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Executive Summary of Air–Ground Teaming for the Battlespace: Extended Analysis of a 2-Week Demonstration of Flexible Human– Machine Integrated Formations

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14. ABSTRACT This technical note synthesizes findings from a 2-week, simulation-based air–ground teaming demonstration conducted at ARL's INFORMS Laboratory. Thirteen Soldiers operated a mixed air–ground formation consisting of a manned control vehicle, two robotic combat vehicles, a Future Vertical Lift platform, and shared launched effects against a human-controlled opposing force under contested conditions. Across multiple analyses, including unmanned asset handoff dynamics, vehicle trajectory structure, operator workload, individual differences, and team communication, the findings show that the formation adapted rapidly and developed effective coordination patterns through repeated cycles of planning, mission execution, and after-action review. Handoff behavior converged on a stable air–ground control relationship, movement patterns reflected role-differentiated tactical behavior, and subjective workload remained stable despite increasing mission complexity. Together, these results suggest that air–ground teaming is feasible under the conditions tested and that Soldiers can integrate autonomous capabilities without incurring unsustainable cognitive burden. The broader implication is that future battlespace advantages will depend in part on how quickly formations can absorb new autonomous capabilities, integrate them into unit practice, and refine tactics as those capabilities evolve. The summary offers implications for Human–Machine Integrated Formation development, training, and future experimentation.					
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1. Introduction

The modern battlespace is changing faster than the doctrine written to describe it. Across recent conflicts, unmanned aerial systems (UAS) have emerged as a decisive capability. Low-cost, proliferated, and increasingly autonomous drones are reshaping how forces sense, strike, survive, and maneuver, often in ways that outpace the institutional responses of larger, more conventionally organized militaries. The lesson being written on those battlefields in real time is clear: formations that can flexibly integrate unmanned systems across domains, under contested communications, and in the face of layered electronic warfare and integrated air defense systems will hold a meaningful asymmetric advantage over those that cannot. The U.S. Army recognizes this imperative. Investment in Human-Machine Integrated Formations (HMIF) is accelerating, with the Army eyeing initial HMIF fielding as early as 2027 and actively developing common control architectures for ground robotics and unmanned air systems (Roaten 2025; Roque 2025). Yet the science needed to support that transition, specifically an empirical understanding of how Soldiers interact with and within these formations, how cognitive load and situation awareness shift under multi-domain teaming demands, and how teams adapt and develop tactics when given flexible tools, remains nascent. Materiel solutions are advancing, and yet the human-systems science to inform their design and employment is working to keep pace.

This report is a contribution toward closing that gap. It presents a deepened scientific analysis of a 2-week, simulation-based air-ground teaming demonstration conducted at the U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory's (ARL's) INFORMS Laboratory at Aberdeen Proving Ground (APG), Maryland. The demonstration is described in full in Crowell et al. (2026), and that report should be considered the foundational reference for the demonstration's design, execution, and initial findings. The present report builds on that foundation, returning to the data with additional analytical methods and a broader scientific purpose (Crowell et al. 2026).

A broader implication also motivates this work. The Army is entering a period in which UAS capabilities, interfaces, and distributions across formations will change more rapidly than legacy modernization cycles. We believe that a central challenge will lie in how to build units that can learn new capabilities quickly, integrate them into tactics and workflows, and continue adapting as those capabilities evolve. Therefore, the findings summarized here affect air-ground teaming as a technical concept, and the larger question of how the Army develops formations that can keep pace with rapid change in the battlespace.

Together, the report is intended to advance the specific science of air-ground teaming and to help establish the empirical, methodological, and conceptual infrastructure on which future work in this space can stand. The battlespace is evolving, and the science must evolve with it, in a manner that is transparent, reproducible, and accessible to the researchers and practitioners who will carry this work forward.

2. Methods

The analyses presented in the report draw on data collected during the Air-Ground Teaming Demonstration, a 2-week, simulation-based study conducted at ARL's INFORMS Laboratory at APG. The INFORMS Laboratory is a reconfigurable, platoon-scale human-in-the-loop simulation environment developed to support research into future combat crew configurations, human-machine interaction, and multi-platform control (Gremillion et al. 2024; Rexwinkle et al. 2024; Crowell et al. 2026).

Thirteen Soldiers participated as the blue force (BLUFOR) air-ground formation during the demonstration. The ground crew comprised seven Soldiers filling commander, gunner, and driver functions across the simulated manned control vehicle (MCV) and two robotic combat vehicles (RCVs). The air crew comprised five Soldiers filling commander, pilot, and UAS operator roles aboard the simulated Future Vertical Lift (FVL) vehicle. The 13th Soldier served as higher control, providing mission oversight and communications. Over a 2-week period, this team engaged a human-controlled opposing force (OPFOR) under contested conditions in a less-structured mission set meant to draw out emergent interactions between BLUFOR and OPFOR (Crowell et al. 2026).

