ACTIVITY THEORY AS A FRAMEWORK FOR INTEGRATING UAS INTO THE NAS: A FIELD STUDY OF CREW MEMBER ACTIVITY DURING UAS OPERATIONS NEAR A NON-TOWERED AIRPORT

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An Activity Theory framework was applied in investigating the pressing issue of Unmanned Aircraft System (UAS) integration into the National Airspace System. As stated in the FAA's *UAS Operational Approval* policy notice, the UAS pilot and/or crew are collectively responsible for successfully exercising see-and-avoid duties. To describe how this is achieved in practice, field recordings of visual observers and other UAS crewmembers were collected during three phases of a long-endurance UAS flight test: takeoff, mid-flight, and landing. Four separate radio communications channels were utilized, and pilots' workload was offloaded in three ways: takeoff and landing flight dynamics were offloaded to the external pilot, see-and-avoid duties were offloaded to visual observers, and some communications were offloaded to the mission commander. Visual observers relied on a combination of visual perception, communication, and team coordination skills to assist pilots and the mission commander in effectively accomplishing see-and-avoid duties during UAS operations.

INTRODUCTION

The human factors of Unmanned Aircraft Systems (UAS) are multifarious, in part due to individual differences but also as a result of interactions among crew members engaged in a unifying purposeful activity (Dolgov & Hottman, 2011; Dolgov et al., 2017). As stated in the *Unmanned Aircraft Systems (UAS) Operational Approval* policy notice (FAA, 2013), UAS pilots and visual observers (VOs) are expected to be responsible for: 1) keeping the aircraft within visual line of sight and 2) exercising see-and-avoid responsibilities by preventing the unmanned aircraft from creating a collision hazard and maintaining compliance with 14 CFR § 91.111, 91.113, and 91.115. To ensure that these functions can be performed adequately, UAS crewmembers must be able to scan the airspace effectively, track aircraft, make accurate and reliable estimates of (relative) aircraft position, assess the need for a potential avoidance maneuver, and communicate that need in a timely manner (Dolgov, 2016).

These guidelines, along with a number of others were reiterated in the FAA's recent Small UAS Rule (14 CFR § 107) for civil UAS operations in the National Airspace System (NAS). The proposed language states that flights are limited to small UAS (sUAS; 55 pounds or less) operated within visual line-of-sight (VLOS) in visual meteorological conditions. In addition, a VO is required in scenarios where the pilot cannot consistently maintain VLOS and carry out see-and-avoid duties, such as when the pilot-in-command (PIC) expects to be in a heads-down position or their view of the airspace is otherwise obstructed. Furthermore, a VO is needed for any operations greater than 400 feet above ground level or beyond 1500 feet laterally from the PIC; two VOs are needed when the PIC is in an enclosure. While the regulations provide medical standards for VOs, training and certification criteria have yet to be pinned down.

While regulations have been established for sUAS, operating larger platforms inherently carries more risk due to the increased momentum of the aircraft while in flight. Compared to sUAS, UAS platforms that are 55 pounds and heavier are more often flown with the PIC inside an enclosure. Thus, it follows that flying such aircraft in the NAS will require VOs to be present in a variety of operational scenarios and settings. The added risk of such operations provides a clear impetus to study UAS crewmember practices, with the goal of informing standards for control station design, training, and certification.

PRACTICE INNOVATION

While team task analysis (see Dyer, 1984 for a comprehensive review of prior literature) has traditionally been used in the context of aviation (e.g., Burke et al., 2004; Mathieu et al., 2000), no specific methodology has been established as a clear industry or academic standard (Baker, Salas, & Cannon-Bowers, 1998). Moreover, while such analyses focus on specific jobs, tasks, and subtasks that are team-based, they often fail to recognize both short- and long-range interdependencies that exist among tasks and ignore the structure and dynamics of purposeful activity (Bedny, 2014; Bedny & Karwowski, 2006; Bedny, Karwowski, & Bedny, 2014).

