

An Ecological Approach to the Supervisory Control of UAV Swarms

C. Fuchs, C. Borst*, G. C. H. E. de Croon, M. M. (René) van Paassen, and M. Mulder
Section Control and Simulation, Faculty of Aerospace Engineering, Delft University of Technology,
2629 HS Delft, The Netherlands

ABSTRACT

This research employs ecological interface design to improve the human machine interface of an existing ground control station for the supervisory control of UAV swarms. As a case study, a general ground surveillance mission with four UAVs is envisioned. An analysis of the swarming work domain is performed to generate a reduced set of means-end relations. This analysis leads to a novel design that shows predicted coverage and range of the UAVs in the swarm. An evaluation study with 10 participants showed that the new interface successfully enables operators to control a swarm of four UAVs and mitigate 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 be solved by fixed procedures.

1 INTRODUCTION

The use of Unmanned Aerial Vehicles (UAVs) has grown rapidly over the past years [1, 2]. Advances in the fields of materials and computer technology provided the means to develop UAVs for a multitude of applications such as military uses [1], search and rescue operations [3] and wild life monitoring and protection [4]. 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, UAVs with different capabilities - even unmanned ground vehicles - may be required. Some tasks must be executed at different locations simultaneously and in general, swarms of UAVs can observe a larger area in a shorter time [5]. Current systems and legislation still require at least one operator if not more to be in control of a single UAV. This would make swarms of UAVs highly labor intensive and considerably more expensive. Just recently, the final demonstration of FireSwarm, a project focusing on UAVs that autonomously find fires was impaired by this legal issue [6]. However, humans do not have sufficient mental resources to manually control multiple UAVs, so support in the form of automation is required [7].

*C.Borst@tudelft.nl

Most research is devoted to solve this technical issue by focusing on improving or increasing the degree of automation [5]. This includes investigating different Levels of Automation (LOAs) [8, 9] or different forms of collaboration between operators and the automation [10]. While these studies show good results, they mostly ignore the positive influence good visualizations can have [11]. As Chen et al. [5] showed, with increasing automation, operators are put into a supervisory role, which can bring its own problems: Depending on workload, operators can “*use, misuse, disuse, and abuse*” [12, p. 230] the automation. Also, imperfect automation can significantly reduce performance [13] and when the operator does not have a proper mental model, frequent automation surprises can occur [14, 15]. When such a joint system faces unexpected circumstances, it is often only because of the adaptability of the human operator that performance can still be adequate [16].

To support that adaptability, this research focuses on the human machine interface of such a UAV swarm, by employing Ecological Interface Design (EID) [17] to improve an existing Ground Control Station (GCS). EID is a constraint based approach to interface design that concentrates on revealing the work domain’s constraints [18]. Usually, GCSs display as much low-level information as possible, leaving it to the operator to connect it to the overall goal of the mission. Using EID, these connections of both the work domain’s constraints and system properties are explicitly connected to the overall goal in the form of means-end relations. That way, it is hypothesized that the operator is supported during unfamiliar and unexpected events [19]. This approach has shown promising results, not just in process control where it originates but also in a military setting [20, 21], in car driving [22] and aviation [23, 24]. 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 research, EID is applied to a simplified search mission consisting of four UAVs and only a subset of the means-end relations identified during the analysis will be visualized in the interface. It is decided to add information about the remaining range - in the form of the current battery level - and weather conditions - in the form of a constant and uniform wind. On top of that, their propagation through the joint mission plan to the abstract function of coverage will be added. This set of means-end relations combines both internal and

external constraints so it covers a broad basis. In addition, the exact effect of these constraints on coverage is not easily recognizable by an operator. After creating the improved interface, a human-in-the-loop evaluation study is performed to gather feedback and test how well operators can control a UAV swarm when unexpected problem jeopardize mission success.

This paper is structured as follows: First, the results of a Work Domain Analysis (WDA) are presented and an existing GCS is analyzed. Second, the aforementioned set of means-end-relations are mapped to the interface and third, the evaluation study is presented.

