The U.S. Military Unmanned Aerial Vehicle (UAV) Experience: Evidence-Based Human Systems Integration Lessons Learned

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ABSTRACT

Background: This study was a 10-year cross sectional analysis of human factors in U.S. military UAV mishaps. Methods: Class A-C UAV mishap reports were reviewed and human factors coded using the Human Factors Analysis and Classification System (HFACS). HFACS codes were linked to human systems integration (HSI) domains. Binary logistic regression was used to create models predicting operator error. Results: $^{133}/_{221}$ (60.2%) UAV mishaps involved human factors. Predictors of operator error were technological environment and cognitive factors in the Air Force ($P < 0.010$), organizational process, psycho-behavioral factors, and crew resource management in the Army ($P < 0.001$), and organizational process, inadequate supervision, planned inappropriate operations, physical and technological environments, and cognitive and psycho-behavioral factors in the Navy ($P < 0.025$). The frequency of specific types of unsafe acts differed between the services with skill-based errors more common in the Air Force ($P = 0.001$) and violations in the Army ($P = 0.016$). HSI failures associated with operator error involved the human factors (functional and cognitive interfaces) and personnel domains in the Air Force ($P < 0.001$), the human factors (cooperational, cognitive, and physical interfaces) and training domains in the Army ($P < 0.001$), and the human factors (environmental, cooperational, organizational, and cognitive interfaces) and training domains in the Navy ($P < 0.001$). Conclusion: Recurring latent failures at the organizational, supervisory, and preconditions levels contributed to more than half of UAV mishaps. The patterns of latent failures and unsafe acts differed between the services. HSI issues pertaining to the human factors domain were common to all services.

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1.0 INTRODUCTION

1.1 Background

Human systems integration (HSI) has been referred to as a "sociotechnical cultural revolution" which seeks the full integration of people, technology, and organizations for the achievement of common goals.[6] More specifically, HSI has been defined as "the technical process of integrating the areas of human engineering, manpower, personnel, training, systems safety, and health hazards with a material system to ensure safe, effective operability and supportability."[4] Department of Defense (DoD) Instruction 5000.2[11] expands this definition of HSI to include habitability, personnel survivability, and environment. The fundamental concept underlying HSI is the consideration of the human element in all aspects of a system's life-cycle so as to reduce resource utilization and system costs from inefficiency while dramatically increasing system performance and productivity. Although current HSI technology and disciplines are focused at the level of major technological systems, future applications may eventually encompass more complex sociotechnical systems such as procurement agencies (e.g., DoD acquisitions) or even entire governmental departments (e.g., DoD). However, currently there is a persistent tendency to consider complex systems as "technology" driven rather than "people-technology" driven. This preferential focus on hardware and software has resulted in numerous system failures to include such well-known incidents as the Three-Mile Island and Chernobyl nuclear accidents and the destruction of an Iranian commercial airliner by the crew of a U.S. naval warship.[6]

Although technology is continuously improving, the frequency of system failures can only be expected to rise, since the opportunity for both human and mechanical failures increase with system complexity, and rapidly developing technologies involve ever increasing complexity.[6] Perhaps no better current case study of this trend exists than DoD's experience with unmanned aerial vehicles (UAVs), also known as remotely piloted vehicles or aircraft (RPVs or RPAs). A great deal of effort has been expended over the last several decades to demonstrate the technical viability and improve the operational utility of UAVs. Current DoD operational UAV systems have demonstrated tremendous capability in recent military operations with at least 100 UAVs of 10 different types utilized in U.S. military operations in Iraq.[25] However, the rapid rise in UAV employment has been accompanied by increased attention to their high mishap rates. For example, since its inception, the Air Force's RQ-1 Predator accumulated a mishap rate of 32 mishaps per 100,000 flight hours, the Navy/Marine's RQ-2 Pioneer 334 mishaps per 100,000 hours, and the Army's RQ-5 Hunter 55 mishaps per 100,000 hours.[24,25,26] When compared to the mishap rate for general aviation of 1 mishap per 100,000 flight hours, the magnitude of the problem becomes readily evident. The reliability of UAVs needs to improve by one to two orders of magnitude to reach the equivalent level of safety of manned aircraft.[24,25,26] Despite the absence of human suffering directly resulting from UAV mishaps to date, there are significant reasons to be concerned. According to two reports by the Office of the Secretary of Defense,[24,26] "the reliability and sustainability of UAVs is vitally important because it underlies their affordability (an acquisition issue), their mission availability (an operations and logistics issue), and their acceptance into civil airspace (a regulatory issue)." Likewise, a Defense Science Board study on UAVs issued in February 2004,[25] identified "high mishap rates" as one of the two biggest threats to realizing the full potential of UAVs. Finally, an Air Force Scientific Advisory Board report from July 2004, on HSI in Air Force weapon systems development and acquisition stated "USAF goals for mishap reduction cannot be achieved without aggressively attacking the problem of human factors" and concluded poor HSI was the leading driver of UAV mishaps (Lindberg RM, 311th Performance Enhancement Directorate. Personal communication; 2005).

1.2 Review of Literature on Human Factors in UAV Mishaps

The Office of the Secretary of Defense's *UAV Reliability Study* issued in 2003,[24] is the most comprehensive review of UAV mishaps to date, the results of which were extracted in large part into

DoD's *UAV Roadmap 2002-2007*[26] and served as the basis for the Defense Science Board's analysis of UAV mishaps.[25] This study found the aggregate sources of failures in the Air Force's RQ-1 Predator, Navy/Marine's RQ-2 Pioneer, and Army's RQ-5 Hunter were power/propulsion (37%), flight controls (26%), communications (11%), human factors (17%), and miscellaneous (9%). It noted "the proportions of human error-induced mishaps are nearly reversed between UAVs and the aggregate of manned aircraft, i.e., human error is the primary cause of roughly 85% of manned mishaps, but only 17% of unmanned ones." Two theories were offered to explain this observation. First, human influence in UAVs is significantly reduced (e.g., "70% less") and is countered by increased automation. Second, human error rates remain constant between UAVs and manned aircraft and are simply overshadowed by the higher unreliability of other subsystems in UAVs. Although no breakdown of human factors was provided, the study reported "three of the areas (e.g., power/propulsion, flight control, and operator training) have historically accounted for 80 percent of UAV reliability failures" and "overall mishap rates for UAVs could be significantly reduced by focusing reliability improvement efforts in these areas," implying human error-induced mishaps were related to training deficiencies. Additionally, the study suggested UAV operator situational awareness may be degraded by the challenges of "human-machine synergy" when the human is on the ground. Recommendations included enhance operator training, particularly through simulation in the ground control station (GCS) environment, automate launch and recovery operations, and employ enhanced synthetic vision technology to help UAV operators maintain flight and sensor perspective. The only additional human factors identified in the Defense Science Board's UAV study[25] were the limited experience level of UAV operators and maintainers, inadequate overall professional development of UAV personnel, and the need to better address takeoff and landing errors.

Given the limited scope of the human factors analysis in DoD's *UAV Reliability Study*,[24] the literature was reviewed for other studies addressing, in total or in part, the role of human factors in UAV mishaps. One of the earliest reviews of UAV mishaps was conducted by Schmidt and Parker[32] with the goal of determining if existing naval aviation safety program human factors efforts could reduce naval UAV mishap rates. They analyzed data from the U.S. Navy's UAV System Safety Working Group minutes, UAV unit safety survey results, informal UAV operator interviews, and UAV mishap reports. Problem areas identified from the safety working group minutes, survey results, and operator interviews included operator selection and training, aeromedical certification and readiness standards, simulator support, crew coordination, and career field development. Their review of UAV mishap reports included 170 RQ-2 Pioneer mishaps over the period 1986-1993. The breakdown of UAV mishap causal factors were 25% engine failure, 24% electrical failure, 22% landing error, 10% mechanical failure, 10% launch error, and 9% miscellaneous to include defective visual acuity, personnel illness, low proficiency, spatial disorientation, poor crew coordination, and crew station design. They reported over 50% of mishaps had human factors elements, such as proficiency and currency issues contributing to launch and landing errors and failures or delays in recognizing and correctly responding to mechanical failures. Based on these findings, they recommended the naval UAV safety program focus on aeromedical screening and monitoring guidelines, criteria based selection procedures and tests, crew coordination and tailored aviation physiology training programs, enhanced human systems integration in crew station design, and UAV community career field development. They also recommended a more comprehensive human factors analysis be conducted and a subsequent database constructed.

