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SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Development and implementation of a sensor system for physiological measurements in simulated flight for Rotorcraft-Pilot Coupligs assessment

Laurea Magistrale in Aeronautic Engineering - Ingegneria Aeronautica

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Abstract

This thesis addresses the critical safety challenge posed by Rotorcraft-Pilot Couplings (RPCs), specifically focusing on the physiological precursors that lead to aeroelastic instability. While traditional certification methodologies emphasize the mechanical response of the airframe, recent research identifies the pilot's biodynamic stiffening — driven by increasing Muscular Activation Level and Mental Workload (MWL) — as a primary trigger for phenomena such as Pilot-Assisted Oscillations (PAO). This work presents the development, integration, and validation of a multi-modal sensor ecosystem within the high-fidelity RPC Test Rig at Politecnico di Milano. By combining Surface Electromyography (sEMG), Eye Tracking, Electrocardiography (ECG), markerless Body Pose tracking, and a novel optical force sensor (OPT-IN), the system generates a synchronized, objective dataset correlating pilot physiology with flight dynamics. Experimental results obtained from ADS-33E vertical maneuvers demonstrate the system's capability to objectively distinguish between expert and novice piloting strategies. Key findings include the identification of spectral compression in muscle activity (fatigue) and the quantification of the "death grip" phenomenon via optical sensing, both of which serve as quantifiable markers for the onset of adverse couplings.

1. Background and the Rotorcraft-Pilot Coupling Phenomenon

The operational safety and mission effectiveness of rotorcraft are intrinsically linked to the stability of the integrated Pilot-Vehicle System (PVS). A paramount challenge within this domain is the susceptibility to RPCs [25], defined as adverse, closed-loop instabilities driven by a mismatch between the pilot's control strategy and the vehicle's dynamic response. These phenomena are broadly classified based on the nature of the pilot's contribution. Voluntary interactions, where a pilot inadvertently excites vehicle modes due to phase lags or system delays, manifest as Pilot-Induced Oscillations (PIOs), typically dominating the low-frequency range ($0-2$ Hz). Conversely, involuntary interactions, termed PAOs or Aeroelastic RPCs, occur at higher frequencies (2 – 8 Hz) and are driven by the pilot's passive biomechanical response to exogenous cockpit accelerations [1, 11].

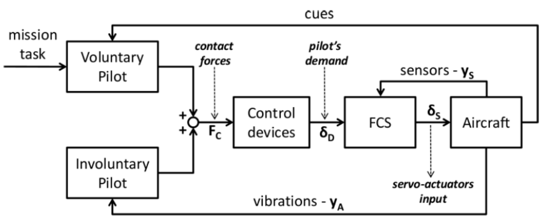


Figure 1: Simplified flow block diagram of the Pilot-Vehicle System illustrating the interaction between voluntary and involuntary pilot control loops. (Source: Adapted from [21]).

The unique high-order dynamics of rotorcraft, compounded by modern Fly-By-Wire (FBW) architectures, expose the airframe to RPCs across various demanding operational scenarios, ranging from slung load maneuvers to shipboard recoveries [20, 28]. A fundamental driver in the development of high-frequency PAOs is the Biodynamic Feedthrough (BDFT)—the transfer function relating vehicle acceleration to involuntary control deflection. Crucially, the BDFT is highly task-dependent [13]. As mission complexity and MWL escalate, pilots instinctively increase muscle co-contraction to meet precision demands. This neuromuscular stiffening alters the mechanical impedance of the pilot's limbs, inadvertently amplifying the passive BDFT feedback loop and eroding the system's stability margins [33]. Consequently, the objective assessment of pilot workload and biomechanical state is not merely a secondary performance metric, but a fundamental prerequisite for predicting and mitigating biomechanically-induced RPCs.

2. Mental Workload and Performance Quantification

The transition towards highly automated flight decks has fundamentally altered the pilot's role from a direct manual executor to a system supervisor. While this shift has contributed to increased overall system reliability, it has simultaneously introduced the "automation paradox," wherein human error remains the predominant contributing factor to aviation accidents [14]. As the industry progresses toward complex operational paradigms, such as Reduced Crew Operations (RCO) and Single-Pilot Operations (SPO), and manages highly demanding scenarios like shipboard landings or emergency autorotations, the cognitive demands placed on the operator are significantly elevated. Consequently, the objective assessment of MWL becomes a vital prerequisite for ensuring operational safety and detecting the precursors to biomechanically-induced instabilities [18, 30].