2 WORK DOMAIN ANALYSIS

The WDA in this research is based upon and extends Amelink's [25] Abstraction Sophistication Analysis. In this analysis, a separate WDA is performed for different levels of control sophistication, ranging from low levels such as flight to high levels such as navigation. Each level is then required for and enables the next higher level.

According to Amelink, the joint operation of multiple UAVs is the highest level of sophistication but he did not perform the actual WDA for it. The WDA in this research starts with the joint operation, specifically a generic surveillance mission with four UAVs. However, instead of focusing on one level of control sophistication, multiple levels of both abstraction and control sophistication are combined. With this more liberal approach, the elements of most interest are captured.

All four UAVs are assumed to possess autonomous navigation capabilities and be able to perform individual missions comprising of different mission elements. How exactly these capabilities are achieved is of no concern for this analysis.

2.1 Abstraction Hierarchy

Performing the WDA produces the Abstraction Hierarchy (AH) [26]. This hierarchy describes the system at different levels of abstraction - ranging from the functional purpose of the entire system to the physical form of individual components [27]. Importantly, it also shows how different elements relate to each other. That is, it shows the means-end relations, or why, what, how interrelations.

The resulting reduced AH for this case study is shown in Figure 1 and is described in the following sections.

Abstract Function

The highest level of abstraction considered for this case study is the abstract function. Following the argumentation in [25], this level consists of principles that govern the coordination between all UAVs.

Coverage refers to the sensing that is required for the mission. A high coverage means that the UAVs' sensors are gathering data from a large area in a short time, which could be achieved by flying at a high altitude.

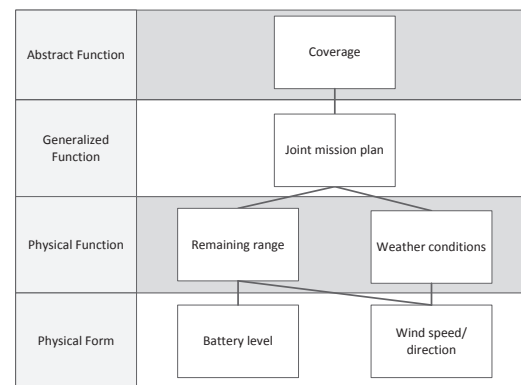


Figure 1: Reduced abstraction hierarchy

Generalized Function

The generalized functions describe how the abstract function of coverage is achieved, independent of the implementation of the system.

The means through which collaboration is achieved is the joint mission plan. This central concept of a joint mission plan is the definition of which UAV has to perform which mission at which location and at what time.

Physical Function

The physical function level is governed by constraints on the generalized function of the joint mission plan. On the one hand, it is shaped through weather conditions such as heavy precipitation. On the other hand, the remaining range of the UAVs constraints the joint mission plan. When the search area is outside the range on a certain UAV, it can obviously not be tasked with covering it.

Physical Form

Though there are several means through which the remaining range and weather conditions can be achieved, only two are considered in the interface: The battery level - or State-Of-Charge (SOC) - as well as the wind speed and direction.

2.2 Analyzing an Existing Ground Control Station

SmartUAV is a UAV research system developed at TU Delft, that is used as a test bed for advanced control of single or multiple UAVs. Development started in 2005 and has continued until now.

A possible layout for the GCS when controlling multiple UAVs, similar to other GCS interfaces like the open-source UAV project Paparazzi, is shown in Figure 2. Due to their availability to the researchers, only these two GCS interfaces are considered. The interface in Figure 2 includes four main elements: First, a mission view with a 2D-map and controls at

different levels of control sophistication ①. Second, several flight control system indicators ②. Third, low-level flight controls and a primary flight display ③. Last, a fleet overview with a small primary flight display for each UAV ④.

The following analysis is based on this configuration for multiple UAVs in a simulated environment.