Seagle[34] attempted a more systematic analysis of the role of human factors in naval UAV mishaps using Shappell and Wiegmann's Taxonomy of Unsafe Operations[35] which describes 3 levels of human causal factors (e.g., unsafe supervisory practices, unsafe conditions of operators, and the unsafe actions operators commit) that are expanded into 17 categories. Seagle reviewed 203 RQ-2 Pioneer mishaps occurring during the period of fiscal years 1986-1997 and found 103 (50.7%) mishaps had human causal factors and 88 (43.3%) mishaps were specifically associated with supervisory and aircrew causal factors. Of these 88 mishaps, 64.1% involved unsafe supervision of which known unsafe supervisory conditions such as inadequate supervision (e.g., training, policies, and leadership) and failure to correct known problems accounted for the largest categories. Forty-six percent involved unsafe conditions of operators, mostly aeromedical conditions and crew resource management (CRM) deficiencies. Fifty-nine percent had unsafe acts with mistakes the most common category. Seagle also noted human causal factors varied based on environmental conditions, service, and phase of flight. Unsafe conditions, particularly aeromedical conditions and CRM failures, were more common during embarked versus ashore operations. Known unsafe supervisory conditions and CRM failures were associated more with Navy than Marine mishaps. The landing phase accounted for 48.9% of the human related mishaps with CRM failures and mistakes the most common factors. Seagle advised unsafe supervisory practices be addressed through improved leadership training and involvement, by ensuring a better understanding of existing procedures, and implementing procedures where none currently exist. Unsafe conditions of operators should be addressed through improved aeromedical standards and a CRM training program, and the frequency of mistakes reduced by acquisition of a flight simulator and improved training programs. He also discussed the need for UAV community career field development.

Ferguson[17] took the systematic analysis of naval UAV mishaps a step further by developing a stochastic model simulation for the evaluation of human factors initiatives in terms of budgetary cost and mission readiness. In creating the stochastic model, he constructed a mishap database using the Taxonomy of Unsafe Operations.[35] He reviewed 228 RQ-2 Pioneer mishaps occurring during the period of fiscal years 1986-1998, but limited his analysis of causal factors to the period of fiscal years 1993-1998 when mishap reports were standardized by the Navy's aviation safety program. During the latter period, there were 93 mishaps of which 55 (59.1%) had human causal factors. Of these 55 mishaps, 72.7% involved unsafe supervision, 67.3% unsafe conditions of operators, and 63.6% unsafe acts. In contrast to Seagle's findings, unforeseen unsafe supervisory conditions were more common than known unsafe supervisory conditions and aircrew attentional errors (e.g., slips) were more common than mistakes. At the unsafe aircrew conditions level, CRM was still the most significant category. Based on his simulation model, human causal factor mishaps significantly reduced mission readiness and were as costly as electromechanical mishaps. Surprisingly, engineering modifications (e.g., engine improvement or replacement) were predicted to have only a marginal effect on mission readiness and cost. He concluded human factors should be the primary target of intervention strategies and recommended the use of simulators, implementation of improved CRM training, and stabilization of the UAV career field.

Manning et al[21] investigated the role of human causal factors in Army UAV mishaps using a refined version of Shappell and Wiegmann's Taxonomy of Unsafe Operations, the Human Factors Analysis and Classification System (HFACS),[36] which describes 4 levels of human related causal factors (e.g., organizational influences, unsafe supervision, unsafe preconditions, and unsafe acts) that are expanded into 17 categories. They reviewed 56 UAV mishaps occurring during the period of fiscal years 1995-2003 and identified 18 (32%) mishaps with human causal factors. Of these 18 mishaps, organizational influences were present in 44% and involved just the category of organizational process. Unsafe supervision was involved in half and included the categories of inadequate supervision (33%), failure to correct a known problem (17%), and supervisory violations (11%). Preconditions for unsafe acts were present in 6%, all CRM failures. Unsafe acts were present in 61% of human causal factor mishaps, with decision errors the most common category. The authors concluded human error played a significant role in Army UAV accidents and the identification of individual unsafe acts as the leading human causal factor suggested the need for interventions targeting individual mistakes.

Rogers et al[30] conducted a review and analysis of the human systems issues involved in UAV mishaps using a human systems issues taxonomy. They analyzed U.S. Army and Air Force UAV mishaps occurring from January 1993 to June 2003 and identified 48 mishaps (e.g., 26 Army and 22 Air Force mishaps), 33 (68.8%) which were caused by operational human systems issues. The breakdown of human systems issues in these 33 mishaps was 27% training, 25% team performance, 18% situational awareness, 16% interface design, and 14% cognitive and decision making. Additionally, they examined mishap UAV operator flight experience for Air Force mishaps only and found the highest frequency of mishaps occurred among those with the least UAV experience (e.g., 0-500 UAV flying hours) and the most total flight experience (e.g., >1,000 total flying hours). They concluded the UAV development community must focus significant attention and resources on human systems issues during both design and testing. They recommended the military services pool their mishap experiences, periodically analyze UAV mishaps to identify human systems issues using a refined human systems issues taxonomy, and ensure any new insights are promptly provided to the acquisition community.

Finally, Williams[41] conducted a review of DoD UAV mishaps using a novel 2-step classification process. Mishaps were first classified as human factors, maintenance, aircraft, or unknown. Human factors were further classified as alerts/alarms, display design, procedural error, skill-based error, or other. He found the types of mishaps and patterns of human factors varied based on the UAV system. Overall, electromechanical failure (33-67%) was more common than human error (21-68%) as a cause of UAV mishaps. Human factors were most prevalent in RQ-1 Predator mishaps (67%) and consisted mainly of procedural error and display design deficiencies. Twenty-eight percent of RQ-2 Pioneer mishaps and 47% of RQ-5 Hunter mishaps were attributed to human factors, the majority of which were external pilot landing errors. In contrast, the RQ-7 Shadow, which is equipped with an automated landing system, had human causal factors present in 21% of mishaps. The specific human factors issues in the RQ-7 included alerts and alarms (40%), display design (40%), and procedural error (40%).

Table 1: Summary of Prior UAV Mishap Studies Using Standardized Human Factors Taxonomies.

Seagle[34]	**Ferguson**[17]	**Manning et al.**[21]	**Rogers et al.**[30]
Navy *n* = 203	Navy *n* = 93	Army *n* = 56	Air Force, Army *n* =48
Taxonomy: Taxonomy of Unsafe Acts	Taxonomy: Taxonomy of Unsafe Acts	Taxonomy: HFACS	Taxonomy: Human systems issues
Human Factors: 43%	Human Factors: 59%	Human Factors: 32%	Human Factors: 69%
Factors:* Unsafe acts (59%) Accidental acts (52%) Slips (2%) Lapses (16%) Mistakes (39%) Conscious acts (7%) Infractions (7%) Unsafe condition (46%) Aeromedical (20%) CRM (27%) Readiness violations (7%) Unsafe supervision (61%) Unforeseen (34%) Foreseen (47%)	Factors:* Unsafe acts (38%) Intended (17%) Mistakes (12%) Violations (7%) Unintended (20%) Slip (14%) Lapse (3%) Unsafe condition (40%) Aeromedical (10%) CRM (28%) Readiness violations (10%) Unsafe supervision (43%) Unforeseen (15%) Foreseen (12%)	Factors:* Unsafe acts (61%) Skill-based (22%) Decision (33%) Misperception (17%) Violations (11%) Preconditions (6%) CRM (6%) Unsafe supervision (50%) Inadequate supervision (33%) Failed to correct known problem (17%) Supervisory violations (11%) Organizational influences (44%) Organizational process (44%)	Factors: Training (27%) Team performance (25%) Situational awareness (18%) Interface design (16%) Cognitive & decision making (14%)

1.3 Problem Statement

Risser et al[29] proposed a 3-step process for joint UAV HSI issue identification and solution coordination at a 2004 UAV human factors workshop (Figure 1). One of the initial inputs to this process is a systematic review of UAV mishaps tailored to specifically identify HSI problems. Unfortunately, none of the aforementioned studies are sufficient for this purpose for a variety of reasons. Although Williams[41] provides a review of human factors in UAV mishaps in all three military services via the UAV systems they operate, he doesn't utilize a standardized accident model or human factors taxonomy that would allow for a hierarchical analysis of human error.[1,35,36,39,40] The other studies do not provide an aggregate DoD-wide look at human factors in UAV mishaps, and with the exception of the studies by Seagle[34] and Ferguson[17] both examining Navy UAV mishaps, none utilize a similar human factors taxonomy allowing the direct comparison of findings. Such a comparison across military services would be useful to determine which human factors are common and likely inherent to all UAV operations versus those which are service-specific and reflect outcomes of different policies and processes or are unique to UAV type. Determining the prevalence of specific human factors would also allow the necessary prioritization of interventions given ever present resource limitations and identify those interventions best initiated at the joint (e.g., DoD) versus individual services level.[29,30] Finally, utilization of a hierarchical model of human error to identify latent as well as active human failures would be of importance since latent failures have the tendency to contribute to more mishaps than active failures.[1,39,40]