Traditional MWL evaluations have historically relied on subjective post-task ratings (e.g., NASA-TLX), which inherently suffer from retrospective bias and lack the temporal resolution required to capture transient spikes in cognitive demand. To overcome these limitations, modern Human-System Interaction (HSI) evaluations necessitate a multimodal assessment framework. This approach integrates subjective ratings with continuous physiological and behavioural metrics to construct a comprehensive, real-time profile of the pilot's state [16].

In the physiological domain, fluctuations in autonomic and somatic responses serve as robust, objective indicators of cognitive stress. Metrics such as Heart Rate Variability (HRV) and Electrodermal Activity (EDA) provide direct insight into the Autonomic Nervous System (ANS) arousal, specifically sympathetic activation. Concurrently, Electromyography (EMG) captures involuntary muscle tension—often utilized as a somatic proxy for psychological stress—validating the link between cognitive effort and physical stiffening [10].

From a behavioural perspective, the pilot's control strategy can be quantitatively evaluated using the Attack Chart methodology. Unlike traditional metrics that track positional error, this approach analyses the dynamic relationship between control input amplitude (Δ) and peak rate (g_{pk}). This allows for the objective categorization of pilot control effort into distinct regions, ranging from deliberate "Guidance" to high-frequency, reactive "Super-stabilization" [4]. By synthesizing these diverse physiological and behavioural data streams, it is possible to differentiate between expert and novice cognitive strategies, ultimately informing the design of adaptive flight systems capable of predicting and preventing pilot saturation [3, 10].

3. Multimodal Measurement Ecosystem

To comprehensively capture the complex interplay between cognitive workload and biomechanical response during RPC events, this research implements a synchronized, non-intrusive multimodal sensor ecosystem. This suite shifts the paradigm from purely subjective post-flight evaluations to continuous, real-time physiological and kinematic monitoring, integrating the following core technologies:

- **Biomechanical and Motor Control (sEMG):** Surface sEMG is utilized to monitor muscle activation and fatigue. By analyzing amplitude and spectral features—specifically the Mean Spectral Frequency (MNF) shifts—the system quantifies the involuntary neuromuscular stiffening and mechanical impedance modulation that pilots instinctively apply to counteract vibrations and high task demands [2, 33].
- **Cognitive State and Attention (Eye-Tracking):** Leveraging the "eye-mind link," oculomotor metrics—such as fixation duration, saccadic scanning patterns, and pupillometry—provide a direct window into the pilot's visual attention allocation. These metrics are crucial for identifying cognitive saturation and phenomena such as "attentional tunneling" during critical maneuvers like autorotations or shipboard landings [9].
- **Autonomic Arousal (HR/HRV):** Cardiac activity serves as a primary indicator of mental stress. Heart Rate Variability (HRV) features, particularly the Low Frequency to High Frequency ratio (LF/HF) reflecting the sympathovagal balance, allow for the robust classification of acute mental effort and the differentiation between cognitive workload and physical fatigue [24, 34].
- **Kinematics and Physical Interaction (Pose Tracking and OPT-IN):** A markerless, depth-based computer-vision system tracks the 3D kinematic trajectory of the pilot's left arm, providing non-intrusive monitoring of control inputs [26]. This kinematic data establishes a framework for cross-correlating behavioural and physiological metrics and validating in-flight biomechanical models. Concurrently, a novel optical force sensor (OPT-IN), based on Frustrated Total Internal Reflection (FTIR), measures grip pressure dynamics on the collective inceptor. This pressure variance is a direct correlate of pilot stress and captures the high-frequency involuntary inputs characteristic of PAOs [7, 32].
- **Subjective Validation (The Bedford Scale):** To anchor the objective telemetry, the Bedford Workload Scale is employed. Centered on the concept of "spare capacity," this hierarchical decision-tree scale provides a standardized, empirical baseline of perceived workload, essential for validating and correlating the continuous physiological data streams [6, 29].

4. Experimental Setup and Sensor Integration

To validate the proposed methodological framework, a comprehensive hardware ecosystem was implemented within the FRAME-Lab RPC Test Rig. The integration of these heterogeneous data streams was achieved utilizing the Modular Architecture for Reconfigurable Simulation of Helicopters (MARSH) as the synchronization backbone [19].