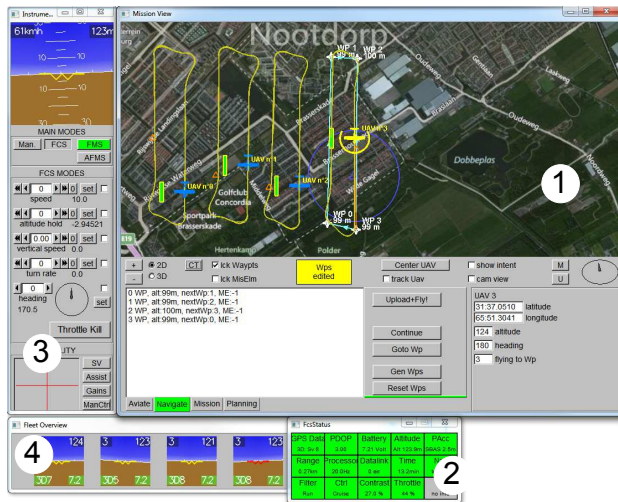


Figure 2: SmartUAV GCS for multiple UAVs, split up into the mission view ①, flight control system status ②, low level flight control ③ and fleet overview ④.

Comparing the available information in the GCS interface of SmartUAV with the set of means-end relations summarized in Figure 1, reveals that a considerable amount of these relations is not fully represented or completely missing. The results are given below, ranging from high to low levels of abstraction.

The abstract function of coverage is only partially shown. While the past track of all UAVs is visible, future waypoints are only shown for the selected UAV. Even so, this leaves the task of converting the flight path to a clear form of coverage to the operator. The same set of information is also representing the joint mission plan. By only seeing the flight plan of one UAV at a time, the operator presumably has a difficult job of integrating the information to a joint mission plan. One level lower, neither the remaining range, nor weather conditions are shown. At the lowest level, information about the selected UAV's battery level is given in terms of the voltage. Given the highly nonlinear relation between battery voltage and charge, this only gives a very crude estimate. Information about the current wind speed and direction is not included.

3 VISUALIZATIONS

Combining the WDA and the mathematical foundation of the problem, a set of visualizations is created. As there is no predefined procedure to follow, this part of the ecological approach is sometimes referred to as overcoming the creative

gap. The basis for all visualizations is a prediction of how much energy a certain flight plan will use, how much energy is left in the batteries at each waypoint and how that influences the higher level of coverage. Following are the visualizations that have been created, sorted from high levels to low levels of abstraction.

3.1 Abstract function

To visualize the abstract function of coverage, a shaded area around the flight plans 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 will be covered are shaded lightly and areas that have been covered are shaded dark. Those areas that cannot be covered leave a "hole" in the shading, e.g., between waypoints 6 and 7 of UAV#2 in Figure 3(a).

The size of the shaded area depends on the altitude of waypoints, i.e., a larger area is shaded at a higher altitude. When the expected SOC at a waypoint is zero and the waypoint can therefore not be reached, no shading is applied. This gives the operator a clear cue that something is amiss and further fault diagnosis is required.

3.2 Generalized function

By showing the flight plan of all UAVs simultaneously like in Figure 3(a), the joint mission plan is shown. This indication is expended by applying a distinct coloring scheme to both the waypoints and the lines connecting them. Using this coloring, information about the expected SOC at every waypoint is given. This is done using three different colors according to the following rules:

- White: This waypoint can be reached and the UAV can return to base afterwards
- Yellow: This waypoint can be reached but the UAV cannot return to base once it arrives at this location
- Red: There is not enough energy in the battery to reach this waypoint

The color of a line connecting two waypoints is based upon the remaining SOC at the next waypoint. As a result, long stretches of a flight plan may be marked as unreachable, even though it is possible to reach part of them. In Figure 3(a), this can be seen between waypoints 6 and 7 of UAV#2. For illustration purposes, the exact location at which the battery will be empty is marked by "0 %". To increase safety, this conservative approach is chosen.

The means-end relation between the joint mission plan and coverage is depicted by drawing the colored waypoints on top of the coverage shading. That way, the operator can see which parts of the flight plan lead to a certain coverage, but also which waypoints fail to do so.

