Nascent Design Principles for Human-Machine Interfaces in Airborne Manned-Unmanned Teaming

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Abstract. Manned-unmanned teaming (MUM-T) design remains theoretically fragmented despite growing operational deployment across civilian and military aviation domains. This research-in-progress addresses this gap through a literature-grounded design science study embedded in the echelon design science research framework. Based on a systematic synthesis of 10 fixed-wing MUM-T empirical studies, we derive four theory-grounded, nascent design principles: *Context-Adaptive Automation Intervention*, *Hierarchical Delegation Granularity*, *Integrated Temporal-Spatial Plan Visualization*, and *Bidirectional Human-Autonomy Negotiation*. The contribution is positioned as Level 1 nascent design theory, consolidating fragmented findings into actionable prescriptions justified by cognitive engineering and human-automation interaction theories. The principles establish an initial prescriptive knowledge base for subsequent artifact instantiation and evaluation with operational pilots.

Keywords: Manned-Unmanned Teaming · Human-Machine Interface · Design Principles · Design Science Research · Airborne Operations

1 Introduction

The operational landscape of aviation is undergoing fundamental transformation driven by artificial intelligence and autonomous systems. MUM-T reshapes aviation paradigms across domains: search and rescue, maritime surveillance, border protection, agricultural aviation, and sixth-generation fighter programs integrate manned aircraft with autonomous platforms in "system of systems" architectures [1–3]. This dual-use evolution signals a paradigm shift from human-operated aircraft with automated subsystems to *human-autonomy teams* where pilots supervise, coordinate, and collaborate with intelligent autonomous agents possessing decision-making authority. For example, in a civilian search-and-rescue mission, a pilot may need to retask several autonomous assets around changing weather, emerging detections or altered mission objectives while maintaining radio communication and flight control; in a military escort mission, the pilot may need to

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approve autonomous task reallocations within seconds under rapidly changing threat conditions.

Despite operational deployment across civilian and military domains, MUM-T human-machine interface (HMI) design remains theoretically fragmented. Empirical studies evaluated specific instantiations addressing interaction modalities [9], adaptive automation [7,17], transparency mechanisms [37], and visualization techniques [23], yet no structured design knowledge guides practitioners developing new MUM-T interfaces. This gap is critical for airborne contexts where pilots supervise multiple autonomous platforms while maintaining concurrent flight control, communication, and tactical decision-making under second-scale time constraints [25,33].

Our research-in-progress addresses this gap by deriving four theory-grounded, nascent design principles from systematic synthesis of 10 fixed-wing MUM-T empirical studies (2019–2024). Note, that "fixed-wing" here relates to the guiding platform, not the Unmanned Aerial Vehicles (UAV). Embedded in the echelon design science research (eDSR) framework [38] and following Möller et al.'s [27] supportive approach, these principles consolidate fragmented findings into actionable, testable prescriptions justified by cognitive and human-automation interaction theories. Each principle specifies a core mechanism, addresses literature-derived requirements, and is supported by convergent evidence from multiple studies. We advance nascent, prescriptive knowledge [13], i.e. Level 1 in Gregor and Hevner's framework, where literature-grounded principles provide testable hypotheses for future artifact instantiation and evaluation.

2 Theoretical Background

Manned-Unmanned Teaming has transitioned from experimental concept to operational doctrine across military and civilian aviation domains, yet the design of human-machine interfaces enabling effective human-autonomy collaboration remains theoretically fragmented [4,31]. While empirical research has evaluated specific MUM-T HMI instantiations such as Bautz et al. [7] who assessed situation awareness (SA) criticality matrices for adaptive automation, Heilemann and Schulte [15,17] validated three-tier delegation in fighter-UCAV (unmanned combat aerial vehicle) scenarios, Tokadli et al. [37] derived information visualization requirements for commercial flight decks or Highland et al. [18] studied trust dynamics in autonomous air combat, these contributions remain *instantiation-specific* rather than *principle-generalized.* Implementers and researchers within the scientific and industrial community lack synthesized, fully-matured and theory-justified principles specifying *what* to design for effective human-autonomy teaming [8].