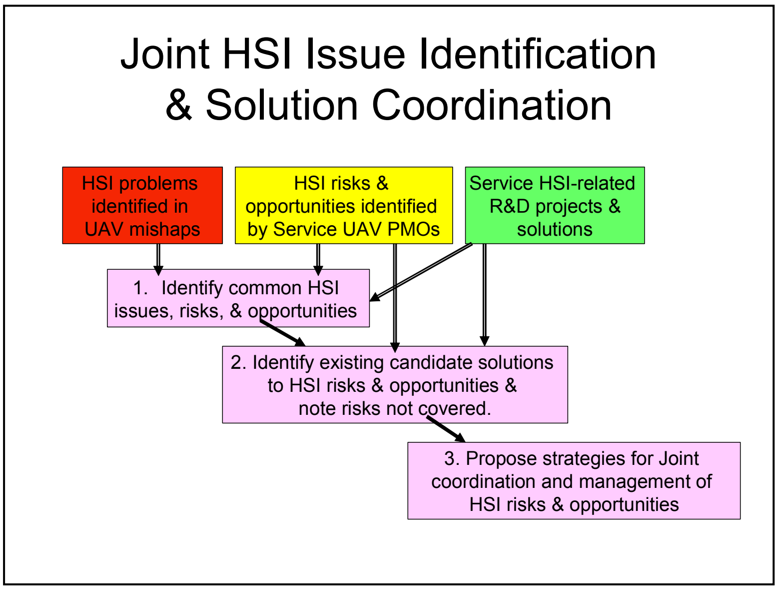

Figure 1. Proposed Process for Joint UAV HSI Issue Identification and Solution Coordination.[29]

1.4 Study Purpose

The purpose of this study is to provide a quantitative analysis of the role and patterns of active and latent human failures in UAV mishaps within the U.S. military services using a standardized human factors taxonomy.[1] Subsequently, these active and latent failures are systematically mapped to an existing DoD HSI taxonomy[9] to assess if there are any joint UAV HSI issues (Figure 1, step 1).[29,30]

2.0 METHODS

2.1 Study Design

This study protocol was approved by the Brooks City-Base Institutional Review Board in accordance with 32 CFR 219 and AFI 40-402. The study design is a 10-year cross sectional quantitative analysis of human factors in UAV mishaps using DoD HFACS[1] version 5.7[†] taxonomy with associated nanocodes (Wurmstein A, USAF Safety Center. Personal communication; 2004). DoD HFACS taxonomy is based on Weigmann and Shappell's HFACS and the reader is referred to their work for a more detailed description of the taxonomy system.[36,40] In brief, HFACS describes four levels of latent and active human failure: 1) organizational influences, 2) unsafe supervisory practices, 3) unsafe preconditions of operators, and 4) acts committed by operators. These four levels are further resolved into root level categories. The purpose of looking at all four levels is to overcome the limitations of many accident models which isolate one factor as causal and the others as contributory when in fact most mishaps involve a variety of events and conditions. In their work to adopt HFACS as the standard DoD human factors taxonomy, the military services' safety centers found there was insufficient resolution at the level of Weigmann and Shappell's root categories to capture some of the detail contained in the service-specific human factors taxonomy systems. To remedy this problem, they developed a system of nanocodes, in essence adding subcategories to Weigmann and Shappell's root categories.[1]

DoD HFACS nanocodes were linked to the 7 HSI domains of manpower, personnel, training, human factors, safety and occupational health, personnel survivability, and habitability as outlined in the HSI chapter of the *Defense Acquisition Guidebook* (DAG).[9] The DAG subdivides the human factors domain into 8 interfaces: functional, informational, environmental, cooperational, organizational, operational, cognitive, and physical. The DAG is based on DoD Directive 5000.1[10] and DoD Instruction 5000.2[11] which address a total systems approach in acquisition management and HSI respectively. The reader is referred to the DAG for a more detailed description of the HSI domains and human factors interfaces.

2.2 Data

The inclusion criteria for this study were a U.S. Air Force, Army, or Navy/Marine UAV Class A, B, or C severity mishap occurring during fiscal years 1994-2003. Department of Defense Instruction 6055.7[12] definitions were utilized. Thus, a UAV was defined as an unmanned weight-carrying device supported in flight by buoyancy or dynamic action. A Class A severity mishap was one in which the total cost of property damage was $1 million or more; a DoD aircraft was destroyed; or an injury and/or occupational illness resulted in a fatality or permanent total disability. Of note, destruction of a UAV did not by itself constitute a Class A severity mishap unless the total costs were at least $1 million. A Class B severity mishap resulted in total property damage of $200,000 or more, but less than $1 million; an injury and/or occupational illness resulted in permanent partial disability; or three or more personnel were hospitalized for inpatient care. A Class C severity mishap resulted in total property damage of $20,000 or more, but less than $200,000; a nonfatal injury caused loss of time from work beyond the day or shift on which it occurred; or a nonfatal occupational illness or disability caused loss of time from work or disability at any time.

Site visits were conducted to the respective safety centers for the U.S. Air Force, Army, and Navy/Marines to access all available mishap records and databases pertaining to UAV mishaps. In total, 271 mishaps were extracted for analysis. However, per OPNAVINST 3750.6R,[13] the Navy specifically excludes "unmanned target drone aircraft" from the definition of UAVs in their aviation safety program. To reduce the heterogeneity of the data between the services, all mishap reports pertaining to unmanned target drones were censored from the study. This left 221 UAV mishaps which were submitted to further analyses using DoD's HFACS taxonomy.

† Version 6.2 is the final, approved iteration of DoD HFACS. DoD HFACS version 5.7 was the most current iteration at the time of data collection for this study. The main difference from version 5.7 to 6.2 involved additions, deletions, and rewording of nanocodes, the end result of which was to increase the total number of nanocodes from 138 to 147. At the level of root categories, "crew resource management" was changed to "coordination/communication/planning factors" and "misperception errors" was changed to "perception errors." For the purposes of this study, changes were significant only with regards to the crew resource management nanocodes.

2.3 Human Factors Classification Using HFACS

Two separate raters (e.g., one aerospace medicine specialist and one research physiologist) analyzed each mishap independently and classified each human causal factor using the DoD HFACS version 5.7 framework with associated nanocodes. After the raters made their initial classification of the human causal factors, the 2 independent ratings were compared. Where disagreement existed, the raters reconciled their differences and the consensus classification was included in the study database for further analysis. A single mishap typically had several human factors associated with it, and this analysis went beyond the primary causal factor and addressed known contributing factors. Mishap coding was done to the lowest possible level given the data available. Only those causes and contributing factors identified by the original investigation were included. No new casual factors were identified or accidents reinvestigated. However, in cases where an inference could reasonably be made as to embedded human causal factors based on the mishap narrative, findings, or recommendations, codes were assigned accordingly. It is important to note there was significant heterogeneity in the amount of detail contained within mishap reports. In particular, Army UAV mishaps were investigated as ground mishaps until October 1, 2003,[14] and as a result many of the mishap reports were incomplete and pointed to only one causal factor.

Several caveats should be highlighted regarding the coding of mishaps involving mechanical failures. Mishaps that were purely mechanical in nature without other human involvement were not coded using HFACS (e.g., the mishap finding was "propulsion failure"). However, mechanical failure did not preclude a mishap from having human causal factors. For example, a mishap involving mechanical failure but the UAV was recoverable save for the delayed or improper actions of the crew (e.g., engine failure within gliding distance of the runway) was coded as human error-related. In such cases, mechanical failures created abnormal conditions or emergencies which fostered human errors. Other mechanical failures were actual manifestations of latent failures at the organizational level and were coded using HFACS. Examples include mishaps where it was noted that a defect in design was known prior to the flight, but was not corrected because of demands of limited budgets or other management or policy constraints. Many mechanical failures involved human error on the part of maintenance crews. Although these errors were coded using HFACS, they were not included in the subsequent analysis of human causal factors with the exception of the initial determination of the crude proportion of UAV mishaps involving any human factors.

2.4 Human Factors Classification Using HSI Domains

The same two raters with the assistance of an experienced HSI practitioner post hoc linked the DoD HFACS nanocodes utilized during the aforementioned mishap coding to the 7 HSI domains and 8 human factors interfaces outlined in the DAG. Each nanocode was linked to a HSI domain and, in the case of the human factors domain, was further linked to one of the 8 human factors interfaces (Tables 2-3). Therefore, linkages were made based on official DoD HFACS nanocode and DAG HSI domain/interface definitions and descriptions. In several cases, mishap reports were reviewed to determine the most appropriate linkage when it was not obvious based on the available definitions and descriptions. Decisions on linking nanocodes and HSI domains/interfaces were made by consensus. As with the nanocodes, a single mishap typically had several HSI domains/interfaces associated with it. Ten percent of mishap reports were randomly selected and reviewed to ensure consistency between HSI domains/interfaces identified directly from the mishap report versus those derived from nanocode linkages.

2.5 Statistical Analysis

A database was constructed using EXCEL (Microsoft, Redmond, WA) and each mishap was assigned an identification number and entered into a master table regardless of causal factors. The data set was partitioned to show all four levels of human factors distribution in relation to 1) all UAV mishaps, 2) mishaps and service, and 3) mishaps and vehicle. Statistica's (StatSoft, Tulsa, OK) log-linear analysis and Statistical Package for the Social Sciences' (SPSS Inc, Chicago, IL) chi-square (χ^2), Cramer's V, Fisher's Exact Test (FET), bivariate correlation, and binary logistic regression were utilized.[31] FET was utilized for 2 x 2 tables and Cramer's V for larger *r* x *c* tables not meeting the conditions for the chi-square test.

Table 2. Linkages Between Human Factors Interfaces and HFACS Nanocodes.

