journal*, 127(1313), 1171-1191.
- [3] Flemisch, F., Heesen, M., Hesse, T., Kelsch, J., Schieben, A., & Beller, J. (2012). Haptic shared control: Smoothly shifting control authority? *Cognition, Technology and Work*, 14(1), 19-28.
- [4] Deroo, M., Mars, F., & Hoc, J. M. (2014). Analysis of human-machine cooperation when driving with different degrees of haptic shared control. *IEEE Transactions on Haptics*, 5(3), 1-11.
- [5] Odabas, C., & Morgül, Ö. (2025). A novel observer design for LuGre friction estimation and control. *IEEE Transactions on Automatic Control*, 1-10.
- [6] Dong, F., Lei, X., Chou, Y., & Li, X. (2023). Active disturbance rejection controller combined with a LuGre friction model for a two-axis optoelectronic stabilized platform. *Electronics*, 12(5), 1261.
- [7] Luo, R., Weng, Y., Wang, Y., Jayakumar, P., Brudnak, M. J., Paul, V.,... & Yang, X. J. (2021). A workload adaptive haptic shared control scheme for semi-autonomous driving. *Accident Analysis & Prevention*, 152, 105968. URL: <https://websites.umich.edu/~tersal/papers/paper113.pdf>
- [8] Flemisch, F. O., Adams, C. A., Conway, S. R., Goodrich, K. H., Palmer, M. T., & Schutte, P. C. (2003). The H-Metaphor as a guideline for vehicle automation and interaction (No. L-18448).
- [9] BAE Systems. (2024). BAE Systems to provide active control sidesticks for JetZero's next-generation sustainable jet. *BAE Systems Newsroom*. <https://www.baesystems.com/en-us/article/bae-systems-to-provide-active-control-sidesticks-for-jetzero-s-next-generation-sustainable-jet>
- [10] Awad, A., et al. (2020). Mechanical design of antagonistic variable stiffness joint. *Journal of Mechanical Design*, 142(10), 1-12.
- [11] Wang, C., Sheng, B., Li, Z., Sivan, M., Zhang, Z. Q., Li, G. Q., & Xie, S. Q. (2023). A lightweight series elastic actuator with variable stiffness: Design, modeling, and evaluation. *IEEE/ASME Transactions on Mechatronics*, 28(6), 3110-3119.
- [12] Federal Aviation Administration. (2022). Pilot medical monitoring: State of the science review on identification of pilot incapacitation. FAA Office of Aerospace Medicine, DOT/FAA/AM-23/16. [https://www.faa.gov/data\\_research/research/med\\_humanfacs/oamtechreports/media/Pilot\\_Medical\\_Monitoring\\_State\\_Science\\_Review\\_on\\_Identification\\_of\\_Pilot\\_Incapacitation.pdf](https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/media/Pilot_Medical_Monitoring_State_Science_Review_on_Identification_of_Pilot_Incapacitation.pdf)
- [13] Mahmoudkhani, S., Gorenstein, J., & Ahmadi, K. (2024). Accurate, non-invasive assessment of muscle strength: Segmental bioimpedance (BioZ) to predict hand grip strength (HGS). *Physiological Measurement*, 45(2), 025001.
- [14] Zhang, W., Zhang, F., Zhang, J., Zhang, S., Zhang, J., & Zhang, Y. (2025). Research and analysis of an enhanced genetic algorithm identification method based on the LuGre model. *PLoS One*, 20(6), e0322844.

- [15] European Union Aviation Safety Agency. (2025). eMCO-SiPO, D-8 report on the preliminary safety risk identification for SiPOs. EASA Official Reports. <https://www.easa.europa.eu/en/downloads/142085/en>