4.1. Physiological Monitoring: sEMG and ECG

Muscle activation and cardiac response were monitored using dedicated high-fidelity acquisition systems:

- **Surface Electromyography (sEMG):** The *Raw-Power* system (LWT-3) was employed to acquire differential signals from upper limb muscles, adhering to SENIAM guidelines for electrode placement. Data processing involved 5^{th}-order Butterworth band-pass filtering ($20 - 500$ Hz) to isolate motor unit action potentials. Custom algorithms extracted Root Mean Square (RMS) amplitude for effort quantification and MNF for fatigue assessment [2, 17].
- **Electrocardiogram (ECG):** Cardiac activity was captured via an AD8232-based single-lead sensor interfaced with an STM32 Nucleo-64 microcontroller. The system utilized a wired trigger from a LabJack T7 for precise synchronization. Post-processing algorithms performed R-

peak detection to compute instantaneous Heart Rate (HR) and Heart Rate Variability (HRV) metrics in both time and frequency domains [5].

4.2. Visual Attention Tracking

Oculomotor metrics were recorded using the *Pupil Core* head-mounted eye-tracking system. To ensure seamless integration with the flight simulation, custom MAVLink messages (`EYE_TRACKING_DATA` and `EYE_TRACKING_EVENT`) were developed within the MARSH protocol.

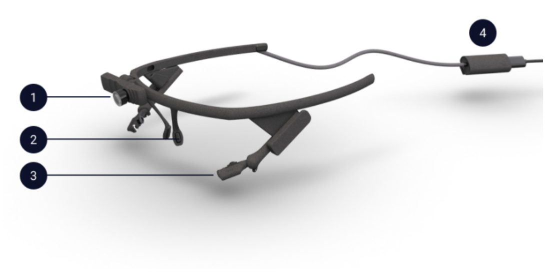


Figure 2: The Pupil Core eye tracking glasses used for recording gaze behavior, integrated into the simulation loop via custom MAVLink telemetry. (Source: Adapted from [27])

This architecture allowed for the real-time logging of 3D gaze vectors, pupil diameter, and discrete events (fixations, saccades, blinks), which were subsequently analyzed to assess cognitive workload and visual scanning strategies [15].

4.3. Kinematic and Force Estimation

To objectively characterize the pilot's physical control strategy, two non-intrusive systems were deployed:

- **Markerless Body Pose Tracking:** An *Intel RealSense D455f* stereo depth camera was utilized to track the 3D kinematics of the pilot's left arm. By fusing Red-Green-Blue (RGB) data with depth sensing, the system reconstructed the skeletal pose of the arm manipulating the collective stick, enabling the analysis of control inputs without physical markers [12].
- **OPT-IN Force Sensor:** A novel optical force sensor based on Frustrated Total Internal Reflection (FTIR) was integrated into the collective grip.

As shown in Figure 3, this sensor measures the deformation of a silicone interface against a polycarbonate waveguide. The resulting pressure data allows for the differentiation between intentional control inputs and involuntary, high-frequency biomechanical feedthrough characteristic of RPC events [8].

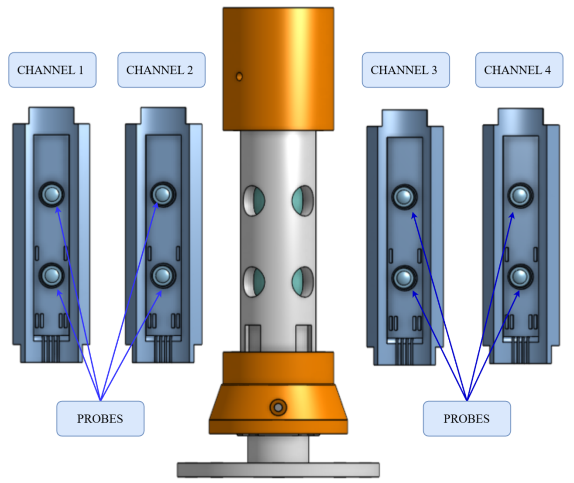


Figure 3: Schematic of the OPT-IN sensor. The system uses FTIR to measure grip pressure variations, distinguishing between voluntary control and involuntary biodynamic feedthrough. (Source: Adapted from [8]).

5. Simulation Environment and Experimental Protocol

To evaluate the integrated PVS under controlled, repeatable conditions, the experimental campaign was conducted using the RPC Test Rig at the FRAME-Lab. The simulation framework consists of a reconfigurable architecture capable of modeling a broad spectrum of rotorcraft, incorporating advanced aeromechanical models based on Padfield's methodologies [23]. These models have been further refined to capture high-fidelity rotor aerodynamics and structural dynamics, which are essential for analyzing complex phenomena such as Rotorcraft-Pilot Couplings [22].