3.3 Physical function

Figure 4 shows how remaining range can be visualized by drawing a circle around the current position or a future waypoint. Assuming an instantaneous change of heading, this

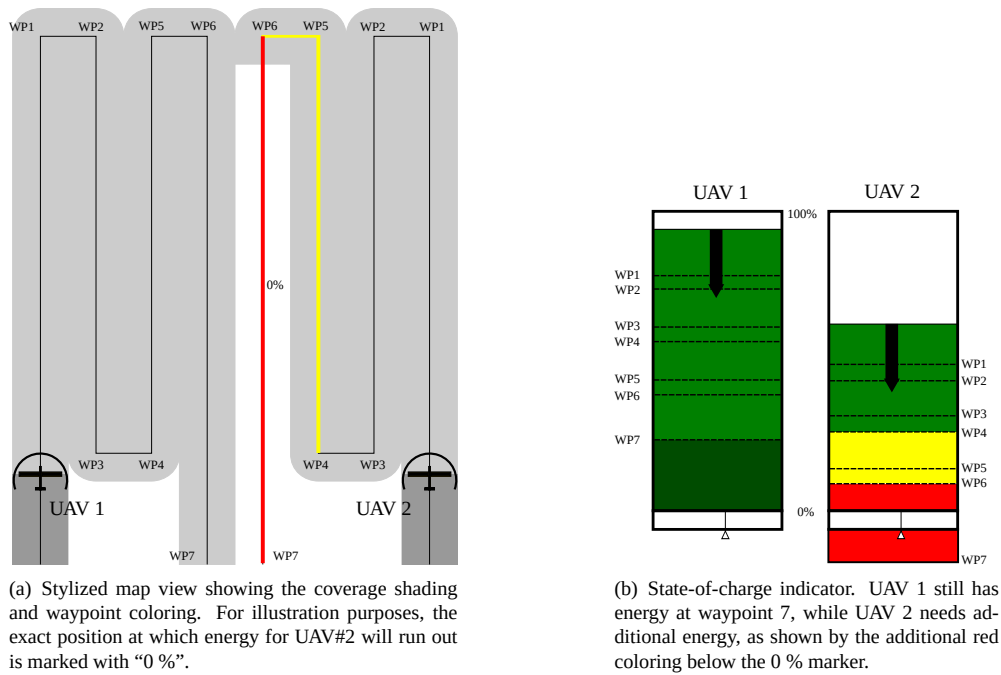


Figure 3: Side by side view of a stylized map view the state-of-charge indicator for two UAVs. Waypoint numbers (WP1 - WP7) in both depictions correspond to each other. UAV#1 is shown on the left and UAV#2 is shown on the right.

visualization is equal to a circle with radius $V_a \cdot E$ that has been shifted by $\vec{V}_w \cdot E$. Depending on whether the range from the current position or a future waypoint is shown, the airspeed and altitude used for the computation differs. At the current position, the current airspeed and altitude are used while at a waypoint, the respective values at that waypoint are taken. To reduce clutter, these circles are not shown by default and must be specifically toggled on.

A second, albeit implicit representation of the range from a future waypoint is the coloring of waypoints. A yellow waypoint shows that the remaining range is less than the distance to the base, while a red waypoint shows the remaining range is zero. This also links both the remaining range and the joint mission plan.

Usage of these range indicators is likely restricted to situations in which the operator wants to check the remaining range at a specific waypoint or compare two waypoints.

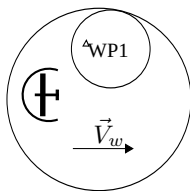


Figure 4: Remaining range from the UAV's current position and from a waypoint.

3.4 Physical form

The SOC indicator as shown in Figure 3(b) combines a set of information related to the battery level and energy usage. Most basically, the height of the colored column is an analog indication of SOC, ranging from 0 % to 100 %. Dashed lines at lower heights show the expected SOC at future waypoints, which can be lower than 0 %. In Figure 3(b), this is the case for waypoint 7 of UAV#2, so additional energy is required to reach that waypoint.

Analogue to the waypoints on the map, different colors are used to further highlight what each expected SOC means: Green represents a good status, equivalent to a white waypoint on the map, like waypoints 1 - 3 of both UAVs in Figure 3. There is, however, a distinction made between a light and dark green. The dark green, as seen below waypoint 7 of UAV#1, shows how much energy will be in the battery once the last waypoint of the flight plan is reached. Yellow shows that the waypoint can be reached but the UAV cannot return to the base afterwards, while red indicates that a certain waypoint cannot be reached at all. In order to increase safety, this coloring is done conservatively, that is the complete block towards a problematic waypoint is colored.