So, as an alternative approach to address the timely and complex issue of UAS integration into the NAS, we designed a two-phase study based on Activity Theory (AT; Kaptelenin & Nardi, 2006). Activity Theory is a meta-analytic research framework that considers an entire work/activity system (including teams, organizations, etc.) beyond just one actor or user. According to Nardi (1996), activity theory "focuses on practice, which obviates the need to distinguish 'applied' from 'pure' science—understanding everyday practice in the real world is the very objective of scientific practice." It accounts for environment, history of the people, culture, role of the artifact(s), motivations, and complexity of real life activity. One of the strengths of AT is that it bridges the gap between the individual subject (in our case: a UAS crew member) and the social reality—it studies both through the mediating activity (in our case: UAS operations). Rather than jobs and tasks, the unit of analysis in AT is the concept of object-oriented, collective and culturally mediated human activity, or *activity system* (Kaptelenin & Nardi, 2006). As illustrated in Fig. 1, this system includes the object (or objective, in our case: Safe UAS Operations in the NAS), subjects (in our case: UAS crew), mediating artifacts (signs and tools, in our case: UAS Control Stations, communications and other technologies), rules (14 CFR § 91.111, 91.113, 91.115 and 107), community (in our case: all other aircraft and other NAS stakeholders), and division of labor (in our case: function allocation).

PRELIMINARY STUDY

In the initial phase of this research, we set out to better understand the heart of the AT diagram in Fig. 1, namely the relationships between UAS platforms, crewmembers, and the aviation community. We began by interviewing three subject matter experts (SMEs) who were licensed manned aircraft pilots. These SMEs also regularly performed the roles of UAS pilot, VO, and mission commander for sUAS and UAS heavier than 55 pounds. We selected these individuals due to their deep understanding of all parts of both manned and unmanned aircraft operations in the NAS. These interviews were transcribed and coded to examine SME's background, training, assessment of vital skills and technologies needed to perform see-and-avoid duties, assessment of UAS operation risks in various conditions, and assessment of various current and potential UAS regulations.

Findings

SMEs reported that crew proficiency with the following see-and-avoid skills is critical for safe UAS operations in the NAS. A pilot and/or VO need to be able to:

- Track unmanned and manned aircraft in various lighting and meteorological conditions
  - o Must be able to maintain VLOS
  - o Must be able to re-engage visual contact after loss and/or distraction
- Scan airspace for approaching air traffic
  - o Must be able to shift visual depth of field
- (If the pilot is enclosed or cannot maintain VLOS). VO(s) must inform pilot of impending near mid-air