5.1. The Experimental Task (ADS-33E)

The testing protocol was standardized utilizing Mission Task Elements (MTEs) rigorously derived from the *Aeronautical Design Standard*

Performance Specification for Handling Qualities of Military Rotorcraft (ADS-33E-PRF) [31]. Specifically, the "Vertical Repositioning" maneuver (Section 3.11.6) was selected to investigate heave axis controllability and rotor coning instabilities.

The maneuver simulates a rapid unmask/remask profile, requiring the pilot to:

1. Initiate a vertical ascent from a stabilized hover at 15 ft Above Ground Level (AGL).
2. Stabilize at a target altitude of 40 ft AGL.
3. Execute a descent back to the initial hover position.
4. Conclude with a landing to evaluate potential ground-effect couplings.

To artificially induce PVS instability and trigger RPC events, the simulator dynamically alters simulation parameters, such as the rotor gain (G_0), and introduces varying turbulence conditions. This effectively erodes the closed-loop stability margins, forcing the pilot into a high-workload, super-stabilization control strategy.

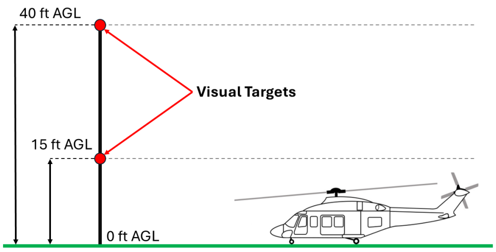


Figure 4: Schematic representation of the Vertical Reposition maneuver proving ground. (Source: Adapted from [31])

5.2. Visual Environment and Participant Cohort

The visual system, developed using the Godot engine and the *LIDIA* library for cockpit instrumentation, provides immersive cues through Virtual Reality (VR) headsets or standard monitors. The environment features specific reference markers (e.g., a red target within a green band) to enforce the "Desired" and "Adequate" performance standards defined by the ADS-33E-PRF for Good Visual Environment (GVE) and Degraded Visual Environment (DVE) conditions.

The experimental campaign involved a diverse cohort, including professional pilots and non-pilot subjects. Prior to the trials, comprehensive demographic and biometric data (e.g., flight hours, specific models flown) were collected to enable a comparative analysis of how flight expertise influences MWL management and the mitigation of adverse biomechanical feedthrough [18].

6. System Integration and Preliminary Experimental Results

A major objective of this thesis was the physical and software integration of the selected multimodal sensors into a cohesive, synchronized architecture within the RPC Test Rig.

6.1. Hardware and Software Integration

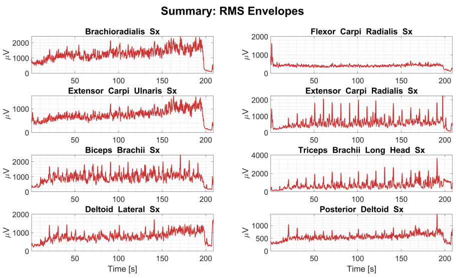
The final assembly centralized data acquisition through a dedicated Pilot PC. High-bandwidth sensors—specifically the sEMG acquisition board, the Pupil Core Eye Tracker, and the Intel RealSense Depth Camera—were connected directly via USB/USB-C interfaces to ensure high-throughput data transfer. Conversely, to manage the bespoke sensors (ECG and OPT-IN), custom 3D-printed enclosures were manufactured to house the microcontrollers and local microSD storage units, which were installed beneath the collective lever to optimize cockpit ergonomics.

Crucially, temporal synchronization across all heterogeneous data streams was achieved utilizing the MARSH protocol. This was governed by a hardware digital trigger system (LabJack T7) that broadcasts a simultaneous start/stop signal to all subsystems, ensuring zero-latency alignment essential for post-hoc correlation analysis.

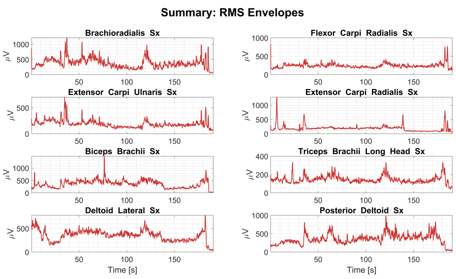
6.2. Comparative Analysis: Expert vs. Novice Operators

Preliminary flight trials executing the ADS-33E vertical repositioning maneuver were conducted to validate the sensor ecosystem. A comparative analysis between a Professional Rotorcraft Pilot and a Non-Pilot subject yielded significant insights into the physiological buffering effect of expertise.