Existing, normative design guidance still appears too immature for airborne MUM-T contexts. Legacy cockpit standards (MIL-STD-1472 [39]) address single-pilot, single-platform operation, and commercial aviation automation policies (FAA Advisory Circulars [12]) focus on deterministic subsystem automation; and NATO interoperability standards (STANAG 4586 [28]) define technical protocols but do not prescribe HMI design principles for managing cognitive challenges unique to airborne MUM-T: concurrent resource competition (manual flight + communication + autonomous asset supervision), time-critical decision-making (5–30 s tactical windows), and safety-critical coordination where errors risk fratricide or mission failure [9,18]. A NATO educational note explicitly states that STANAG 4586 "does not impose detailed human factors or HMI design requirements" beyond interface protocol standardization [34]. These standards establish compliance baselines but provide no design patterns for workload-adaptive assistance, multi-asset mission visualization, hierarchical task delegation, or bidirectional human-autonomy negotiation in fighter cockpits. Consequently, these standards must be treated as *boundary conditions*, i.e. constraints within which our design principles operate, rather than as sources of prescriptive design knowledge.

The design knowledge gap in airborne MUM-T HMI, which is a fragmented empirical findings without synthesized principles, motivates our research question: **What theory-grounded design principles address the cognitive challenges of supervising multiple autonomous platforms in airborne contexts, and what are their mechanisms, boundary conditions, and empirical support?**

3 Methodology

Our methodological approach follows *literature-grounded Design Science Research* [20,22,27], wherein design principles are derived from systematic synthesis of prior empirical work. Within Gregor and Hevner's [13] DSR knowledge contribution framework, our work constitutes *nascent design theory* (Level 1): we advance from disparate empirical observations to generalized, theory-justified design principles prescribing *how* MUM-T HMIs should be constructed to achieve desired outcomes (reduced workload, maintained situation awareness, calibrated trust). These principles are *hypothetical candidates* requiring validation through artifact instantiation and field evaluation, which is a planned extension of this research-in-progress. Following Möller et al. [27], we employ kernel theories from cognitive engineering (Adaptive Automation Theory [29], Multiple Resource Theory [42], Situation Awareness Theory [10]) and human-automation interaction (Levels of Automation [36], Trust in Automation [24], Mixed-Initiative Interaction [19]) at two stages: (i) deriving meta-requirements from theoretical constructs; and (ii) justifying design principles by explaining mechanisms through which principles achieve intended effects.

Our principles target levels of intervention (LOI) 4–5 contexts [28] where operators control multiple (≥3) autonomous platforms with significant decision-making authority, typical of airforce fighter-UCAV teaming (Next Generation Air Dominance Collaborative Combat Aircraft, Future Combat Air System Remote Carriers, Global Combat Air Programme loyal wingmen) and civilian applications (search and rescue coordination, maritime surveillance, border protection) [2,18]. Airborne MUM-T imposes cognitive demands exceeding ground-based teleoperation and commercial aviation automation: pilots perform concurrent tasks with resource conflicts, face time-critical decision-making (5–30 s tactical windows), and require safety-critical coordination where errors risk fratricide, mission failure, or aircraft loss [9,18,33]. These demands establish boundary conditions for our design principles: they apply to contexts where operators supervise multiple autonomous agents under concurrent task demands, time pressure, and safety constraints. Accordingly, our design principles are intended to cover both civilian and military airborne MUM-T settings, provided these cognitive and operational conditions are present.

This study adopts a DSR approach following the echeloned design science research (eDSR) methodology, which decomposes complex DSR projects into self-contained units delivering validated intermediate artifacts [38]. For design principle development, we follow the supportive approach, deriving principles ex-ante from systematic knowledge bases to guide future artifact design [27]. The eDSR methodology organizes DSR work into five design echelon types: problem analysis, objectives and requirements definition, design and development, demonstration, and evaluation [38]. Our study constitutes the first echelon, focusing on problem analysis and initial objectives and requirements definition. Within eDSR, we treat the resulting design principles as nascent, literature-grounded prescriptive outputs of this echelon that guide later instantiation and evaluation.

A systematic literature review was conducted to establish the knowledge base. At this point in time, the search was executed only in SCOPUS using a query combining MUM-T terminology: TITLE-ABS-KEY ((“manned unmanned” OR “manned-unmanned” OR “crewed uncrewed” OR “crewed-uncrewed” OR “manned-unmanned teaming” OR “manned unmanned teaming” OR MUM-T OR MUMT OR “loyal wingman” OR “unmanned wingman” OR CCA OR “collaborative combat aircraft” OR UCAV OR “uncrewed combat aerial vehicle” OR “air-launched effect” OR ALE OR “human machine teaming” OR “human-autonomy teaming”) AND (“human machine interface” OR HMI OR “human computer interaction” OR HCI OR cockpit OR avionics OR “pilot-vehicle interface” OR “crew station” OR “workstation” OR “ground control station” OR GCS OR “control station” OR “decision aid*” OR “adaptive interface” OR “adaptive automation” OR transparency OR explainab* OR “situation awareness” OR workload OR trust)) AND PUBYEAR > 2014 AND PUBYEAR < 2027.