Each vehicle (MCV, the two RCVs, and the FVL) began each scenario with a stock of several UAS, referred to as Launched Effects (LEs). Eight LEs started on the FVL, and six LEs were distributed among the three ground-crew vehicles (two LEs on each of the MCV, RCV2, and RCV3). Crews were able to flexibly reallocate ownership over LEs during a mission. For example, the MCV could issue commands to one of the RCV's LEs if the crews decided the MCV needed to do so. LEs were capable of four functions: Follow, instructing the LE to follow any BLUFOR vehicle; Loiter, directing the LE to orbit a designated point; Waypoint, sending the LE along a defined path to execute a terminal action; and Attack, designating an OPFOR target for a lethal strike. LEs were thus capable of both intelligence, surveillance, and reconnaissance and kinetic effects.

Data were collected across multiple streams throughout the demonstration. The simulation recorded synchronized event and telemetry logs, including time-

stamped handoff records capturing the origin vehicle, destination vehicle, and subsequent commands issued to each launched effect following transfer. Voice communications were recorded throughout missions and after-action reviews (AARs). Post-mission questionnaires captured subjective workload and situation awareness ratings. Together, these data streams supported the range of analyses presented in the report, including UAS handoff dynamics, vehicle trajectory analysis, operator workload and individual differences, and sentiment analysis of team communications (Hart 2006; Chhan et al. 2025; Kucukosmanoglu et al. 2025; Crowell et al. 2026).

3. Formation Adaptation and Control of Unmanned Assets

The proliferation of unmanned capabilities, and the Army's posture toward rapid acquisition and integration into the force structure, suggests a future battlespace where Soldiers will have autonomous assets (such as UAS, UGVs, etc.) that they can flexibly reassign throughout their force structure. Thus, at the center of the Air–Ground Teaming Demonstration, a central goal was to provide insights into how Soldiers organize and adapt their air–ground force structure to most effectively leverage their unmanned systems, given repeated opportunities to plan, execute, and conduct AARs.

To be operable, the LEs required valid signal connections to any other vehicle (MCV, RCV, or FVL). The two RCVs required valid connections to either the MCV or the FVL to be operable. Crews were able to hand off ownership of LEs and RCVs during a mission.

One of the more consequential findings of the demonstration from an air–ground teaming standpoint is that the crew organically developed a formation and handoff structure that was identifiably different between Weeks 1 and 2. During Week 1, the FVL was the primary source and recipient of handoffs of LEs, as over three-fourths of handoffs involved that platform. These handoffs were evenly spread across the other vehicles, which infrequently engaged in handoff interactions with each other. During Week 2, handoffs to or from the RCVs declined substantially, as the MCV and FVL primarily exchanged handoffs with each other. Over half of all observed handoffs during Week 2 were exchanged between these two vehicles, with the air platform receiving slightly more handoffs than it sent to the ground command vehicle.

The MCV spent most missions as the host of both RCVs, though in some rare cases (particularly in Week 2), the crew handed off an RCV to the FVL to adapt to emergent situations such as the loss of mobility in the MCV, or to execute more complex attack plans.

This progression from a broadly air-centered hub in Week 1 to a tight, reciprocal air-ground pairing in Week 2 reflects a formation that was learning through experience and filtered through its existing tactics, techniques, and procedures, which control pathways were most tactically efficient. By Week 2, the formation had effectively converged on an air-ground command channel as its primary mechanism for redistributing autonomous assets. We interpret this as a direct indication that, when given flexible tools and repeated opportunities to operate and reflect, Soldiers can discover and refine rational control structures without being told precisely what those structures should be.

The relational event model reinforces that interpretation. The timing and sequencing of team member actions provide unique insight into behavioral strategies, cognitive states, and team attributes, and the handoff results show clearly that the formation's handoff behavior was not primarily a response to workload signals—it was shaped by the rhythm and structure of prior interactions. Both weeks showed increased rates of short-term handoff reciprocity and handoff-handoff sequencing, and Week 2 featured stronger and more structured timing effects overall. The behavioral signature is one of a team that was learning, discussing, and adapting with intention across missions (Crowell et al. 2026).