Neuromuscular Response (sEMG): Both subjects exhibited distinct "Active" and "Relaxation" phases corresponding to maneuver execution and subsequent collective release. The RMS amplitude successfully captured muscle activation peaks, particularly during the simulated landing phase—a known trigger for ground-effect couplings (Figure 5). Fatigue analysis based on MNF confirmed progressive muscle fatigue during the active tracking phase.



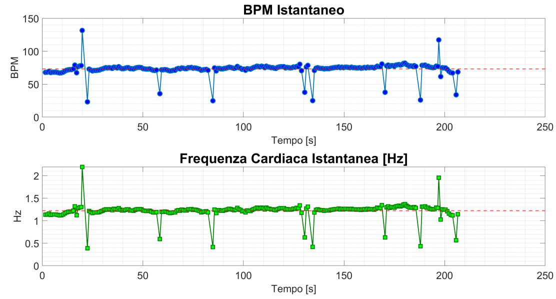
(a) Professional Pilot



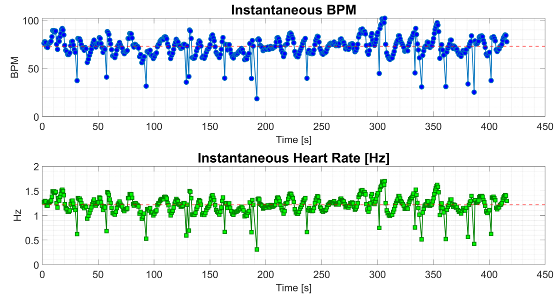
(b) Non-Pilot

Figure 5: Comparison of sEMG RMS values. Distinct activation peaks are visible during the active maneuver phase and particularly during the simulated landing, highlighting the physical effort required to counteract ground-effect dynamic couplings.

Autonomic Stability (ECG): The cardiac response vividly illustrated the impact of expertise on MWL. As shown in Figure 6, the Professional Pilot maintained a highly stable heart rate (averaging 71 BPM) with minimal variance throughout the demanding maneuver. In stark contrast, the Non-Pilot exhibited significantly larger fluctuations in Heart Rate, indicative of more acute stress and cognitive load.



(a) Professional Pilot



(b) Non-Pilot

Figure 6: Heart Rate and BPM evaluation. The Professional Pilot (a) demonstrates remarkable autonomic stability, while the Non-Pilot (b) shows higher variability correlating with task difficulty.

Visual Attention (Eye Tracking): Analysis of the Non-Pilot's oculomotor behavior demonstrated significant variations in visual attention. Figure 7 illustrates a marked decrease in blink rate specifically during the visual tracking phases of the vertical repositioning and the final landing, successfully highlighting the periods of maximal information processing demand.

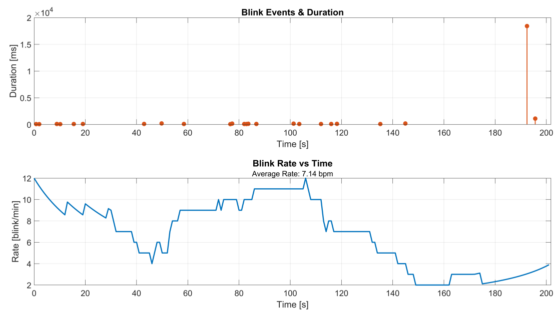
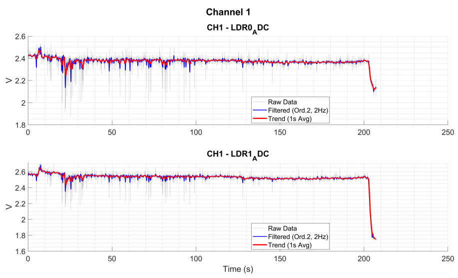
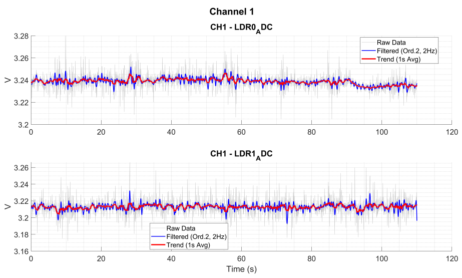


Figure 7: Blink rate analysis for the Non-Pilot subject. The distinct minima correspond directly to the high-workload visual tracking phases and the precision landing task.

