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An Ecological Approach to the Supervisory Control of UAV Swarms

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Advances in miniaturized computer technology have made it possible for a single Unmanned Aerial Vehicle (UAV) to complete its mission autonomously. This also sparked interest in having swarms of UAVs that are cooperating as a team on a single mission. The level of automation involved in the control of UAV swarms will also change the role of the human operator. That is, instead of manually controlling the movements of the individual UAVs, the system operator will need to perform higher-level mission management tasks. However, most ground control stations are still tailored to the control of single UAVs by portraying raw flight status data on cockpit-like instruments. In this paper, the ecological interface design paradigm is used to enhance the human-machine interface of a ground control station to support mission management for UAV swarms. As a case study, a generic ground-surveillance mission with four UAVs is envisioned. A preliminary evaluation study with 10 participants showed that the enhanced interface successfully enables operators to control a swarm of four UAVs and to resolve failures during mission execution.

The use of Unmanned Aerial Vehicles (UAVs) has grown rapidly over the past years. Advances in the fields of materials and computer technology provided the means to develop UAVs for a multitude of civil applications, such as search and rescue operations and wildlife monitoring and protection. While the reasons to use a single UAV are manifold, it is often advantageous to use several UAVs that are operating as a team, for example, to execute tasks at different locations simultaneously or observe a larger area in a shorter time.

Current systems and legislation, however, still require at least one operator, if not more, to be in control of a single UAV. As a result, a ground control station is tailored to the control of a single UAV by portraying raw flight status data on cockpit-like instruments. For a UAV swarm, the number of instruments would then simply multiply, making the control of UAV swarms highly labor intensive and difficult in terms of extracting higher-level mission management information. Thus, some form of automation support and interface enhancements would be required to successfully control UAV swarms.

Whereas the majority of UAV swarming research is focused on improving or increasing the degree of automation (Prinet, Terhune, & Sarter, 2012; Cummings & Mitchell, 2006), the work described in this paper focuses on improving the visual representation in an existing ground control station to support higher-level mission management. By utilizing Ecological Interface Design (EID) principles (Vicente & Rasmussen, 1992), the enhanced interface will make the connections between low-level state information and higher-level mission management more salient. The resulting interface is expected to give operators a better understanding of the system and enable them to creatively solve arising problems, without being limited to prescribed solutions.

In this preliminary research, the scope of the work domain is limited to a simplified ground-surveillance mission consisting of four UAVs, where the emphasis is put on how the lower-level system constraints (e.g., the UAV battery levels and the wind condition of the environment) affect the higher-level joint mission plan of the swarm. To study the effect of the visualizations on human performance, a human-in-the-loop evaluation study is performed to gather feedback and test how well operators can control a UAV swarm when unexpected problems are introduced that jeopardize the mission’s success.

**Work Domain Analysis**

The scope of the work domain analysis entails a generic ground-surveillance mission consisting of four UAVs. All four UAVs are assumed to possess autonomous navigation capabilities and be able to perform individual missions comprising of different mission elements. How and by what technologies these capabilities are achieved is out of the scope for this analysis, however.
The results of a WDA can be summarized in an Abstraction Hierarchy (AH). This hierarchy describes the system at different levels of abstraction – ranging from the functional purpose of the entire system at the top to the physical form of individual components at the bottom. Importantly, it also shows how different elements relate to each other. According to Vicente and Rasmussen (1992), the AH is a psychological-relevant way to organize and structure information in order to facilitate top-down and bottom-up reasoning about the system. Thus, a WDA and the AH should be considered as powerful critical thinking tools to help an interface designer make informed decisions about what to put on the interface and how all constraints relate to each other. It does not, however, inform the designer how to visualize the constraints on the interface. Given the scope of this work domain, the resulting AH for this case study is shown in Figure 1.

The resulting AH (Figure 1) clearly indicates that the individual mission of each single UAV simply adds up to the global mission of the swarm. Further, to enhance, or, improve, the human-machine interface of a typical UAV ground control station, it would be wise to first study how well the work domain elements, found in the AH, are represented in such interfaces. An analysis of two popular ground control stations indicated that a typical UAV interface depicts low-level state information in the form of raw numbers and/or in the form of cockpit-like flight status instruments, but fails to integrate that into higher-level system functionalities, such as the expected endurance and range of the UAV, that ultimately propagates upward into the expected ground coverage required to complete the surveillance mission. Thus, the opportunity to improve such a UAV interface would be to make the higher-level system functionalities explicit by means of visualizations that enable a system operator to link higher-level system functionalities to lower-level system properties (i.e., support top-down problem-solving activities) and vice versa (i.e., bottom-up reasoning and problem-solving activities).

To visualize the constraints and their dynamics, capturing the laws of physics governing them is necessary. Here, the equations describing this swarming domain consist primarily of aircraft performance equations for fixed-wing, propeller-type aircraft with electric propulsion.