Two findings from the handoff analysis deserve particular emphasis for what they reveal about air-ground teaming as a human-systems integration challenge. The first is the null workload finding. Neither week showed a significant effect for workload, as neither sending nor receiving LEs were associated with a change in perceived workload. Although the air platform was involved in most handoffs during both weeks, its crew did not appear to hand off more LEs to reduce cognitive burden, nor did they report increased cognitive workload despite receiving a disproportionate number of handoffs. This is a meaningful positive signal for the air-ground teaming concept: it suggests that autonomous aerial assets can be integrated into a formation's workflow without imposing a cognitive penalty on the operators managing them, at least at the levels of complexity and operational tempo represented in the demonstration.

More broadly, this finding suggests that the key problem for future formations may be less of how to train for specific control architectures, and more on how to help units discover, test, and refine effective control relationships as autonomous capabilities change. In a future force where UAS types, quantities, and performance characteristics may vary across units and over time, the most valuable outcome is unlikely to be rote proficiency with one configuration—it will be the ability to learn a new configuration quickly, to understand what the available assets can and cannot do, and to convert that understanding into workable tactics, techniques, and procedures. The week-over-week evolution observed in the demonstration suggests

that repeated planning, mission execution, and AAR cycles may be one of the principal mechanisms through which that adaptive capacity is built.

4. Movement, Communication, and Team Behavior

The trajectory analysis adds a spatial and temporal dimension to the picture established by the handoff analysis. Where the handoff findings showed that the formation self-organized its control pathways around the complementary strengths of its air and ground elements, the conditional entropy analysis showed that this functional differentiation was also expressed in how those elements actually moved through the battlespace, and that the signature of high-intensity events, specifically engagements between BLUFOR and OPFOR, is recoverable from movement data alone. The formation's spatial behavior was not random; it was structured, role-differentiated, and sensitive to the tactical conditions it encountered, in ways that a sufficiently sensitive analytical method can detect and characterize.

The practical importance of this analysis lies in its ability to interpret vehicle trajectories and identify moments of significant duress. By analyzing the paired velocities of friendly vehicles, the report shows that it is possible to determine the instances when BLUFOR movement is disrupted by external factors such as direct or indirect fire engagements. This capability provides a data-driven tool for AAR and suggests a promising avenue for automated tactical analysis in future studies and operationally relevant simulation environments. For stakeholders concerned with training, experimentation, and assessment, our findings suggest that movement data can do more than reconstruct what happened—it can help identify when formations are under tactical stress and where coordination patterns are breaking down.

The workload and individual-differences findings complement this picture from the perspective of the operators inside the formation. Across missions, roles, and vehicles, self-reported workload remained relatively stable, and repeated-measures analyses revealed no significant main effects or interactions across mission, role, or vehicle. This pattern indicates that while small fluctuations were detected across the mission set, participants generally reported manageable and consistent workload levels throughout the demonstration. In context, that finding is meaningful rather than merely null: the formation was executing increasingly complex missions, managing multiple LEs, adapting to contested conditions, and developing novel tactics across 2 weeks, and yet subjective workload did not escalate. For force designers and trainers, the significance of this result is that increasing autonomy did not automatically translate into escalating operator burden

under the conditions tested, which is an encouraging baseline for further HMIF development.

The report also found that the most consistent and meaningful demographic correlates with performance centered on gaming experience, self-assessed gaming skill, and prior use of a robot in military operations. No significant correlational relationships were observed between age or time served in the military and performance variables across missions. The practical implication is that the cognitive skills most relevant to managing semi-autonomous systems in a human–autonomy teaming environment appear to be associated with prior experience in fast-paced, multi-object interactive control environments, whether through gaming or through prior hands-on use of robotic systems in military contexts. This does not imply that gaming experience should substitute for military expertise, but it does suggest that future selection, training, and familiarization approaches may benefit from paying closer attention to the cognitive skills associated with rapid multi-object control and interactive system management.

5. Implications for HMIF Development

The most important implication of the report is that the central challenge of air–ground teaming is adaptive integration, rather than rote employment of autonomy capabilities. Based on the outcomes, we argue that the highest-leverage question is not how to use a particular drone, interface, or control pathway most efficiently, it is how to build formations that can absorb new autonomous capabilities quickly, understand their strengths and limits in context, and revise their tactics accordingly. That challenge is likely to become more important as UAS and related autonomy capabilities continue to evolve on timelines shorter than those associated with traditional platform modernization.