Biomechanical Interface (OPT-IN): Data from the FTIR-based grip sensor revealed a profound difference in control strategy. While both subjects showed increased pressure during the active phase, the Non-Pilot exerted substantially higher static grip pressure compared to the expert (Figure 8). This behavior characterizes the "death grip" phenomenon, which drastically modifies the mechanical impedance of the pilot's limb, thereby increasing susceptibility to high-frequency PAOs.



(a) Professional Pilot



(b) Non-Pilot

Figure 8: Voltage values from Channel 1 of the OPT-IN sensor. The consistently high signal amplitude for the Non-Pilot (b) during the active flight phase indicates a stiffening control strategy ("death grip"), significantly altering the biomechanical feedthrough to the vehicle.

7. Conclusions and Future Developments

The primary objective of this thesis—to successfully equip the RPC Test Rig with a synchronized, non-intrusive, multimodal physiological sensor suite—was fully realized. The mechanical integration preserved the ergonomics of the cockpit, ensuring that the measured workload reflects genuine flight task demands rather than artifacts of the measurement equipment. Simultaneously, the software architecture, anchored by the MARSH protocol, achieved the precise temporal synchronization required to correlate transient physiological events with specific aerodynamic phenomena.

Building upon this validated baseline, future research and development will focus on three main trajectories:

- **System Refinement and Automation:** Transitioning from hybrid local storage to fully centralized, real-time telemetry logging for all sensors (ECG, OPT-IN, sEMG). This includes implementing automated MARSH digital triggers to eliminate manual synchronization latency. Additionally, mechanical optimization of the OPT-IN sensor housing is planned to resolve structural vulnerabilities observed under high shear loads.
- **Advanced Data Analytics:** Enhancing post-processing algorithms to extract higher-order metrics. This includes implementing full 3D kinematic reconstruction for the Body Pose module (mapping 2D pixels to 3D Euclidean space to validate biomechanical models) and developing dynamic Area of Interest (AOI) mapping for the Eye Tracking system to automatically correlate gaze fixations with specific cockpit instruments.
- **Objective Workload Index:** The ultimate goal is to fuse the muscular, ocular, cardiac, and kinematic data streams using Machine Learning techniques to generate a real-time, objective workload index.

To validate this predictive MWL model, a comprehensive 6-DOF flight test campaign has been defined. This protocol will utilize Specific Test Objects (STOs) derived from the ADS-33E-PRF standard (e.g., Precision Hover, Accel/Decel, Depart/Abort). Cognitive demand will be systematically modulated by testing pilots across varying visibility conditions—ranging from standard Visual Meteorological Conditions (VMC) to severe DVE. By correlating the continuous physiological telemetry with subjective Bedford Workload Scale ratings across these high-stress scenarios, the FRAME-Lab will be positioned to pioneer the next generation of adaptive, workload-aware flight control systems.

Abbreviations

The following table lists the abbreviations used throughout this Executive Summary.

List of Abbreviations

Acronym	Definition
AGL	Above Ground Level
ANS	Autonomic Nervous System
AOI	Area of Interest
BDFT	Biodynamic Feedthrough
BPM	Beats Per Minute
DVE	Degraded Visual Environment
ECG	Electrocardiogram
EDA	Electrodermal Activity
EMG	Electromyography
FBW	Fly-By-Wire
FDM	Fused Deposition Modeling
FTIR	Frustrated Total Internal Reflection
GVE	Good Visual Environment
HITL	Human-in-the-Loop
HRV	Heart Rate Variability
HSI	Human-System Interaction
MARSH	Modular Arch. for Reconfigurable Simulation of Helicopters
MNF	Mean Spectral Frequency
MTE	Mission Task Element
MWL	Mental Workload
PAO	Pilot-Assisted Oscillation
PIO	Pilot-Induced Oscillation
PVS	Pilot-Vehicle System
RCO	Reduced Crew Operations
RGB	Red-Green-Blue
RPC	Rotorcraft-Pilot Coupling
sEMG	Surface Electromyography
SPO	Single-Pilot Operations
STO	Specific Test Object
VMC	Visual Meteorological Conditions
VR	Virtual Reality

Table 1: Summary of acronyms used in the text.

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