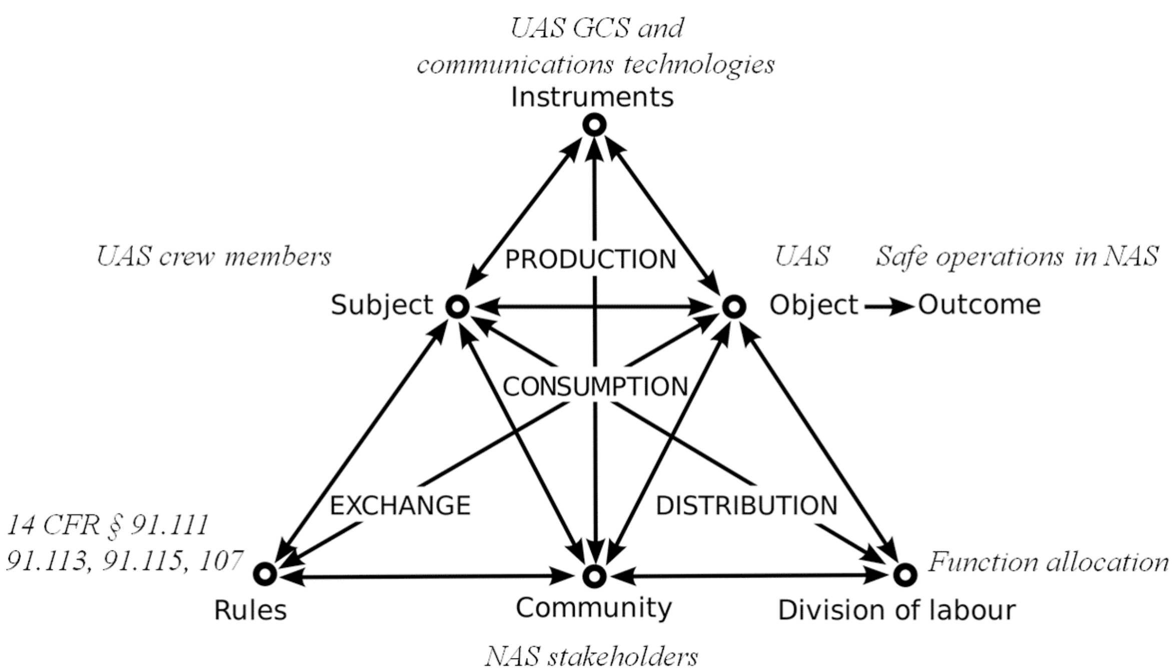

Figure 1. Activity Theory diagram of UAS operations in the NAS; the typical components of the AT diagram are depicted in standard font and in CAPS, and the specific components of the current research are labelled in *italics*.

collision (NMAC) or some other danger with enough time for the pilot to take appropriate action

- o Must maintain cockpit discipline
- o Must use appropriate language when communicating with the pilot
- o Must be able to use global positioning and local landmarks to identify both the location and respective bearings of UAS and other air traffic
- o Must be able to estimate aircraft flight paths, altitudes, and closure rates in order to determine the likelihood of an NMAC
- o Must be able to determine and communicate correct course of action and a safe deviation from the flight path to avoid a potential NMAC

This above list, other statements made by SMEs, and the Activity Theory framework illustrated in Fig. 1 informed the design of the main experiment, where UAS operations were assessed in the field.

MAIN STUDY

To verify and elaborate on our preliminary findings, we collected field recordings of UAS crewmembers during a UAS flight test. A visual observer was fitted with a GoPro camera to monitor their activity and a digital video camera recorded activity in an enclosed, mobile ground control station during three phases of operations: takeoff, mid-flight, and landing. A researcher was positioned near the VO and took notes on their behaviors and communications. Field notes and digital recordings were examined with attention to duties performed and communications between the VO and other crewmembers.

The flight test occurred at the NMSU UAS flight test site, which is located at Las Cruces International Airport (LRU) in New Mexico. The airport is non-towered and has 3 runways including a precision instrument approach. The platform that we studied was Vanilla's VA001, a large (36-foot wingspan) long-endurance UAS.

Findings

The VA001 UAS remained in a stable pattern around LRU throughout the 56-hour flight, with appropriate course deviations for cooperative and non-cooperative air traffic. Data were collected during takeoff and landing, and during three twenty-minute samples from the flight.

Crew Composition. The flight crew consisted of the mission commander, an internal pilot, an external pilot (for takeoff and landing), a payload operator, two visual observers, and the tow vehicle driver. Due to the duration of the flight, multiple people rotated in each role. In accordance with the flight test plan, two visual observers were utilized at time of takeoff and landing for better visual coverage of the airspace. In addition, the aircraft's primary designer, who also played the part of systems engineer, was part of the flight test team.

Communication Networks. As illustrated in Fig. 2, the mission commander, internal pilot (also serving as the PIC), and payload operator were all co-located in the ground control station. The external pilot, tow vehicle driver, and visual observer(s) were located outside, with the external pilot and VOs positioned strategically along a runway and near the ground control station.

Fig. 2 also depicts the four radio communication networks that were utilized during the flight test: 1) The internal pilot, external pilot, and payload operator communicated with the UAS (shown with dash-and-dotted black lines); 2) The external pilot, internal pilot, and tow-vehicle driver communicated with each other on an isolated radio network during takeoff and landing (shown with gray dashed lines); 3) The mission commander and VOs communicated with each other on another radio network; these communications were audible to the internal pilot, who never communicated directly with the VOs (shown with solid gray lines), and 4) The mission commander monitored and advised cooperative air traffic over a public communications frequency (shown with a dashed black line). Proper cockpit atmosphere was maintained with allowances for communications needed for a successful flight-test.

Purposeful Activity: Preparation. The entire crew was engaged in pre-flight activities. Members in the ground control station coordinated with each other regarding the flight-plan, the external pilot and tow-vehicle driver inspected the runway and UAS harness, and the visual observers conducted communications checks with the mission commander.