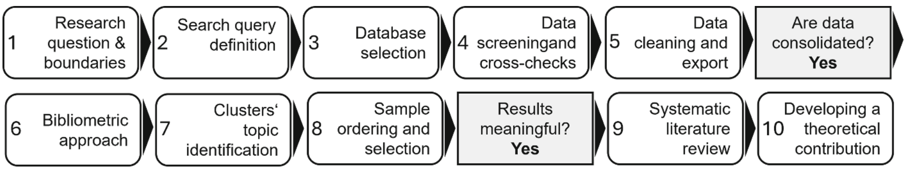

Fig. 1. Simplified B-SLRS Process of Marzi et al. [26]

We adapted the bibliometric-systematic literature review (B-SLRS) approach of Marzi et al. [26], see Fig. 1: we formulated the research question (step 1), defined the query and selected SCOPUS (steps 2–3), refined and cleaned the dataset (steps 4–5), imported the corpus into the bibliometrix tool in RStudio, and conducted thematic map synthesis on abstracts to identify relevant themes (step 6). The "human-autonomy teaming" cluster is one of two clusters, located in the "Motor Themes" quadrant. The other three quadrants in the thematic map are "Basic", "Niche" and "Emerging or Declining" themes. Hence, the "Motor theme" represents the most dense and relevant part of documents [6]. The other motor theme cluster is labeled with "artificial intelligence" but has a lower relevance score. Hence, the human-autonomy cluster, indicating high centrality and density, was selected as our initial source of relevant documents (step 7). Document analysis identified 282 papers strongly associated with this cluster. The papers were ordered according to their associative power to the cluster (step 8), yet none were removed at this point but rather scanned in the next step.

The 282 papers were screened for relevance by two independent coders using ASReview Lab (https://asreview.nl/), a tool for systematic reviews. Inclusion criteria were organized into three tiers. Tier 1 included papers addressing airborne crewed-unmanned teaming with explicit HMI focus: empirical studies, simulations, design frameworks, and systematic reviews examining displays, controls, workload, trust, situation awareness, autonomy transparency, or multi-asset control interfaces. Tier 2 comprised ground or maritime MUM-T domains or adjacent human-autonomy teaming in safety-critical environments, provided HMI challenges were domain-agnostic and transferable to airborne contexts. Tier 3 excluded papers focused purely on autonomy algorithms without human interaction, generic HCI (Human-Computer Interface) without autonomy context, speculative pieces without empirical grounding, and robotics applications lacking operator-interface focus. Screening identified 27 Tier 1 papers. Following full-text examination verifying methodological quality and HMI content depth, 10 papers focusing specifically on fixed-wing MUM-T platforms, which guide the unmanned assets, were selected as the primary knowledge base for this echelon. These papers span from 2019 to 2024 and encompass cockpit interface design, adaptive automation studies, multi-modal interaction research, and human-autonomy teaming transparency investigations. Note, that the downsizing to 10 papers followed an informal author discussion. However, more rigorous methodology and metrics will follow in the ongoing analysis. Steps 9–10 in the B-SLRS process are represented in the following section by deriving and contributing nascent design principles.

4 Design Principle Derivation

From the 10 selected papers, design-relevant findings were extracted following bottom-up clustering. Each paper was analyzed to identify prescriptive statements, empirical findings with design implications, and requirements for effective human-machine interaction in teaming contexts. Extracted elements were coded by underlying mechanisms and grouped into thematic clusters based on addressed human factors challenges.

Clustering yielded four mechanism clusters: adaptive automation intervention (Cluster A), hierarchical task delegation (Cluster B), integrated plan visualization (Cluster C), and bidirectional human-autonomy communication (Cluster D). For each cluster, source-specific findings were synthesized into generalized nascent design principles following the anatomy of a design principle [14]. Table 1 summarizes the design requirements extracted from the literature and serves as the basis for the subsequent principle development.