As an example, waypoints 1-4 of UAV#2 in Figure 3 are not problematic, as shown by the green part of the column. At waypoint 5, the UAV's SOC will have dropped so far that a safe return to the base is impossible. Therefore, the complete block between waypoints 4 and 6 is colored yellow. Simi-

larly, waypoint 7 cannot be reached at all and would require additional energy, so the column below waypoint 6 is colored red.

Lastly, the horizontal indicator at the 0 % height shows the instantaneous power consumption. The black arrow at the top of the column gives a prediction of how much energy would be used to return to base from the current position.

Each UAV that is controlled is represented by one of these SOC indicators, which are placed next to each other. That way, the operator can easily compare the SOC of all UAVs, even though they are visualized by an analog display.

Wind information is given by a simple wind sock, as depicted in Figure 5. The wind sock rotates to show the direction of wind, while the wind speed is given as a number. This enables the operator to quickly get an estimate of wind direction and a precise measurement of wind speed. For the assumed constant and uniform wind, such a display is sufficient.

Wind speed and direction considerably affect the energy usage for a given flight plan and the result is shown in other indicators. As an example, flying upwind reduces the range compared to flying downwind, which is visualized through the range circles. Therefore, while not explicitly showing the relation between wind and the remaining range, it can be deduced.

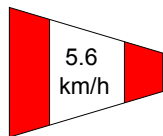


Figure 5: Wind sock

3.5 Final Interface

A screenshot of the final SmartUAV GCS interface including the aforementioned ecological improvements is shown in Figure 6. Additions to the mission view ① are the addition of the wind sock in the top left corner, coverage shading, coloring of waypoints and the ability to view all flight plans at once. Circles showing the remaining range are also added but cannot be seen in this particular screenshot. The fleet overview ② is supplemented with the SOC indicator. The flight control system status window ③ remains as it was before.

4 EVALUATION STUDY

To test if operators can indeed use the interface as intended, an evaluation study was performed. This study was carried out in the ATM-Lab of the Faculty of Aerospace Engineering, Delft University of Technology. The ATM-Lab is equipped with computers running Windows 7 on an Intel Core i7-3770 processor and an Nvidia Geforce GT 640 graphics card. In addition, a 26 inch monitor with a resolu-

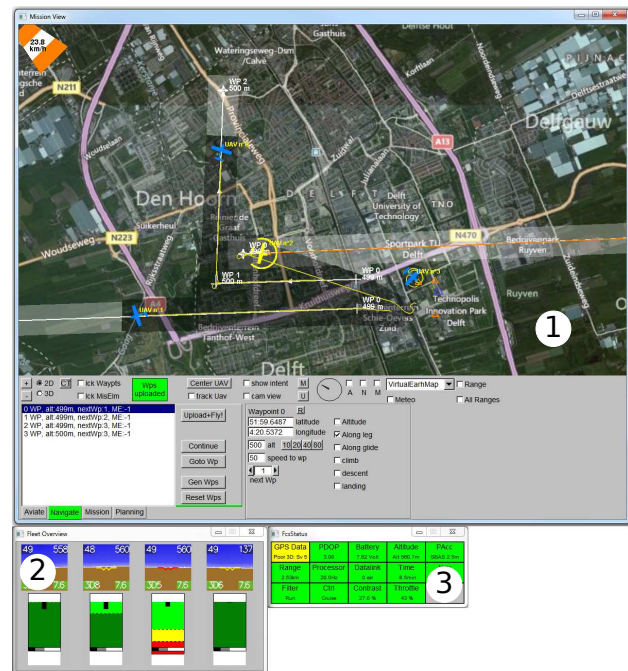


Figure 6: SmartUAV interface with ecological additions. Depicted are the mission view ①, fleet overview ② and flight control system status window ③.

tion of 2560x1600 was used to display the GCS as depicted in Figure 6.