Purposeful Activity: Take-off. The entire crew was engaged in take-off activities. The internal pilot communicated with the external pilot and tow-vehicle driver to coordinate a safe and effective takeoff. He also communicated with the mission commander, who, in turn, communicated with visual observers regarding having clear airspace for take-off. The payload operator provided assistance monitoring to the UAS control station.

Purposeful Activity: Flight. All members of the crew except the tow-vehicle driver and external pilot were involved during flight. The internal pilot maintained the aircraft under safe operational parameters and communicated with the mission commander regarding the flight plan and any surrounding air traffic. In turn, the mission commander referenced a schedule of planned air traffic and communicated with the visual observers. This allowed the members inside the ground control station to maintain a high level of situation

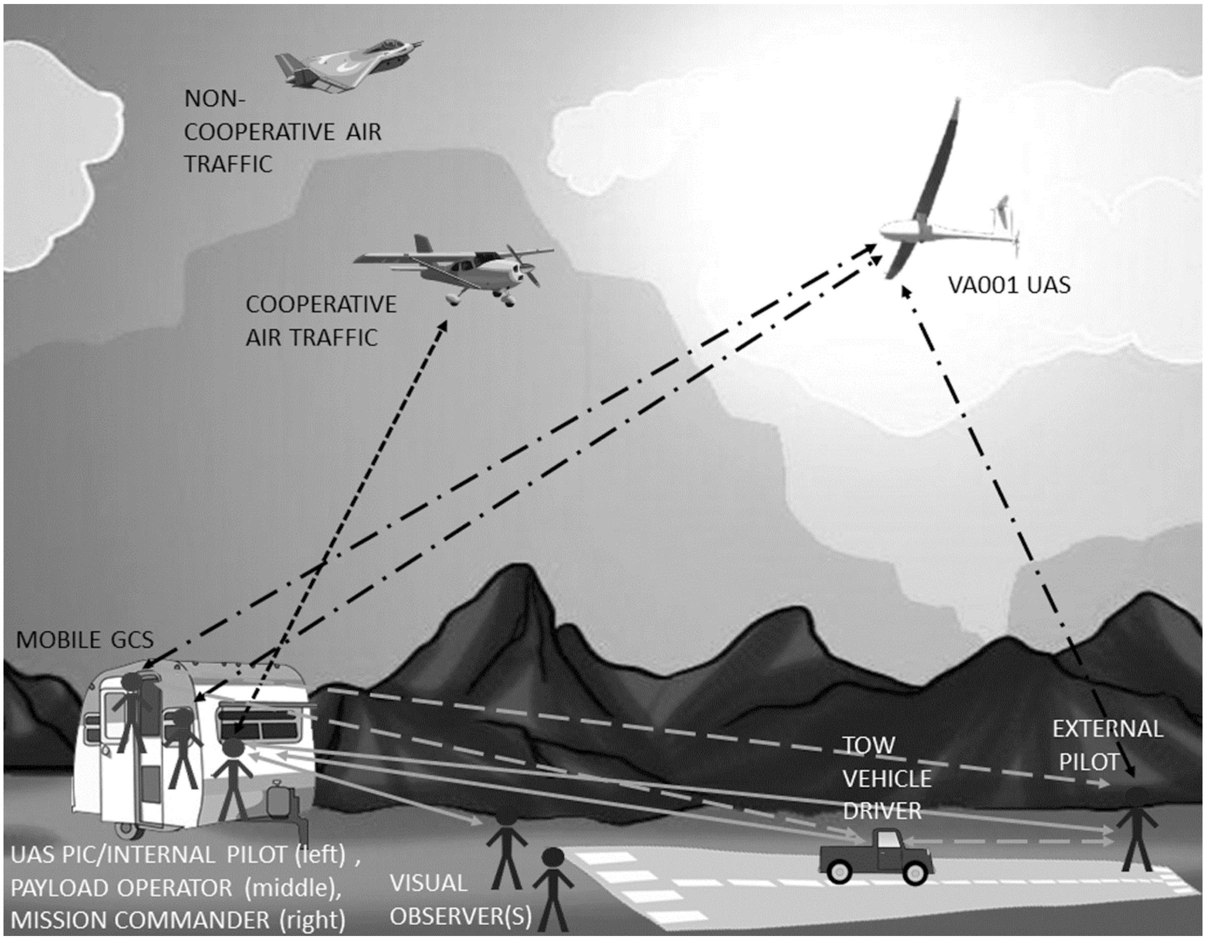

Figure 2. Diagram of crew member posts and communications networks used during the UAS flight test.

awareness regarding the state of the airspace during the test flight and fulfill see-and-avoid responsibilities.