![Figure 1](image-url) Preliminary abstraction hierarchy (with means-ends links) for a generic ground-surveillance mission of a UAV swarm.
Ecological Ground Control Station

Combining the WDA and the mathematical foundation of the UAV control problem, a set of visualizations is created to enhance the UAV ground control station. As there is no predefined procedure or recipe to follow to create the visual forms of the constraints discovered in the WDA, this part of the ecological approach is sometimes referred to as overcoming the creative gap. Here, the basis for all visualizations is a depiction of the required system behavior (e.g., required coverage, required power and energy, required battery state of charge, etc.), the expected system behavior (e.g., predicted coverage, predicted power, predicted battery level, etc.), and the current state of system behavior (e.g., current coverage, current power, current battery level, etc.). It is expected that such visualizations would help the operator to identify deviations from the mission, trace back the cause of the deviation (e.g., a low battery level in a single UAV), and formulate and implement alternative solutions to complete the mission. A screen capture of the proposed enhanced interface is shown in Figure 2. Besides coloring the waypoints, flight segments, and predicted/expected coverage according to the current and predicted energy state of the UAVs, the most notable addition the state of charge indicator for each UAV (Figure 2, fleet overview) and how it connects to the mission plan view.

Figure 2. Ground control station interface with ecological additions. Depicted are the mission view (1), fleet overview (2) and flight control system status window (3).

To visualize the abstract function of coverage, a shaded area around the flight trajectories of all UAVs is used, as shown in Figure 3(a). By using different shades, it is possible to show different states of coverage. Areas that are expected to be covered are shaded lightly and areas that have already been covered are shaded dark. Those areas that cannot be covered (e.g., a UAV cannot complete its flight plan and return to home, because of a low
battery level) leave a “hole” in the shading, e.g., between waypoints 6 and 7 of UAV 2 in Figure 3(a). This would give the system supervisor a clear cue about the predicted mission accomplishment of a single UAV, and thus also the mission accomplishment of the entire swarm. The size of the shaded area depends on the altitude of the waypoints that define the flight trajectory, i.e., a larger area will be covered (and thus shaded) at a higher altitude of the UAV. This thus represents the means-ends link between the flight status of the UAV and the higher-level coverage goal of the system. However, a higher altitude also means less surveillance accuracy when the camera has a fixed resolution. In this prototype, however, this relationship has not yet been modeled. The link between the battery’s state of charge (SOC) and coverage is that no shading will be applied when the expected SOC at a waypoint is zero and the waypoint can therefore not be reached. This gives the operator a clear cue that something is amiss and further fault diagnosis is required.

Figure 3. Side by side view of a stylized map view and the state-of-charge indicator for two UAVs. Waypoint numbers (WP1 - WP7) in both depictions correspond to each other. UAV 1 is shown on the left and UAV 2 is shown on the right.

Working with the Interface

The envisioned usage of the ecological interface developed for this study is as follows. If the goal is to surveil a particular area on the Earth’s surface, the operator can setup the individual flight plans of the UAVs by positioning waypoints so as to create a cumulative search pattern that fully covers the target area. Entering and dragging waypoints by direct manipulation can be regarded as skill-based behavior, whereas comparing the surveillance area with the expected cumulative coverage patterns would be classified as rule-based behavior (driven by “if-then” rules). After creating the flight plans of the UAVs, the plans can be uploaded to individual UAVs, and each UAV will then automatically fly the intended trajectories. During flight, the operator can monitor the progress of the surveillance mission by comparing the expected coverage with the current (completed) coverage. As such, the operator can stay at higher levels of (control) abstraction and can use rule-based behavior to monitor the mission. If everything is working according to plan, the operator will most likely remain at this level. Whenever a problem would arise, it is expected that the operator will first be alerted by observing a gap in the expected coverage. This would then trigger problem-solving activities to replan the UAV trajectories so as to fill the gap in coverage. The gap in coverage can be caused by many things, such as a higher battery-depletion rate than expected, a changed...
The wind condition that requires more energy to fly the ground-referenced trajectory and still return safely to home, a failed data transmission (data link problem) to the ground station, or perhaps a combination of these events. In case a problem is identified with a UAVs battery level, such as shown in Figure 3, the operator could alter the flight plan of another UAV (e.g., by choosing a UAV with an excess in battery charge after it has completed its own single mission plan) to fill the coverage gap. For instance, the position of the waypoints and/or the altitude settings can be manipulated to have another UAV successfully take over the mission of a failing UAV. Considering Figure 3, the operator could let UAV2 fly back to home upon reaching its WP4, and change the positions and altitudes of WP6 and WP7 of UAV 1 to make up for the gap in coverage. Of course, upon manipulating the waypoints the operator should ensure that the new flight pattern is feasible by observing the required energy and expected battery power at the new waypoints. As such, the expected nominal strategy to resolve a mission problem would be to delete the problematic waypoints and increase the altitude of the remaining waypoints, while sticking to the general search pattern of the predefined flight plans.