4.1 Setup

Ten subjects - four of which have previous experience with SmartUAV - were asked to perform a mission with five different starting conditions. The objective of the mission was to survey the town of Nootdorp by loading and maintaining a predefined flight plan. This flight plan is 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. Furthermore, coverage of a predefined area had to be perfect and there should be no waypoint from which a UAV cannot return to base. Possible collisions could be ignored. To reduce learning effects in the comparison of scenarios, the scenario a participant started with was alternated but the order of scenarios stayed constant. That is, two participants solved scenarios 1, 2, 3, 4, 5, two participants solved scenario 2, 3, 4, 5, 1, etc.

The five scenarios covered failures induced internally at the battery and externally at 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. How-

ever, the altitude of waypoints was limited between 200 m and 500 m.

Scenarios 1, 3, and 5 were expected to be solved by deleting unreachable waypoints and increasing the altitude of the remaining ones. Scenario 2 contained no failure while scenario 4 was designed to be unsolvable.

4.2 Measurements

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 scale from one (bad) to ten (good), according to their usefulness. The list of improvements that were to be rated is given in Table 1.

Table 1: Participants are asked to rate the usefulness of the following items on a scale from 1 to 10

A	Predicted coverage
B	Actual coverage
C	Coloring of waypoints
D	Coloring of lines between waypoints
E	Current state-of-charge
F	Expected state-of-charge at future waypoints
G	Energy required to return to base
H	Current power consumption
I	Current range
J	Range at future waypoints
K	Windsock

Next to the questionnaire, data was gathered by recording the screen images and voice of the participants. For that reason, participants were asked to think aloud at all times.

4.3 Results

The results of the rating feedback show some clear trends in which interface elements were considered useful or not. Figure 7 shows a bar plot of the average usefulness rating for each combination of interface element and scenario. Three of the elements appear to be the most useful, while the majority was considered not useful. Based on the usefulness rating interface elements can be put into three categories.

Very useful

- A Predicted coverage
- C Coloring of waypoints
- D Coloring of lines between waypoints

The high usefulness ratings for the predicted coverage, coloring of waypoints and coloring of lines between waypoints are in line with how the participants solved problems. Feedback to the open questions as well as the audio recording reveals 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

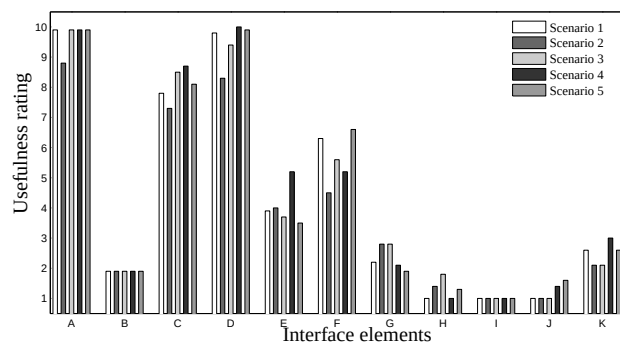


Figure 7: Bar plot of average usefulness ratings - grouped by interface element. The list of interface elements is given in Table 1.

problems are found at the highest level abstraction, i.e., the abstract function of coverage. However, adding a bright red line to the map shows to be a stronger indication than removing a light shading.

Somewhat useful

- E Current state-of-charge
- F Expected state-of-charge at future waypoints

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 indicator to find potential problems. Mostly though, 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. By showing all flight plans concurrently, without further distinction, operators were forced to use alternative means to identify the problematic UAV. Incidentally, this is the number one feedback given by participants.

Not useful

- B Actual coverage
- G Energy required to return to base
- H Current power consumption
- I Current range
- J Range at future waypoints
- K Windsock

The high number of interface elements with a low rating has different reasons. During the evaluation, problems were solved while the UAVs were en route to the search area, which implies that most of the time, the past track of the UAVs was not visible on screen. Also, participants were specifically told to ensure a perfect predicted coverage. Therefore, the low rating for the actual coverage was expected. Focusing on the prediction also caused the indication of how much energy is required to return to base to be rated low. While this indication shows more information, the yellow coloring of waypoints provides a sufficient binary feedback in the form of yes or no. As a result, the energy required to return to base is re-

dundant. However, when there was no problem as in scenario 2, this indication became more important again - an effect that carried over to the next scenario. As outlined previously, the range indicators are likely limited to very specific situations in which a direct comparison is required. During this evaluation, that was not necessary as the same information could be retrieved from the color of waypoints when they were moved around.