Human factors interfaces	Human Factors Analysis and Classification System		
	Top level	**Root category**	**Nanocode**
Functional	Preconditions	Technological environment	Automation
Environmental	Organizational	Resource/acquisition management	Airfield resources
	Preconditions	Physical environment	Vision restricted by icing/windows fogged Vision restricted by weather/haze/darkness Lighting of other aircraft/vehicle
Cooperational	Preconditions	Crew resource management	Crew coordination/flight integrity Communication Mission preparation Analysis Crew leadership Authority gradient
Organizational	Organizational	Resource/acquisition management	Air traffic control resources Acquisition policies/processes
		Organizational climate	Unit/organizational values/culture
		Organizational process	Procedural guidance/publications Doctrine Program oversight/program management
	Supervision	Inadequate supervision	Leadership/supervision/oversight inadequate Supervision policy
		Planned inappropriate operations	Ordered/led on mission beyond capability Risk assessment - deliberate
		Supervisory violations	Supervision – discipline enforcement Supervision – defacto policy Authorized unnecessary hazard
Cognitive	Preconditions	Cognitive factors	Inattention Channelized attention Cognitive task oversaturation Confusion Negative transfer Distraction Habit pattern interference
		Psycho-behavioral factors	Emotional state Overconfidence Pressing Complacency
		Perceptual factors	Illusion – visual Misperception of flight conditions Spatial disorientation – recognized
Physical	Preconditions	Technological environment	Instrumentation and sensory feedback systems Visibility restrictions Controls and switches Communications - equipment

Table 3. Linkages Between HSI Domains and HFACS Nanocodes.

HSI domains	Human Factors Analysis and Classification System		
	Top level	**Root category**	**Nanocode**
Personnel	Organizational	Resource/acquisition management	Accession/selection policies
	Supervision	Planned inappropriate operations	Limited recent experience Limited total experience
	Preconditions	Psycho-behavioral factors	Pre-existing personality disorder Pre-existing psychological disorder
		Physical/mental limitations	Learning ability/rate Motor skill/coordination or timing deficiency
Training	Organizational	Organizational process	Organizational training issues/programs
	Supervision	Inadequate supervision	Local training issues/programs
		Planned inappropriate operations	Crew/flight makeup/composition Proficiency
Manpower	Organizational	Resource/acquisition management	Personnel resources
		Organizational process	Ops tempo/workload
Safety and occupational health	Organizational	Organizational process	Risk assessment - strategic
	Supervision	Failed to correct known problem	Personnel management Operations management
	Preconditions	Adverse physiological states	Pre-existing physical illness/injury/deficit
Personnel survivability	Preconditions	Adverse physiological states	Fatigue – acute Fatigue - chronic

3.0 RESULTS

3.1 Frequencies of Human Factors Mishaps

Of the 221 UAV Class A, Class B, and Class C mishaps occurring during the period of fiscal years 1994-2003, 38 (17.2%) involved the RQ-1 Predator, 127 (57.5%) the RQ-2 Pioneer, 4 (1.8%) the RQ-4 Global Hawk, 25 (11.3%) the RQ-5 Hunter, 20 (9.0%) the RQ-7 Shadow, and 7 (3.2%) miscellaneous or unspecified UAVs. Overall, 151 (68.3%) mishaps involved operations or maintenance organizational, supervisory, or individual human causal factors. Excluding 18 mishaps solely caused by maintenance error which were not analyzed further, 133 (60.2%) mishaps involved operations human causal factors, here forthwith referred to simply as human causal factors. The frequency distribution of human causal factors mishaps within the services differed significantly ($\chi^2_{2df} = 15.974$, $P < 0.001$) with 79.1% in the Air Force, 39.2% in the Army, and 62.2% in the Navy/Marines. Mechanical failure was present in 150 (67.9%) mishaps, although it was the sole causal factor in only 70 (31.7%) mishaps. In contrast, human causal factors were solely involved in 53 (24.0%) mishaps and 80 (36.2%) mishaps were attributed to the combination of mechanical and human causal factors (FET, $P = 0.003$). No cause was identified in 18 (8.1%) mishaps.

3.2 HFACS Analysis

The data set of UAV mishaps was partitioned to distinguish between the services and human causal factors distributions in HFACS (Tables 4-6), the top-level results of which are summarized in Figure 2. Since HFACS is a hierarchical model based on the premise latent failures at the levels of organizational influences, supervision, and preconditions predispose to active failures (e.g., acts), the dependent variable in this analysis was acts. Latent failures at the levels of organizational influences, supervision, and preconditions were the independent variables. Human causal factors mishaps were explored to verify the presence of independent variables was associated with the occurrence of an act. This was indeed the case for the independent variables supervision and preconditions. However, 47 (44.8%) human causal factors mishaps involving organizational influences did not have an associated act.

Table 4. UAV Mishap Nanocode Summary Chart for Organizational Influences and Supervision Levels.

DoD HFACS (v5.7)	Air Force No.	Air Force %HF* (n=34)	Air Force %tot† (n=43)	Army No.	Army %HF* (n=20)	Army %tot† (n=51)	Navy/Marines No.	Navy/Marines %HF* (n=79)	Navy/Marines %tot† (n=127)
Organizational influences	27	79.4%	62.8%	13	65.0%	25.5%	65	82.3%	51.2%
Resource/acquisition management	21	61.8%	48.8%	7	35.0%	13.7%	53	67.1%	41.7%
Air traffic control resources	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Airfield resources	1	2.9%	2.3%	1	5.0%	2.0%	2	2.5%	1.6%
Acquisition policies/processes	20	58.8%	46.5%	6	30.0%	11.8%	49	62.0%	38.6%
Accession/selection policies	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Personnel resources	0	0%	0%	1	5.0%	2.0%	3	3.8%	2.4%
Organizational climate	3	8.8%	7.0%	0	0%	0%	1	1.3%	0.8%
Unit/organizational values/culture	3	8.8%	7.0%	0	0%	0%	1	1.3%	0.8%
Organizational process	18	52.9%	41.9%	9	45.0%	17.6%	27	34.2%	21.3%
Ops tempo/workload	3	8.8%	7.0%	1	5.0%	2.0%	4	5.1%	3.1%
Risk assessment - strategic	5	14.7%	11.6%	0	0%	0%	5	6.3%	3.9%
Procedural guidance/publications	11	32.4%	25.6%	6	30.0%	11.8%	20	25.3%	15.7%
Organizational training issues/programs	2	5.9%	4.7%	4	20.0%	7.8%	10	12.7%	7.9%
Doctrine	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Program oversight/program management	2	5.9%	4.7%	0	0%	0%	0	0%	0%
Supervision	13	38.2%	30.2%	8	40.0%	15.7%	21	26.6%	16.5%
Inadequate supervision	8	23.5%	18.6%	5	25.0%	9.8%	19	24.1%	15.0%
Leadership/supervision/oversight inadequate	2	5.9%	4.7%	2	10.0%	3.9%	5	6.3%	3.9%
Local training issues/programs	6	17.6%	14.0%	2	10.0%	3.9%	8	10.1%	6.3%
Supervision - policy	2	5.9%	4.7%	1	5.0%	2.0%	9	11.4%	7.1%
Planned inappropriate operations	6	17.6%	14.0%	3	15.0%	5.9%	9	11.4%	7.1%
Ordered/led on mission beyond capability	1	2.9%	2.3%	0	0%	0%	2	2.5%	1.6%
Crew/flight makeup/composition	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Limited recent experience	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Limited total experience	1	2.9%	2.3%	2	10.0%	3.9%	1	1.3%	0.8%
Proficiency	1	2.9%	2.3%	1	5.0%	2.0%	6	7.6%	4.7%
Risk assessment - deliberate	2	5.9%	4.7%	0	0%	0%	1	1.3%	0.8%
Failed to correct known problem	2	5.9%	4.7%	0	0%	0%	3	3.8%	2.4%
Personnel management	1	2.9%	2.3%	0	0%	0%	2	2.5%	1.6%
Operations management	1	2.9%	2.3%	0	0%	0%	1	1.3%	0.8%
Supervisory violations	2	5.9%	4.7%	2	10.0%	3.9%	0	0%	0%
Supervision - discipline enforcement	0	0%	0%	2	10.0%	3.9%	0	0%	0%
Supervision - defacto policy	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Authorized unnecessary hazard	1	2.9%	2.3%	0	0%	0%	0	0%	0%

*Factor frequency as a percentage of only mishaps caused by human factors.
†Factor frequency as a percentage of mishaps of all causes.

Table 5. UAV Mishap Nanocode Summary Chart for Preconditions Level.