As specified in 14 CFR § 107, visual observers' primary duties entail helping the pilots accomplish effective see-and-avoid. Appropriately, the VO spent the overwhelming majority of the time tracking the UAS and occasionally breaking off to scan the sky and/or to acquire other traffic in the airspace. In instances where incoming aircraft were in the vicinity of the UAS or on a trajectory that may bring them within the UAS's operational area, the VOs communicated this observation to the mission commander via radio. In some instances the mission commander was already aware of the incoming traffic, in which case they informed the VO that the traffic was cooperative. In other instances, the mission commander acknowledged the new traffic and awaited updates from the VO. In addition, the mission commander forewarned the VOs of scheduled traffic in the airspace.

Visual observers' radio messages to the mission commander included the following information, when appropriate: 1) Nature of the communication (new air traffic present or update), 2) Location of the air traffic in relation to the UAS, 3) Estimated flight path of air traffic (global or relative to the UAS and/or local landmarks), 4) Approximate altitude of air traffic relative to the UAS, 5) Relative closing speed and/or time estimate, 6) Assessment of the potential for NMAC or some other mishap, and, when needed, 7) Suggested avoidance maneuvers.

Field notes and recordings demonstrated that tracking the UAS was not difficult, regardless of the time of day. However, when the VO needed to divert their attention to other air traffic, visually re-acquiring the UAS was not always instantaneous. In such instances auditory cues became even more important and the VO was observed responding to the sound of the UAS engine before locating it visually.

Purposeful Activity: Landing. All members of the crew except the tow-vehicle driver were involved during landing. As in the prior stages, see-and-avoid responsibilities were handled by the visual observers and mission commander. The internal and external pilots coordinated with one another to land the aircraft, with the payload operator serving as support.

DISCUSSION

In this study we sought to apply the paradigm of Activity Theory to the timely issue of UAS integration into the NAS. While 14 CFR § 107 has allowed for sUAS flight, research examining crews of operators flying larger-scale systems needs to be conducted to inform industry and regulatory standards.

Our findings show that UAS crew members rely on a combination of cognitive, visual perception, communication, and team coordination skills to safely and effectively fly the UAS and accomplish see-and-avoid duties. In the current scenario, the internal pilots' workload was offloaded in three ways: takeoff and landing flight dynamics were offloaded to the external pilot (and tow-vehicle driver), see-and-avoid duties were offloaded to VOs and some communications were offloaded to the mission commander. The mission commander monitored cooperative air traffic communications and only relayed mission critical information to the pilot. In a crew configuration where any of the noted personnel are not present, the task of the UAS pilot becomes that much more difficult.

PRACTITIONER TAKEAWAYS

As Baker, Salas, and Cannon-Bowers (1998) assert, the practice of team task analysis is somewhat lost. To this end, Activity Theory presents a viable alternative paradigm to study both human and human-machine teams and systems. We make the following recommendations regarding the application of this paradigm in the following settings:

- The generalized Activity Theory framework is appropriate to be used in any context where people are accomplishing work, or purposeful activity, in a social context. For an overview, see Engeström, Miettinen, & Punamäki (1999).
- When investigating human-human teams and/or organizations, the cultural-historical activity theory branch of the field is most appropriate. See Roth and Lee (2007) for an introduction and Igira and Gregory (2009) for a review. See Foot (2001) and Feldman and Weiss (2010) for illuminating case studies.
- When studying human-machine teams, a systemic-structural activity theory paradigm is most appropriate. See Bedny and Karwowski (2006), Bedny (2014), and Bedny, Karwowski, and Bedny (2014) for a comprehensive review, experiments, case studies, and tutorials.

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