A surprising result is the low rating for both the current power consumption and windsock. It was expected that participants use the interface to exercise top-down reasoning to find the root cause of problems. That way, it is possible to follow the AH from failed coverage down to the battery level or wind. Instead, participants noticed and solved problems at high levels of abstraction, without looking for the cause. To give an example, during scenario 4 only one participant noticed that the wind was stronger than usual. This interface was therefore successful in not forcing a processing at a higher level of cognitive control than required.

Mission success

Out of 40 individual runs, eight were not finished successfully. Of those eight failures, four missions arguably failed due to unnecessary mistakes such as not uploading the flight plans or missing a small part of the search area. Most notably, the 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 pattern. This shows exactly why it is important to support operators in creative problem solving.

5 DISCUSSION

The low usefulness rating of the windsock and the current power consumption was surprising, as participants were expected to use this information to find the cause of the problems. In hindsight, this behavior makes sense. With the assumption of a constant and uniform wind, the windsock does not change during the mission. Therefore, operators only needed to look at it once, which is negligible compared to other elements of the interface. In a setting with a non-constant wind, this behavior is likely to change and the usefulness of the windsock to increase. Similarly, the power usage of the UAVs only changed slightly when the UAVs were climbing and stayed constant otherwise. This indicator suffers from its small size compared to the spectrum it has to represent. So to make it more useful for operators, either the changes in power usage have to be bigger, e.g., with a different UAV, or a different visualization has to be found.

Despite the high usefulness rating of the coloring of waypoints and lines, it also received the number one comment

from all participant. By applying the same color scheme to all waypoints, operators sometimes had significant trouble finding the right UAV for the waypoints they were looking at. This makes it necessary to update how waypoints and lines are drawn. A possible solution would be to only color the lines and use different waypoint colors to indicate which waypoint corresponds to which UAV.

Future research in this field should expand the interface to include more means-end relations from the full AH, specifically the abstract function of data quality. Currently, the best solution to solve problems of coverage is to increase the altitude as much as possible. Without the restriction of a maximum altitude, that is exactly what participants would have done "because that always works". Adding data quality as a constraint should solve that issue.

6 CONCLUSION

Following an ecological approach, the human machine interface of an existing ground control station was improved to support the control of a UAV swarm. These improvements visualize how battery level (an internal constraint) as well as wind speed and direction (an external constraint) influence a higher level goal of achieving coverage in a surveillance mission. An evaluation study shows that operators can successfully use these new interface elements to control the swarm 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 be solved by fixed procedures. It therefore shows that ecological interface design is a viable option to support operators of UAV swarms.

REFERENCES

- [1] S. A. Cambone, K. J. Krieg, P. Pace, and L. Wells. Unmanned aircraft systems roadmap 2005-2030. Technical report, US Department of Defense, 2005.
- [2] Parrot. Parrot establishes itself on the civil drones market, 2013.
- [3] C. Pearson. Police use drone helicopter in search, 2012.
- [4] Daily Mail Reporter. Animal welfare charity is to use DRONES to spy on people illegally hunting, 2013.
- [5] J. Y. C. Chen, M. J. Barnes, and M. Harper-Sciari. Supervisory Control of Multiple Robots: Human-Performance Issues and User-Interface Design. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 41(4):435–454, July 2011.
- [6] Almende B. V. Fireswarm takes technical and legal hurdles, 2013.
- [7] M. Lewis, J. Wang, and P. Scerri. Teamwork coordination for realistically complex multi robot systems.