Table 1. Design Requirements for MUM-T HMI derived from Literature

Source	DR	Description
Bautz et al. 2024 [7]	1	Assistance systems must balance workload and decision-making efficacy without under/overloading pilots
	2	Adaptive assistance must adjust based on operator mental state and environmental assessments
	3	Support situational awareness during multi-UAV delegation under threat
Heilemann & Schulte 2019 [16]	4	Prevent complacency by balancing automation levels and pilot activity in multi-UCAV control
	5	Support task assignment across multiple abstraction levels for varying workload
Heilemann & Schulte 2020 [17]	6	Take-over only tasks human cannot accomplish or are too high risk/cost
	7	Adapt intervention level to mission criticality
Highland et al. 2023 [18]	8	Support cognitive load management for pilots controlling multiple UAVs
	9	Enable real-time measurement and calibration of pilot trust in autonomy
Schulte et al. 2021 [33]	10	Support meaningful human control through adequate workshare/function allocation with controllability and transparency
	11	Manage high work demands from multi-platform mission management
Lindner & Schulte 2020 [25]	12	Keep pilot in decision-making process without overtaxing
	13	Support adaptive transparency to prevent SA loss when autonomy increases
Laudien 2024 [23]	14	Integrate multi-modal interaction (beyond keyboard/mouse) for usability and efficiency
Tokadli et al. 2021 [37]	15	Support bi-directional communication for mission goals, intent, and rationale
	16	Support transparency of behavior, intentions, and goals to build mental model
	17	Support dynamic task allocation based on workload, capabilities, and mission state
	18	Support trust calibration through assessment of skill, experience, and performance

4.1 Cluster A: Adaptive Automation Intervention

The first cluster addresses the challenge of dynamically adjusting automation support based on operator state and mission demands. Source contributions include workload-scaled intervention modes ranging from passive monitoring to automatic execution [15], a situation awareness-criticality matrix determining appropriate levels of automation [7], graduated intervention intensities from hints through simplification to takeover [17], and trust-adaptive interface decluttering and augmentation [18]. The common mechanism across these contributions is the real-time assessment of operator cognitive capacity combined with situational demands to determine appropriate automation behavior while preserving human override authority. The resulting nascent design principle is summarized in Table 2.

Table 2. Nascent Design Principle 1: Context-Adaptive Automation Intervention

DP1	Context-Adaptive Automation Intervention
Aim, Implementer, User	HMI designers (implementer) provide appropriate automation support (aim) for pilots controlling multiple autonomous platforms (user).
Context	Airborne MUM-T with variable workload, dynamic situations, and time-critical decisions requiring supervisory control.
Mechanism	Assess operator cognitive state via SA and workload indicators. Evaluate situational criticality. Select graduated intervention intensity from notification to full automation. Preserve override authority.
Rationale	Grounded in adaptive automation theory [29], multiple resource theory [42], and empirical SA-criticality findings [7,17].

4.2 Cluster B: Hierarchical Task Delegation

The second cluster addresses scalable control mechanisms for managing multiple autonomous platforms. Source contributions include three-tier delegation architectures spanning team, task, and parameter levels [15], four-level delegation schemes enabling mission-appropriate control granularity [33], task-based guidance paradigms abstracting low-level commands [25], and area-of-responsibility concepts for spatial task abstraction [25].

The unifying mechanism is the provision of multiple abstraction levels that operators can select based on their available cognitive resources and the precision required by current mission demands. Table 3 presents the corresponding nascent design principle.

4.3 Cluster C: Integrated Plan Visualization

The third cluster addresses visualization requirements for complex multi-asset mission planning and monitoring. Source contributions include radial context

Table 3. Nascent Design Principle 2: Hierarchical Delegation Granularity

DP2	Hierarchical Delegation Granularity
Aim, Implementer, User	HMI designers (implementer) provide flexible control precision scaling with cognitive resources (aim) for pilots supervising multiple platforms or swarms (user).
Context	Multi-asset teaming balancing tactical control against mission management with varying cognitive resources.
Mechanism	Provide team-level, agent-level, task-level, and parameter-level delegation enabling goal assignment at appropriate abstraction.
Rationale	Grounded in supervisory control theory [35], hierarchical task analysis [5], and empirical delegation studies [15,33].

menus overlaid on tactical maps for rapid task assignment [15], timeline-based interfaces for temporal task insertion and sequencing [15], real-time feedback mechanisms displaying plan impacts and constraint violations [33], and comparative evaluations of 3D versus augmented 2D representations for mission planning [23]. The common mechanism is the integration of spatial and temporal representations with dynamic feedback on plan consequences. The resulting principle is summarized in Table 4.

Table 4. Nascent Design Principle 3: Integrated Temporal-Spatial Plan Visualization

DP3	Integrated Temporal-Spatial Plan Visualization
Aim, Implementer, User	HMI designers (implementer) provide comprehensive mission awareness and efficient plan modification (aim) for pilots coordinating multiple autonomous assets (user).
Context	Complex teaming requiring spatial, temporal, and resource coordination during pre-flight planning and in-flight replanning.
Mechanism	Provide tactical map displays, timeline interfaces, real-time feedback on plan modifications, and proactive conflict detection.
Rationale	Grounded in cognitive fit theory [40], ecological interface design [41], and empirical evaluations [23,33].