DoD HFACS (v5.7)	Air Force No.	Air Force %HF* (n=34)	Air Force %tot† (n=43)	Army No.	Army %HF* (n=20)	Army %tot† (n=51)	Navy/Marines No.	Navy/Marines %HF* (n=79)	Navy/Marines %tot† (n=127)
Preconditions	20	58.8%	46.5%	13	65.0%	25.5%	36	45.6%	28.3%
Physical environment	0	0%	0%	1	5.0%	2.0%	8	10.1%	6.3%
Vision restricted by icing/windows fogged	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Vision restricted by weather/haze/darkness	0	0%	0%	1	5.0%	2.0%	6	7.6%	4.7%
Lighting of other aircraft/vehicle	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Technological environment	16	47.1%	37.2%	2	10.0%	3.9%	8	10.1%	6.3%
Instrumentation/sensory feedback systems	9	26.5%	20.9%	0	0%	0%	0	0%	0%
Visibility restrictions	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Controls and switches	1	2.9%	2.3%	1	5.0%	2.0%	3	3.8%	2.4%
Automation	10	29.4%	23.3%	1	5.0%	2.0%	2	2.5%	1.6%
Communications - equipment	0	0%	0%	0	0%	0%	2	2.5%	1.6%
Physical/mental limitations	1	2.9%	2.3%	0	0%	0%	1	1.3%	0.8%
Learning ability/rate	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Motor skill/coordination or timing deficiency	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Cognitive factors	9	26.5%	20.9%	3	15.0%	5.9%	15	19.0%	11.8%
Inattention	1	2.9%	2.3%	1	5.0%	2.0%	3	3.8%	2.4%
Channelized attention	5	14.7%	11.6%	1	5.0%	2.0%	7	8.9%	5.5%
Cognitive task oversaturation	1	2.9%	2.3%	1	5.0%	2.0%	4	5.1%	3.1%
Confusion	1	2.9%	2.3%	1	5.0%	2.0%	1	1.3%	0.8%
Negative transfer	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Distraction	1	2.9%	2.3%	1	5.0%	2.0%	4	5.1%	3.1%
Habit pattern interference	1	2.9%	2.3%	0	0%	0%	1	1.3%	0.8%
Adverse physiological states	3	8.8%	7.0%	0	0%	0%	3	3.8%	2.4%
Pre-existing physical illness/injury/deficit	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Fatigue - acute	2	5.9%	4.7%	0	0%	0%	2	2.5%	1.6%
Fatigue - chronic	1	2.2%	2.3%	0	0%	0%	0	0%	0%
Psycho-behavioral factors	4	11.8%	9.3%	6	30.0%	11.8%	11	13.9%	8.7%
Pre-existing personality disorder	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Pre-existing psychological disorder	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Emotional state	0	0%	0%	1	5.0%	2.0%	0	0%	0%
Overconfidence	0	0%	0%	5	25.0%	9.8%	1	1.3%	0.8%
Pressing	2	5.9%	4.7%	0	0%	0%	1	1.3%	0.8%
Complacency	2	5.9%	4.7%	0	0%	0%	9	11.4%	7.1%
Perceptual factors	3	8.8%	7.0%	2	10.0%	3.9%	6	7.6%	4.7%
Illusion - visual	0	0%	0%	2	10.0%	3.9%	0	0%	0%
Misperception of flight conditions	3	8.8%	7.0%	0	0%	0%	5	6.3%	3.9%
Spatial disorientation - recognized (type 2)	0	0%	0%	0	0%	0%	1	1.3%	0.8%
Crew resource management	6	17.6%	14.0%	7	35.0%	13.7%	25	31.6%	19.7%
Crew coordination/flight integrity	4	11.8%	9.3%	4	20.0%	7.8%	6	7.6%	4.7%
Communication	1	2.9%	2.3%	2	10.0%	3.9%	9	11.4%	7.1%
Mission preparation	1	2.9%	2.3%	1	5.0%	2.0%	6	7.6%	4.7%
Analysis	1	2.9%	2.3%	1	5.0%	2.0%	5	6.3%	3.9%
Crew leadership	0	0%	0%	1	5.0%	2.0%	4	5.1%	3.1%
Authority gradient	0	0%	0%	0	0%	0%	3	3.8%	2.4%

*Factor frequency as a percentage of only mishaps caused by human factors.
†Factor frequency as a percentage of mishaps of all causes.

Table 6. UAV Mishap Nanocode Summary Chart for Acts Level.

DoD HFACS (v5.7)	Air Force No.	Air Force %HF* (n=34)	Air Force %tot† (n=43)	Army No.	Army %HF* (n=20)	Army %tot† (n=51)	Navy/Marines No.	Navy/Marines %HF* (n=79)	Navy/Marines %tot† (n=127)
Acts	24	70.6%	55.8%	16	80.0%	31.4%	44	55.7%	34.6%
Skill-based errors	17	50.0%	39.5%	6	30.0%	11.8%	21	26.6%	16.5%
Inadvertent operation - mechanically induced	1	2.9%	2.3%	1	5.0%	2.0%	1	1.3%	0.8%
Checklist error	3	8.8%	7.0%	1	5.0%	2.0%	1	1.3%	0.8%
Navigational error	1	2.9%	2.3%	0	0%	0%	0	0%	0%
Procedural error	14	41.2%	32.6%	1	5.0%	2.0%	10	12.7%	7.9%
Overcontrol/undercontrol	1	2.9%	2.3%	1	5.0%	2.0%	7	8.9%	5.5%
Breakdown in visual scan	2	5.9%	4.7%	3	15.0%	5.9%	6	7.6%	4.7%
Judgment and decision-making errors	13	38.2%	30.2%	9	45.0%	17.6%	30	38.0%	23.6%
Risk assessment - time critical	9	26.5%	20.9%	4	20.0%	7.8%	21	26.6%	16.5%
Task misprioritization	2	5.9%	4.7%	1	5.0%	2.0%	9	11.4%	7.1%
Necessary action - rushed	0	0%	0%	1	5.0%	2.0%	0	0%	0%
Necessary action - delayed	5	14.7%	11.6%	2	10.0%	3.9%	4	5.1%	3.1%
Caution/warning ignored	1	2.9%	2.3%	1	5.0%	2.0%	1	1.3%	0.8%
Misperception errors	3	8.8%	7.0%	2	10.0%	3.9%	6	7.6%	4.7%
Violations	3	8.8%	7.0%	9	45.0%	17.6%	6	7.6%	4.7%

*Factor frequency as a percentage of only mishaps caused by human factors.
†Factor frequency as a percentage of mishaps of all causes.

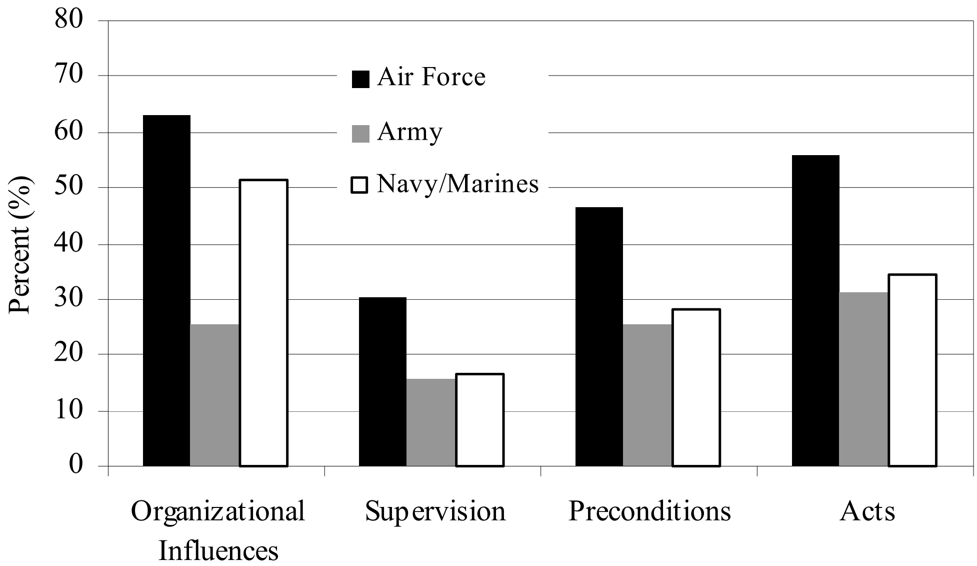

Figure 2. Top Level HFACS Human Causal Factors by Military Service as Percentage of Total Mishaps.

The relationship of organizational influences and acts was further evaluated to explain the apparent deviation from the underlying assumptions of the HFACS model of error. Organizational influences is composed of 3 root categories, resource/acquisition management, organizational culture, and organizational process. For the Air Force and Navy/Marines, organizational influences was the most frequent type of latent failure and was present in 79.4% and 82.3% of human causal factors mishaps respectively. The services differed significantly in the frequency distribution of mishaps involving organizational influences (P = 0.002), which was largely attributable to the frequency distribution of mishaps involving the resource/acquisition management root category (P < 0.001). The frequency distribution in the resource/acquisition management root category was nearly entirely the result of the frequency distribution of the acquisition policies/processes nanocode. This nanocode predominated in Air Force (46.5%) and Navy/Marine (38.6%) versus Army (11.8%) mishaps. Mishaps involving the resource/acquisition management root category had a significantly higher likelihood of being associated with an electromechanical malfunction (OR 3.2, 95% CI 1.5-6.6) rather than an act (OR 0.2, 95% CI 0.1-0.4) as the active failure.