- In *NATO Symposium on Human Factors of Uninhabited Military Vehicles as Force Multipliers*, pages 1–12, 2006.
- [8] J. C. Prinnet, A. Terhune, and N. B. Sarter. 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, October 2012.
- [9] M. L. Cummings and P. J. Mitchell. Automated Scheduling Decision Support for Supervisory Control of Multiple UAVs. *Journal of Aerospace Computing, Information, and Communication*, 3(6):294–308, June 2006.
- [10] M. L. Cummings, J. P. How, A. Whitten, and O. Toupet. The Impact of HumanAutomation Collaboration in Decentralized Multiple Unmanned Vehicle Control. *Proceedings of the IEEE*, 100(3):660–671, March 2012.
- [11] M. L. Cummings, A. S. Brzezinski, and J. D. Lee. Operator Performance and Intelligent Aiding in Unmanned Aerial Vehicle Scheduling. *IEEE Intelligent Systems*, 22(2):52–59, March 2007.
- [12] R. Parasuraman and V. Riley. Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 39(2):230–253, June 1997.
- [13] C. D. Wickens, S. R. Dixon, and M. S. Ambinder. 15. Workload and Automation Reliability in Unmanned Air Vehicles. In Nancy J Cooke, Heather L Pringle, Harry K Pederse, and Olena Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7 of *Advances in Human Performance and Cognitive Engineering Research*, pages 209–222. Emerald Group Publishing Limited, 2006.
- [14] N. B. Sarter and D. D. Woods. How in the World Did We Ever Get into That Mode? Mode Error and Awareness in Supervisory Control. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1):5–19, March 1995.
- [15] N. B. Sarter and D. D. Woods. Team Play with a Powerful and Independent Agent: Operational Experiences and Automation Surprises on the Airbus A-320. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 39(4):553–569, December 1997.
- [16] K. Christoffersen and D. D. Woods. 1. How to make automated systems team players. In *Automation*, volume 2 of *Advances in Human Performance and Cognitive Engineering Research*, pages 1–12. Emerald Group Publishing Limited, 2002.
- [17] J. Rasmussen and K. J. Vicente. Coping with human errors through system design: implications for ecological interface design. *International Journal of Man-Machine Studies*, 31(5):517–534, November 1989.
- [18] J. M. Flach, F. Tanabe, K. Monta, K. J. Vicente, and J. Rasmussen. An Ecological Approach to Interface Design. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 42(3):295–299, October 1998.
- [19] K. J. Vicente and J. Rasmussen. Ecological interface design: theoretical foundations. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(4):589–606, 1992.
- [20] M. P. Linegang, H. A. Stoner, M. J. Patterson, B. D. Seppelt, J. D. Hoffman, Z. B. Crittendon, and J. D. Lee. Human-Automation Collaboration in Dynamic Mission Planning: A Challenge Requiring an Ecological Approach. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 50(23):2482–2486, October 2006.
- [21] D. S. Hall, L. G. Shattuck, and K. B. Bennett. Evaluation of an Ecological Interface Design for Military Command and Control. *Journal of Cognitive Engineering and Decision Making*, 6(2):165–193, March 2012.
- [22] B. D. Seppelt and J. D. Lee. Making adaptive cruise control (ACC) limits visible. *International Journal of Human-Computer Studies*, 65(3):192–205, March 2007.
- [23] C. Borst, M. Mulder, and M. M. Van Paassen. Design and Simulator Evaluation of an Ecological Synthetic Vision Display. *Journal of Guidance, Control, and Dynamics*, 33(5):1577–1591, September 2010.
- [24] R. Klomp, M. Mulder, M. M. Van Paassen, and M. Roerdink. Re-design of an Inbound Planning Interface for Air Traffic Control. In *AIAA Guidance, Navigation, and Control Conference*, Guidance, Navigation, and Control and Co-located Conferences. American Institute of Aeronautics and Astronautics, August 2011.
- [25] M. H. J. Amelink. *Ecological Automation Design, Extending Work Domain Analysis*. Phd, Delft University of Technology, 2010.
- [26] K. J. Vicente. Ecological Interface Design: Progress and Challenges. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 44(1):62–78, January 2002.
- [27] Jens Rasmussen, Annelise Mark Pejtersen, and L. P. Goodstein. *Cognitive Systems Engineering*. Wiley Series in Systems Engineering and Management. Wiley, 1994.