Perhaps the most consistent finding across the report is that the formation developed its operational patterns organically, through experience and deliberate reflection, rather than resulting from explicit assignment or instruction. The handoff network analysis showed that the air platform emerged as the dominant control node in Week 1, and that by Week 2 the formation had converged on a tight bilateral air–ground exchange as its primary LE management channel. The trajectory analysis showed that movement patterns were role-differentiated in ways consistent with the tactical functions each vehicle was performing. The AAR record documented in Crowell et al. (2026) confirms that this self-organization was not purely implicit: Soldiers were leveraging mission planning and AAR phases to discuss, reflect on, and deliberately adjust their coordination strategies between

missions, building a shared understanding of their assets' strengths and limitations that was carried forward into each subsequent session.

This convergent finding has a direct implication for the design of future HMIF. A formation given flexible tools, an unscripted mission environment, and structured opportunities for inter-mission reflection will tend to develop rational, role-differentiated coordination patterns without being told to do so. The HMIF design challenge is therefore to provide the interfaces, training structures, and unit-level learning opportunities that allow formations to discover how best to employ those systems under changing conditions, precisely because the future battlefield is going to be dynamic, multi-domain, and present rapid, evolving challenges to Warfighters (Roaten 2025; Roque 2025; Crowell et al. 2026).

Across multiple measurement approaches, the formation did not report escalating or unsustainable workload across the demonstration, despite facing increasingly complex missions, developing novel tactics, techniques, and procedures, and managing multiple LEs across a contested environment. Together, these findings suggest that autonomous aerial assets can be integrated into a formation's workflow without imposing a cognitive penalty on the operators managing them, at least at the levels of complexity and operational tempo represented in the demonstration. This is a meaningful positive signal for the air-ground teaming concept and for the foundation of HMIF more broadly. It does not mean that cognitive limits will not be encountered as formations scale, operational tempo increases, and autonomous asset counts grow. Whether the stable workload finding holds under those conditions remains an important open question. But it does establish a useful baseline: a well-designed air-ground formation, given appropriate tools and sufficient time to develop coordination patterns, can manage a substantial autonomous asset portfolio without the kind of workload escalation that poorly integrated autonomy is known to produce (Harris-Watson et al. 2023; Collins et al. 2025; Cummings et al. 2025).

For broader Army stakeholders, our outcomes point toward an "Organize, Train, and Equip" problem as much as a technology problem. The Army's autonomous capabilities are likely to change more rapidly than any legacy combat system in history. As such, we envision that units will need ways to build and sustain proficiency that are not tied too narrowly to one platform or one interface. Structured planning-mission-AAR cycles, simulation-enabled rehearsal, and capability-agnostic tactical playbooks for functions such as reconnaissance, movement to contact, security, and cross-domain handoff may all be promising ways to accelerate adaptation. The key requirement is that these approaches help Soldiers learn how to evaluate and employ the capabilities they actually have, rather than assuming a stable and uniform autonomous toolkit across the force.

Our findings also suggest that future experimentation should be designed to look beyond whether a given autonomous capability improves performance. Science gaps remain in how quickly units can learn to integrate that capability, how durable that learning is, and what kinds of interfaces and training structures accelerate it. In a rapidly changing capability environment, the speed of adaptation may be as operationally important as the capability itself.

At the same time, several scientific priorities remain clear. Future studies should examine how these findings scale under greater operational tempo, larger autonomous asset portfolios, and more demanding mission conditions. Communication analysis should be extended from AARs to in-mission voice traffic, where temporally precise links between mission events, team language, and cognitive state may be more directly observable. More broadly, the report demonstrates the value of multimethod analysis for understanding human–autonomy teaming, suggesting that future HMIF research should continue to integrate behavioral, spatial, subjective, and linguistic measures to provide a broader picture than single-method analysis approaches.

The foundational result of the report is that air–ground teaming proved feasible in a high-fidelity simulation with Soldiers, appropriate tools, and sufficient time and structure for learning to occur. The sharper implication is that future advantages on the battlefield will depend on how quickly formations can absorb new autonomous capabilities, integrate them into unit practice, and continue refining their tactics as those capabilities evolve. The question now becomes how to design formations, interfaces, training pipelines, and experimentation frameworks that build this adaptive capacity in a way that is widespread, repeatable, and scalable across the force. This report offers one contribution toward that empirical and conceptual foundation.

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List of Symbols, Abbreviations, and Acronyms

AAR	After-Action Review
APG	Aberdeen Proving Ground
ARL	Army Research Laboratory
BLUFOR	Blue Force
DEVCOM	U.S. Army Combat Capabilities Development Command
FVL	Future Vertical Lift
HMIF	Human–Machine Integrated Formation
LE	Launched Effect
MCV	Manned Control Vehicle
OPFOR	Opposing Force
RCV	Robotic Combat Vehicle
UAS	Unmanned Aerial Systems

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