Because of concerns about potential latent failure detection biases caused by differences in individual service mishap investigation methodologies, the mishap database was stratified by service. Service-specific binary logistic regression models were then computed using the 16 root categories of latent failure as potential predictor variables for the dichotomous dependent variable acts. Models were estimated using a forward stepwise method, the results of which are summarized in Table 7. The service-specific logistic regression models differed substantially with regards to the root categories of latent error retained in each model. No single root category of latent error was present in all three models. Based on the percentage of acts correctly classified by each service's model, good models were computed for the Army and Navy/Marine mishap data while only a fair model could be computed for the Air Force mishap data. The breakdown of nanocodes associated with each of the root categories of latent error included in the services' models are also presented in Table 7.

Given the complexity of the initial Navy/Marines logistic regression model which contained 7 predictor variables, a factor analysis was conducted to evaluate for redundancy among the predictor variables. Specifically, a principle component analysis was utilized yielding 2 factors. The first factor, which was labeled "work and attention," encompasses organizational issues regarding the characteristics and conditions of work (e.g., ops tempo) and the procedures for doing work (e.g., training and formal procedures), the tools for conducting work (e.g., technological environment), and the operators allocation of attention in conducting work (e.g., cognitive attentional spotlight and motivation to attend to tasks). The second factor, labeled "risk management," includes situations where squadron supervision failed to adequately identify, recognize, assess, or control and mitigate risks through guidance, training, or oversight, often manifest as operations in physical environments that exceeded the capabilities of mishap UAV operators.

Having determined the independent variables most closely associated with acts based on service, the nature of the acts by service was analyzed next. Figure 3 summarizes the root categories of acts (e.g., skill-based error, judgment and decision-making error, misperception error, and violations) as a percentage of the total acts by service. The services differed significantly with regards to the frequency distribution of acts involving skill-based errors (Cramer's V = 0.246, P = 0.001) and violations (Cramer's V = 0.193, P = 0.016). The Air Force had the highest frequency of skill-based errors (47.2%), followed by the Navy/Marines (33.3%) and Army (23.1%). Of these skill-based errors, the procedural error nanocode was more frequent in the Air Force and Navy/Marines while the breakdown in visual scan nanocode predominated in the Army. The frequency distribution of acts involving violations was greatest for the Army (34.6%) as compared to the Air Force (8.3%) and Navy/Marines (9.5%). There was no significant difference between the services in the frequency distribution of acts involving judgment and decision-making or misperception errors.

Table 7. Root Categories of Latent Error and Associated Nanocodes by Service Model.

Model Variables	Associated Nanocodes†	Human-Factors Mishaps‡
Air Force (70.8%)*		79.1%
Technological environment ($P = 0.001$)		47.1%
	Automation	29.4%
	Instrumentation /sensory feedback systems	26.5%
Cognitive factors ($P = 0.009$)		26.5%
	Channelized attention	14.7%
Army (93.8%)*		39.2%
Organizational process ($P < 0.001$)		45.0%
	Procedural guidance/publications	30.0%
	Organizational training issues/programs	20.0%
Psycho-behavioral factors ($P < 0.001$)		30.0%
	Overconfidence	25.0%
Crew resource management ($P < 0.001$)		35.0%
	Crew coordination	20.0%
	Communication	10.0%
Navy/Marines (93.2%)*		62.2%
Organizational process§ ($P < 0.001$)		34.2%
	Procedural guidance/publications	25.3%
	Organizational training issues/programs	12.7%
	Risk assessment - strategic	6.3%
	Ops tempo/workload	5.1%
Inadequate supervision$^{\Delta}$ ($P < 0.001$)		24.1%
	Supervision - policy	11.4%
	Local training issues/programs	10.1%
	Leadership/supervision/oversight inadequate	6.3%
Planned inappropriate operations$^{\Delta}$ ($P = 0.010$)		11.4%
	Proficiency	7.6%
	Ordered/led on mission beyond capability	2.5%
Physical environment$^{\Delta}$ ($P = 0.010$)		10.1%
	Vision restricted by weather/haze/darkness	7.6%
Technological environment§ ($P = 0.021$)		10.1%
	Controls and switches	3.8%
	Automation	2.5%
	Communications - equipment	2.5%
Cognitive factors§ ($P < 0.001$)		19.0%
	Channelized attention	8.9%
	Cognitive task oversaturation	5.1%
	Distraction	5.1%
	Inattention	3.8%
Psycho-behavioral factors§ ($P = 0.005$)		13.9%
	Complacency	11.4%

*Percentage of acts correctly classified by the service model.
†Nanocodes with an absolute frequency < 2 were excluded from the table.
‡More than one nanocode may have been identified per mishap, so reported model variable frequencies may not be simple summations of component nanocode frequencies.
§Component of “workload and attention” factor in refined Navy/Marines model derived from factor analysis.
$^{\Delta}$Component of “risk management” factor in refined Navy/Marines model derived from factor analysis.

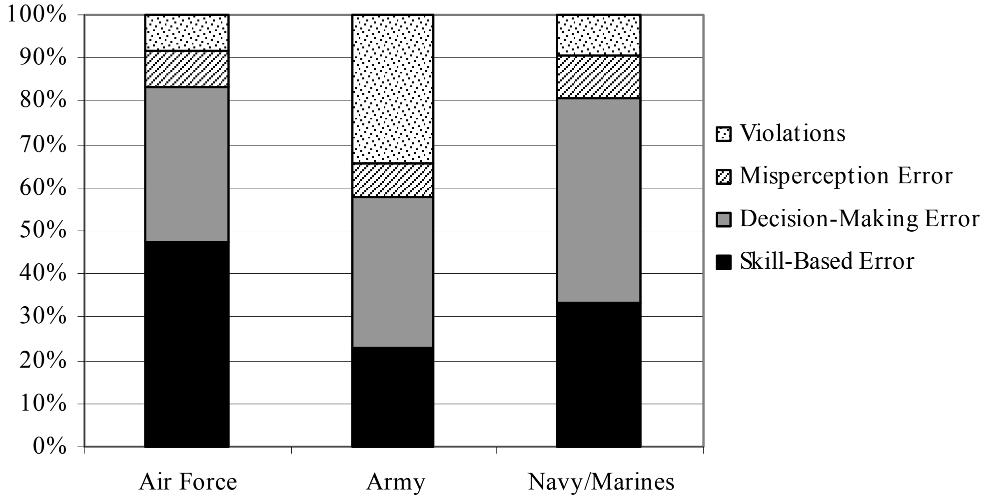

Figure 3. Root Categories of Acts as Percentage of Total Acts by Service.

3.3 HSI Analysis

The data set of UAV mishaps was partitioned to distinguish between the services and HSI domains/interfaces, the results of which are summarized in Figure 4. The services differed significantly in the frequency distribution of mishaps involving the human factors (Cramer's V = 0.225, P = 0.004), personnel (Cramer's V = 0.171, P = 0.040), and safety and occupational health (Cramer's V = 0.181, P = 0.027) domains. Within the human factors domain, the services also differed significantly in the frequency distributions of mishaps involving functional (Cramer's V = 0.363, P < 0.001) organizational (Cramer's V = 0.244, P = 0.001), and physical (Cramer's V = 0.277, P < 0.001) interfaces. By simple graphical analysis, there was a predominance of mishaps involving the human factors domain, largely due to the frequency distribution of organizational interfaces. Sixty percent of Air Force, 50% of Navy, and 26% of Army mishaps involved organizational interfaces failures. Across the services, the frequency of mishaps involving organizational interfaces was 1.6-2.6 times greater than that for the next most frequent domain/interface. Like organizational influences in HFACS, organizational interfaces failures contributed to both operator error and electromechanical malfunctions. Army and Navy mishaps involving organizational interfaces failures were significantly more likely to involve operator errors (Army: OR 10.0, 95% CI 2.4-41.9; Navy: OR 5.0, 95% CI 2.2-11.4) than Air Force mishaps (OR 2.7, 95% CI 0.8-9.5). This is consistent with the prior HFACS analysis in which a greater frequency of Air Force mishaps involved acquisition failures which were more likely to be associated with electromechanical malfunctions.

Service-specific binary logistic regression models were computed using the 8 human factors interfaces and the remaining 6 HSI domains as potential predictor variables for the dichotomous dependent variable acts. Models were estimated using a forward stepwise method, the results of which are summarized in Table 8. The service-specific logistic regression models differed with regards to the HSI domains/interfaces retained in each model although cognitive interfaces was present in all three models. The Army and Navy models were relatively homogeneous given both included cooperational interfaces and the training domain. As with the HFACS analysis, good models were computed for the Army and Navy/Marine mishap data while only a fair model could be computed for the Air Force mishap data.