4.4 Cluster D: Bidirectional Human-Autonomy Negotiation

The fourth cluster addresses communication patterns between human operators and autonomous teammates. Source contributions include agent-initiated task allocation suggestions [37], modification notification protocols requiring human approval before execution changes [37], swarm avatar interfaces representing collectives as single entitiy [25,33], and warnings against fully distributed autonomous negotiation due to demonstrated situation awareness degradation [33]. The unifying mechanism is bidirectional communication enabling autonomous initiative while maintaining human approval authority through centralized coordination. Table 5 summarizes the corresponding nascent design principle and Fig. 2 shows the DPs as well as their respective DRs and sources.

Table 5. Nascent Design Principle 4: Bidirectional Human-Autonomy Negotiation

DP4	Bidirectional Human-Autonomy Negotiation
Aim, Implementer, User	HMI designers (implementer) enable human-autonomy collaboration maintaining human authority (aim) for pilots teaming with autonomous agents (user).
Context	Dynamic teaming where autonomous agents can assess situations and propose allocations, but human oversight remains essential.
Mechanism	Provide agent-initiated suggestions, modification notifications, explicit approval interfaces, and centralized coordination displays.
Rationale	Grounded in mixed-initiative interaction [19], team coordination theory [32], and empirical findings [33,37].

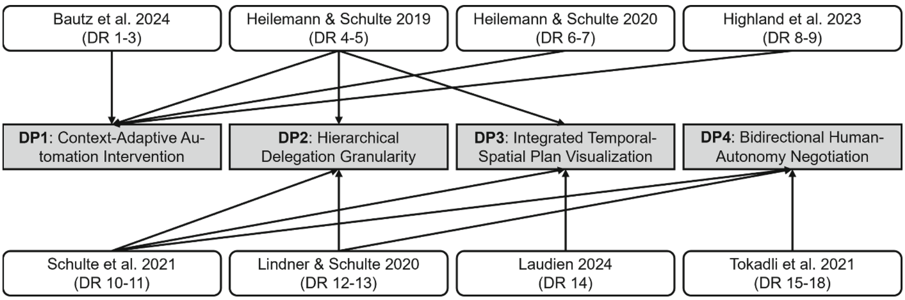

Fig. 2. Mapping of Design Requirements to Design Principles for MUM-T HMI

5 Conclusion and Outlook

Existing guidance for airborne MUM-T leaves room for improvement: legacy standards address single-platform operation [39], commercial policies focus on deterministic subsystem automation [12], and NATO standards define technical protocols without HMI prescriptions [28]. Our nascent principles operationalize kernel theories, hence, adaptive automation [29], supervisory control [35], cognitive fit [40], ecological interface design [41], and mixed-initiative interaction [19], into actionable mechanisms: SA-criticality assessment with graduated intervention, hierarchical delegation, integrated spatial-temporal displays, and agent-initiated suggestions with human approval authority.

The design principles presented in this paper represent the output of echelon 1 in our eDSR research program. Subsequent echelons will expand the knowledge base by incorporating Tier 2 papers and studies from additional domains (rotary-wing, ground, maritime, and space contexts) to validate and refine the principles across operational environments. Echelon 2 will instantiate selected principles in prototype interfaces, while later echelons will conduct demonstration and evaluation activities with domain experts and operational personnel.

For practitioners, our principles provide theory-justified nascent prescriptions complementing standards to address interaction design. For researchers, each mechanism-outcome relationship is testable: failure to produce intended outcomes requires revision. This falsifiability distinguishes our contribution, we make commitments future eDSR echelons can confirm or refute. However, some limitations constrain findings: the 10-study corpus limits grounding and requires maturation across additional contexts [38]; unpublished military research excludes classified knowledge; fixed-wing focus limits transferability. Despite limitations, the study's contribution is an echelon 1 output in the form of nascent, literature-grounded design principles that require later instantiation and evaluation [38].

Research continues through three activities. First, expand the knowledge base with rotary-wing, ground-based, maritime, and space studies to assess generalizability. Second, conduct reusability evaluation [21] assessing accessibility, importance, novelty, actability, and effectiveness. Third, instantiate artifacts in subsequent eDSR echelons [38] through prototype development and human-in-the-loop experimentation. Long-term objective: mid-range design theory integrating principles into coherent frameworks, potentially connecting to abstraction hierarchy frameworks [30,41]. Through this eDSR program, we accumulate validated design knowledge supporting effective HMI for human-autonomy teaming and the youngest research studies [11].

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