Evaluation Study

To observe how operators would use the ecological enhancements and interface features, an exploratory evaluation study was performed. The focus of this evaluation study was to observe a user’s problem-solving activities during mission management of a UAV swarm, consisting of four UAVs, in the presence of several system failures. Ten subjects – consisting of four faculty employees, who had previous experience with UAVs, and six aerospace students – were asked to perform a mission with five different initial conditions. The objective of the mission was to survey the town of Nootdorp (nearby the city of Delft, in The Netherlands) by loading and maintaining a predefined flight plan. This flight plan was equal to the one shown in Figure 3, but extended to four UAVs. Since pairs of UAVs are converging, this flight plan makes it easy to compensate for failures by a single UAV. Further, coverage of a predefined area had to be perfect and there should be no waypoint from which a UAV could not return to base. Finally, possible collisions between UAVs could be ignored under the assumption that each UAV has an autonomous sense-and-avoid capability.

Five test scenarios were defined that covered failures induced internally at the battery and externally by the wind condition. On top of that, they covered failures at a single UAV and at multiple UAVs. To solve problems during the mission, it was possible to change the number and position of waypoints. Participants were therefore not constrained to only use the predefined flight plan but could choose any order of waypoints. However, the altitude of waypoints was limited between 200 m and 500 m. Based on the flight plan and the definition of the scenarios in Table 1, the expected solution strategies are summarized as follows:

1. Scenario 1: Delete problematic waypoints of all four UAVs and increase the altitude of the remaining waypoints to 500 m
2. Scenario 2: No solution required
3. Scenario 3: Delete problematic waypoints of UAV4 and increase altitude of UAV3’s waypoints to 500 m
4. Scenario 4: No solution possible (with nominal strategy)
5. Scenario 5: Delete problematic waypoints of UAV2 and increase altitude of UAV 1’s waypoints to 500 m

After each run, participants had to fill out a questionnaire. The first part of this questionnaire contained open questions about the participants’ decision process. The second part contained a list of the improvements made to the interface that had to be rated on a Likert-scale from one (bad) to ten (good), according to their perceived usefulness.

Results

Participant feedback

The interface items that were considered very useful were the predicted coverage, the coloring of the waypoints, and the coloring of the lines connecting the waypoints. This is also in line with the observation how the participants solved problems encountered in the scenarios. Feedback to the open questions, as well as the audio recordings, reveal that participants found and solved problems at a high level of abstraction. Specifically, the coloring was used to realize that a problem was present, while a solution was found using the coverage shading. Originally it was expected that problems are found at the abstract function of coverage. However, adding a bright
red line to the map provides a much stronger cue than removing a light shading. The interface features that were considered somewhat useful were the current SOC and the expected SOC at future waypoints. It was observed that the participants used the SOC indicator for two purposes: When the map was not centered at the search area, so that the waypoints were not visible on screen, participants used the SOC indicators to find potential problems. Most of the time it was used to match the flight plans visible on the map with the corresponding UAVs. This reveals a considerable problem with how the joint mission plan is visualized in the interface. By showing all flight plans simultaneously, without further distinction between flight plans, operators were forced to use alternative means to identify the problematic UAV. Incidentally, this is the number one feedback given by participants. Thus it appears that the means-ends relationship between the UAV icon and its corresponding flight plan is not made explicit enough in the interface. This problem will likely be amplified for a swarm consisting of more than four UAVs.

Mission success

Out of 40 individual runs, eight were not finished successfully. Of those eight failures, four missions arguably failed due to unnecessary mistakes made by the participant, such as not uploading the flight plans or missing a small part of the search area. Most surprisingly, the envisioned unsolvable scenario 4 was solved six out of ten times. Participants did so by adopting a different strategy than anticipated, which was to delete the problematic waypoints and increase the altitude of the remaining waypoints, while sticking to the general pattern of the predefined flight plan. Instead, they also changed the order of UAVs within the search pattern – a simple, but unanticipated solution strategy. This result clearly demonstrates the power of a constraint-based interface, as it supports creative problem-solving activities.

Conclusion

Following an ecological approach to interface design, the human-machine interface of an existing ground control station was enhanced to support mission management and fault diagnosis of a UAV swarm. These improvements visualize how low-level system properties, such as battery level, wind speed, and wind direction propagate to a higher-level system goal of achieving coverage in a generic ground-surveillance mission. An evaluation study showed that operators could successfully use these new interface elements to control a swarm of four UAVs and solve problems during mission execution. The results of the evaluation study showed that operators had a better system understanding and that it promoted creative problem-solving activities to scenarios that could not have been solved by a predetermined strategy. However, the results also showed that the current interface still required control actions to be performed per single UAV, making it labor intensive to change mission parameters for swarms consisting of more than four UAVs.

References

Prinet, J.C., Terhune, A., & Sarter, N.B. (2012). Supporting Dynamic Re-Planning In Multiple Uav Control: A Comparison of 3 Levels of Automation. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56(1):423–427. ISSN 1541-9312.

Cummings, M.L., and Mitchell, P.J. (2006). Automated Scheduling Decision Support for Supervisory Control of Multiple UAVs. Journal of Aerospace Computing, Information, and Communication, 3(6):294–308. ISSN 1542-9423.

Vicente, K.J., and Rasmussen, J. (1992). Ecological interface design: theoretical foundations. IEEE Transactions on Systems, Man, and Cybernetics, 22(4):589–606.