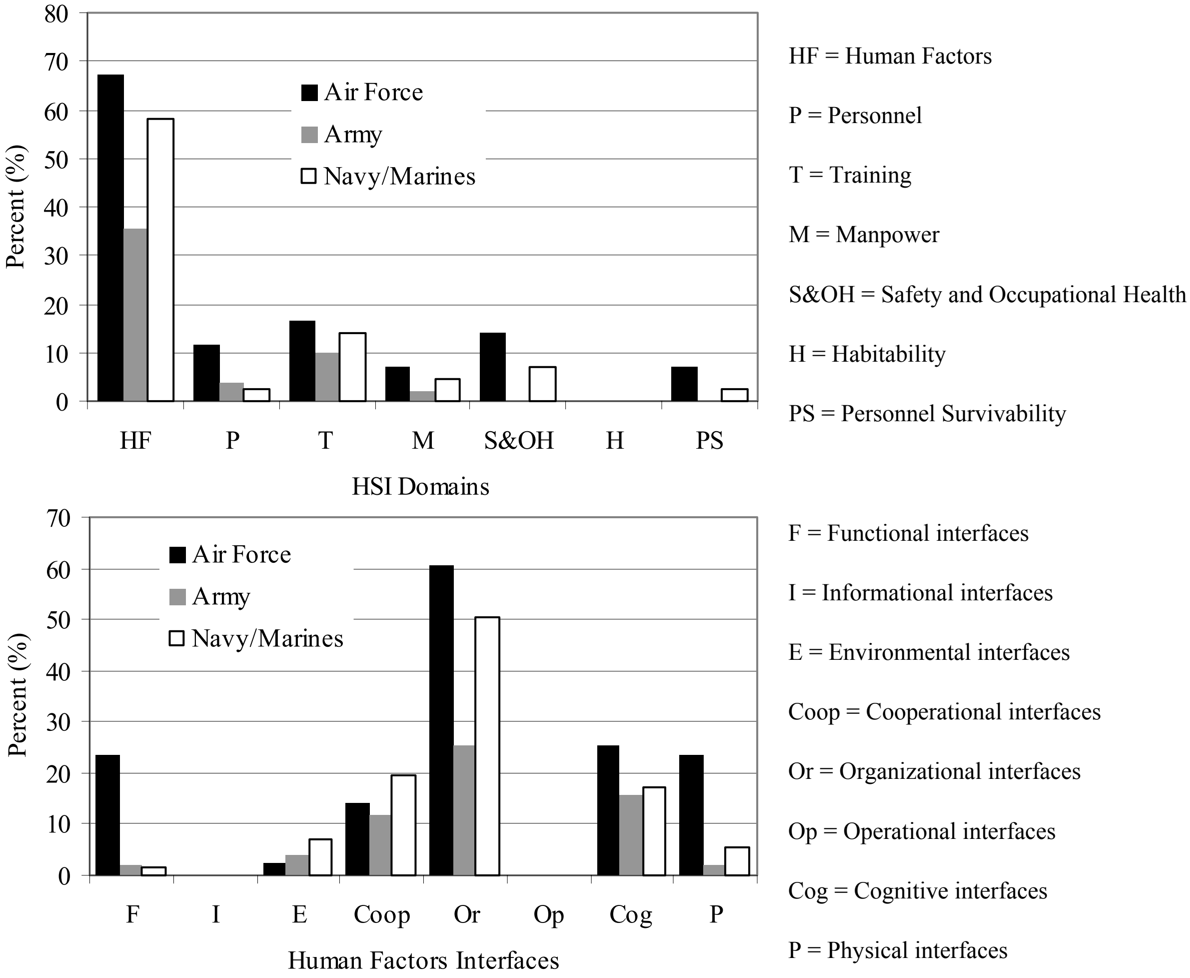

Figure 4. HSI Domains/Interfaces by Service as Percentage of Total Mishaps.

Table 8. HSI Domains/Interfaces by Service Model.

Model variables	R^2 (*P*-value)	Percentage of acts estimated correctly
Air Force Human factors Functional interfaces Cognitive interfaces Personnel	0.695 (< 0.001)	81.0
Army Human factors Cooperational interfaces Cognitive interfaces Physical interfaces Training	0.856 (< 0.001)	92.6
Navy/Marines Human factors Environment interfaces Cooperational interfaces Organizational interfaces Cognitive interfaces Training	0.776 (< 0.001)	95.4

4.0 DISCUSSION

Before embarking on a discussion of this analysis of UAV mishaps, it is important to highlight the significant limitations inherent in using mishap reports for data. As noted by Weiss et al[39] in their discussion on the analysis of causation in aerospace accidents, filtering and bias occur in mishap reports due to the subjective interpretation of events by both the individuals involved in the mishap and the investigators. The accident model used by investigators also imposes patterns on the mishap and influences the data collected and the factors identified as causative (e.g., detection bias), either narrowing or expanding the consideration of certain factors. Additionally, there is the trend towards oversimplification when one factor is chosen out of many contributing factors and labeled causal despite all factors involved being equally indispensable to the occurrence of the mishap. Thus, mishaps are often attributed to operator error or equipment failure without recognition of the systemic factors that made such errors or failures inevitable. These limitations were present in this study given each of the military services used different accident models and human factor taxonomies in their mishap reports. The Army's policy prior to 2003 of investigating UAV mishaps as ground instead of aviation mishaps[14] appeared to lead investigators to focus mainly on the last or most conspicuous factor preceding the mishap. The forms used to investigate Army ground mishaps, which often involved "checking the most appropriate box," had an inherent predilection of narrowing the factors considered. The authors believe these factors biased the Army's UAV mishap data in favor of factors at the acts, and to a lesser extent, the preconditions levels. Finally, the military services operate distinctly different UAV systems which cannot be discounted as a confounder when examining differences between the services. For example, Air Force UAV operators fly from a vehicle-centric perspective (e.g., from within the UAV via a nose camera image) while Army and Navy/Marine external pilots fly from an exocentric perspective (e.g., observing the UAV from a position aside the runway). Collectively, these limitations led to the decision to stratify the statistical analysis based on military service, consequently limiting the ability to directly compare the frequency distribution of latent failures between services. However, since active failures (e.g., operator acts) are the traditional focus of mishap investigations, the authors felt their identification in the mishap process was not likely to be significantly skewed by any detection bias and thus were comparable across services.

Despite the tendency of mishap reports to focus mainly on the active failures of operator error or equipment malfunctions immediately antecedent to a mishap, a major finding of this study was the predominance of latent failures relatively distant from the mishap at the organizational level. Organizational factors were present in two-thirds of Air Force UAV mishaps and one-half of Navy/Marine mishaps, mainly involving acquisition policies and processes. While organizational factors were only present in one-quarter of Army mishaps, this was felt to be under-representative of the true frequency secondary to the aforementioned aberrances in the Army's investigative process for UAVs. There were no studies with which to compare this finding since Seagle[34] and Ferguson[17] both used the predecessor taxonomy to HFACS[35] which lacked an organizational level. While some may object to the categorization of mechanical failures as human factors in HFACS, the taxonomy correctly highlighted the latent failure underlying the majority of UAV mishaps. While DoD's *UAV Reliability Study*[24] attributed the majority of UAV mishaps to subsystem component reliability problems which exist in all current operational UAV systems, the Defense Science Board's UAV study found:[25]

> Many of these early systems were not developed or procured under classical 5000 series acquisition rules. As such, specifications on system reliability were often absent…[Predator's] propulsion subsystem has caused the vast majority of the system losses that were not combat losses. Predator was first procured in 1995; there was no system reliability specification levied at that time (p. 17).

Using HFACS terminology, the Defense Science Board identified an organizational latent failure in acquisition policies and processes (e.g., the lack of specifications on system component reliabilities), thus echoing the findings of the present study. In short, the excessive numbers of mechanical failures analyzed in the *UAV Reliability Study*[24] are physical manifestations of a recurring latent failure in the acquisitions process. To effectively address current UAV mishap rates and safeguard investments in future UAV systems, the investigational spotlight must move from mechanical failures as the cause of UAV mishaps to failures in the organizational culture, management, or structure of DoD's acquisition processes for UAVs.

For the Air Force, latent failures at the individual and environmental preconditions level involving instrumentation/sensory feedback systems, automation, and channelized attention were mostly strongly associated with operator error. These results are consistent with the findings of Rogers et al[30] and Williams[41] that display or interface design was a significant factor in Air Force UAV mishaps. A number of studies have demonstrated that poorly designed automation degrades system performance, especially in multi-task vigilance situations typical of the GCS environment.[2,3,23,27] With regards to instrumentation/sensory feedback, the UAV operator often lacks peripheral visual, auditory, and haptic cueing and is thus relatively sensory deprived compared to the traditional pilot.[22] However, the effect of this sensory deprivation has not been well researched and little is known where UAV operators direct their attentional focus or what information they are sampling. For instance, a study of visual scan patterns using the Predator head-up display (HUD) revealed nonstandard instrument scan patterns.[37] Preliminary work with multimodal displays has had mixed to promising results but still needs to be further studied.[7,16,22] Interestingly, NASA reported in a summary of their UAV flight test experience[8] that incorporating a microphone in the UAV and providing a sound downlink to replicate cockpit environmental noise in the GCS "proved invaluable and potentially saved the UAVs in some instances." Additionally, they recommended "multifunction switches be limited or eliminated" and the "status of critical parameters should be easily observable." However, the Predator GCS is heavily reliant on multifunction keys driving a hierarchical system of computer windows. Given sensory deprivation is common to all current UAV operations, it is curious instrumentation and sensory feedback was not closely associated with operator error in the other military services. One possible explanation is experienced pilots (e.g., Air Force UAV operators) are more prone to note the relative sensory deprivation of UAV operations vice the non-flyer (e.g., Army and Navy/Marine UAV operators) who has not developed skill-based habit patterns in association with the multiple sensory modalities present in the flight environment.[28] Nevertheless, the obvious recommendation for the Air Force is to undertake a comprehensive program to evaluate and optimize the GCS with regards to basic human systems integration principles.

In contrast to the Air Force, the errors of Army UAV operators were most closely associated with latent failures at the organizational influences and individual and personnel preconditions levels. The specific latent failures included procedural guidance and publications, organizational training issues and programs, overconfidence, and crew coordination and communication. These findings agree with Manning et al[21] who found organizational process, which includes the DoD nanocodes for guidance/publications and training, and crew resource management to be prevalent latent failures in Army UAV mishaps. However, this study found the unsafe supervisory factors identified by Manning et al[21] were not strongly associated with the occurrence of errors. This study also confirms the findings of Rogers et al[30] that training, team performance, and situational awareness were frequent human systems issues in Army mishaps. Based on this evidence, recommendations to mitigate Army UAV mishaps should focus on improving technical publications and checklists and initial operator training programs to include a specific curriculum emphasis on crew resource management. Utilization of a UAV simulation environment capable of facilitating team training, especially in challenging off-nominal situations, would be important in both the initial and recurrent training of Army UAV operators. Barnes et al[2] stressed the importance of the latter recommendation in their evaluation of Army external pilots, noting "with experience, the operator is able to devote…attentional resources to future problems while attending to the immediate perceptual and motor tasks in an automatic mode."

The model for Navy/Marine UAV mishaps was the most complex, involving latent failures at the organizational, supervisory, and environmental and individual preconditions levels. This may be a reflection of the Navy's earlier acceptance of HFACS which would be expected to improve the identification and documentation of latent failures in their mishap reports. After factor analysis, Navy/Marine UAV mishaps were found to be closely associated with workload and attention and risk management latent factors. The workload and attention factor included issues of ops tempo, formal training programs and procedures, workstation design, and UAV operator attentional focus and motivation. Interventions for this factor should focus on a thorough job task analysis of UAV operator crew positions with the goal of improving job and workstation design, assessing manpower requirements, and developing empirically-based training programs and formal procedures and guidance. The risk management factor included inadequate supervisory oversight and policies, inadequate supervisory risk assessment with regards to operator capabilities and mission demands, and operations in degraded visual environments (e.g., darkness, weather, etc.). This factor is best addressed by the institutionalization of operational risk management (ORM) at all levels of UAV acquisitions and operations. This is especially true with regards to launch and recovery operations conducted in environments with a paucity of visual references, such as shipboard and night operations. With the exception of the absence of a finding for the need for aeromedical screening guidelines, the results of this study are consistent with those of Schmidt and Parker[32] who identified proficiency and currency issues and crew station design as significant human causal factors in Navy UAV mishaps. This study also confirms Seagle's[34] and Ferguson's[17] findings regarding unsafe supervisory practices which were captured in our risk management factor. However, this study differs in that aeromedical conditions and CRM failures were not significant categories of latent failure.

Given prior concerns regarding inadequate aeromedical screening and monitoring guidelines[5,17,32,34] and questions raised about the suitability of assigning pilots aeromedically disqualified from traditional flying duties to UAV duties (Landsman G, Nellis AFB. Personal communication; 2004), it is noteworthy there were very few mishaps involving the adverse physiological states category, pre-existing physical illness/injury/deficit nanocode, or the pre-existing personality disorder and psychological disorder nanocodes. This finding was consistent with the recent study by Manning et al[21] which did not identify any Army mishaps attributable to physical or mental disease or deficits. Although there currently is no uniform standard across the military services for the aeromedical certification of UAV operators,[38] which has made formulating a standard for the future aeromedical certification of UAV operators in the National Airspace System (NAS) somewhat problematic, it suggests that the aggregate of the current standards is adequate, at least with regards to "selecting out" aeromedically unsound individuals from UAV duties. Whether current standards can safely be made less restrictive or whether they should be augmented (e.g., neuropsychological testing) to "select in" those with certain innate abilities that might be associated with an increased likelihood of success as a UAV crewmember[5,15] has yet to be thoroughly evaluated and is beyond the scope of this study.

An unexpected finding of this study was at the level of acts, where the Air Force had a significantly higher proportion of mishaps attributed to skill-based errors. Skill-based errors are essentially errors in basic flight skills and entail highly automatized psychomotor behaviors that occur without significant thought.[40] The majority of these skill-based errors were procedural errors where the technique employed by the operator unintentionally set them up for the mishap. There are currently vast differences between the services in the selection and training of UAV operators. The Air Force uses experienced pilots who already have at least one operational tour of duty in another aircraft. By contrast, the Army and Navy/Marines use enlisted personnel who are generally non-pilots and are given a UAV specific training program.[5,19,33,38] Although two Air Force studies[19,33] have concluded that manned aircraft flying experience is necessary for Predator operators, the study by Schreiber et al[33] specifically found by 150-200 hours of flight time, most pilots had developed the skills necessary to learn basic maneuvers and landing in the Predator. Experienced Air Force pilots selected for Predator duty did not perform significantly better on a simulated UAV task than some less experienced groups and experience with the T-1 aircraft (e.g., a business class jet) did not transfer well to the Predator. There was also some evidence suggesting experienced pilots may need to unlearn certain aspects of piloting such as dependence on vestibular and peripheral visual cueing, especially during landings. Additionally, their study found a small but significant relationship between the number of lifetime hours playing flight simulation computer games and landing performance. Gopher et al[18] also demonstrated the value of a flight simulation computer game, particularly with regards to training conceptual skills, which the Israeli Air Force adopted into their training program. Per this study's dataset, 66.7% of Predator mishaps involving skill-based errors occurred during landing and 60.0% occurred in training operations. Given the current Predator flight simulator does not accurately reproduce the handling characteristics of the actual vehicle (USAF Safety Center. Predator mishap report; 2004), recommendations include acquiring a simulator with high-fidelity to vehicle handling characteristics to increase operator proficiency or automate the landing phase of flight to eliminate the need for proficiency in the landing skill set.

In contrast to skill-based errors, there was no difference between the services in the frequency of mishaps involving judgment and decision-making errors. Also noteworthy is the fact this study found no difference between the services in the frequency of mishaps involving crew resource management. Together these findings contrast with the results from a Predator operator focus group summarized by Hall and Tirre[19] where the justification for not utilizing enlisted personnel was the need to quickly and accurately make difficult decisions, effectively communicate those decisions to superiors and subordinates, and be responsible for implementing those decisions. This also challenges the assumption officers, particularly rated pilots, already possess these skills and additional training is not required in their case. Further empirical work is needed to optimize policies regarding future UAV operator selection and training.

Finally, HSI failures within the human factors domain, particularly organizational interfaces, were most frequent irrespective of service and would be prime targets for joint HSI issues coordination as proposed by Risser et al.[29] Examples of organizational interfaces issues include job design, unit structure, and policies and regulations.[9] Organizational interfaces failures contributed to both operator error and electromechanical malfunctions. When the association between HSI failures and operator error was specifically assessed, only HSI failures involving cognitive interfaces were common to all three services. Thus, opportunities exist to jointly leverage work involving cognitive interfaces such as decision support systems, interface enhancements for maintaining situational awareness and mental models of the tactical environment (e.g., synthetic vision overlay),[24] and provisions for knowledge generation, cognitive skills and attitudes, and memory aids.[9] Based on the analysis of the service-specific HSI models, it may be potentially more useful to focus on HSI issues common to tactical (e.g., Army and Navy) versus strategic (e.g., Air Force) UAVs[20] rather than joint issues common to all services. Taking the former approach, opportunities exist for coordination on tactical UAVs with regards to cooperational interfaces and the training domain in addition to cognitive and organizational interfaces. Such an approach makes intuitive sense given the substantial differences in UAV characteristics and complexity of the operational environment between these two groups of UAVs. Such an approach is also consistent with the findings of Williams[41] that types of mishaps and patterns of human factors varied based on UAV system. Differences in service-specific HSI issues may diminish in the future as the types of UAVs operated by the services become more homogenous, thereby making joint HSI issue coordination even more practical.

5.0 CONCLUSIONS

The potential benefits and promise offered by UAVs in a multitude of applications have captured the attention of both the military and commercial sectors. It is imperative to address UAV mishap rates now so that their full potential is realized. When technology changes rapidly or new and radical designs are introduced, previous accident data may no longer be valid.[39] This assessment of UAV mishaps using a validated hierarchical model of human error linked to the 7 domains of HSI has identified recurring human factors trends which need to be addressed in order to make UAVs more viable in the near and distant future. As noted by Weeks:[38] "because UAVs are just beginning to be adapted into the U.S. military, human factors research is needed not only to help resolve the controversy over operator qualifications but also to support programs similar to those for manned aviation including physical standards, simulator training, and crew coordination training." Rather than being the solution to human error, UAVs have instead opened a new and critical chapter in aviation human factors.

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