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IFAC-PapersOnLine 49-19 (2016) 450–455

Ecological Interface for Collaboration of Multiple UAVs in Remote Areas

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Abstract: Unmanned Aerial Vehicles (UAVs) can be used to access remote areas, e.g., for surveillance missions. Collaboration between them can help overcome communication constraints by building airborne relay networks that allow beyond line of sight communication. This research investigates whether a single human operator can supervise multiple UAVs in a collaborative surveillance task under communication constraints. We designed an ecological interface to support operators in their task and increase system flexibility. A preliminary human-in-the-loop study was done to investigate operator task performance and evaluate interface components. It was shown that operators are able to successfully operate surveillance missions under communication- and battery constraints. Participants did, however, not succeed to do this without separation conflicts and communication losses, which indicates that the interface lacks elements representing endurance and separation assurance. To an extent, the interface design turned out to be scalable, with a few remaining visualizations that cause clutter for large numbers of UAVs. More advanced ways of displaying information on request and grouping of select information is warranted to further improve the interface. *Copyright ©2016 IFAC*

Keywords: human-machine interface, supervisory control, ecological interface design

1. INTRODUCTION

UAV operations grow exponentially (FAA, 2014) and new technologies enable them to perform search and rescue, exploration and surveillance missions. Unmanned operations do not expose human pilots to dangers, have a longer endurance, and enable access to remote areas. Having multiple UAVs that operate as a team, can further enhance mission performance and robustness to failures.

Successful team performance requires individual UAVs to collaborate. Communication is crucial, to share state information between the airborne vehicles, and including the human operator supported by a Ground Control Station (GCS). This often leads to a dependence on Line-of-Sight (LOS) communications (Olsson et al., 2010), limited by obstacles and small communication ranges. To enable communication also in remote areas, UAVs can form a *relay network* (Palat et al., 2005). Algorithms were developed to optimize these networks for reachability and coverage of Regions of Interest (ROIs) (Cetin and Zagli, 2012). However, high computational demand and inflexibility to unexpected mission changes, often still require a human operator as the main decision-maker.

In this paper, Ecological Interface Design (EID) (Vicente and Rasmussen, 1992; Vicente, 2002; Borst et al., 2015) is applied to support the operator in the control of multiple UAVs. The mission aimed at conducting a surveillance task of one or more ROIs, in a remote area, requiring the operator to build a relay network for communication, extending our previous work (Fuchs et al., 2014). A Work Domain Analysis (WDA) was performed to analyze the work domain constraints, and several visualizations were designed to map these constraints on the interface. Direct manipulation was implemented through having a tablet-based touch screen platform (Android). A human-in-the-loop evaluation was done to investigate whether the current GCS interface design supports operator problem-solving performance.

In the following, we first discuss UAV team collaboration in remote areas, followed by an introduction to our proposed interface. Results of the preliminary evaluation are presented, with a discussion and conclusions.

2. TEAM COLLABORATION IN REMOTE AREAS

Sharing information between UAVs and GCS, such as flight states, operational modes and sensed data, is crucial for any mission. Often a centralized system architecture is adopted, where all UAVs communicate with a GCS, that coordinates the activities of all individual vehicles. This system architecture is considered to lead to the best collaborative performance but can also suffer from communication constraints (Godwin et al., 2007).

Communication between UAV and GCS comprises downlink of telemetry- and sensed data as well as uplink of commands. Small UAVs ($<5kg$) generally use Wi-Fi signals ($2.4GHz$), which are constrained to line-of-sight. The link budget is very limited because of severe payload limitations. Flights beyond the maximum communication range lead to a loss of communication, where the UAV

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Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.620

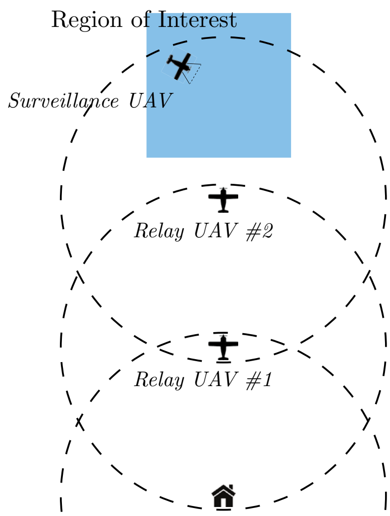

Fig. 1. A UAV relay and surveillance network.

continues to fly autonomously, uncontrollable from the GCS, possibly leading to a crash.

To reach remote areas, the LOS range is extended through a relay of the communication signal. An example is the "Tour de France" bicycle race where multiple aircraft are used to relay live video streams, filmed from motorcycles, to the ground station. In our application, chains of relay UAVs can be used, as illustrated in Figure 1. To form such networks in an optimal way, coordination is required for positioning and task allocation – commanding the UAV to perform a surveillance or communication relay task – of the whole UAV team. To maximize communication range, the UAVs that act as relay units can be placed as close as possible to the communication range (assumed to be circular). Note that the battery/energy requirements of a relay UAV can be different from a UAV that is assigned to have a surveillance role. Clearly, human operators need a good GCS interface to support their decision-making.

3. PROPOSED GCS INTERFACE

A work domain analysis (WDA) was conducted to reveal the surveillance mission constraints. Here we describe the main WDA findings and how these affected the ecological interface. Whereas our earlier research focused on higher-level information (Fuchs et al., 2014), here our aim was to study those lower-level information variables that affect communication most: UAV position and heading, battery level, communication status and altitude. Also some higher-level information, such as communication range and (ground) coverage is visualized to be better able to perform the overall surveillance mission.

Figure 2 illustrates the proposed interface design, the main elements of which will be briefly discussed next. In order to keep the interface as scalable as possible, that is, still usable for larger numbers of UAVs, information is presented close to the individual vehicle icons.

Functional Purpose The surveillance mission goal is to obtain ground coverage of one or more ROIs, which are indicated on the map-view display by a colored shading. The functional purpose to "safely return home" is not represented in the current interface: all UAVs are assumed to automatically return to the ground station once they have a near empty battery level.

Abstract Function The (camera) sensor coverage per UAV is indicated around surveillance waypoints on the map using a shading which changes color depending on status. Areas that are being covered are green, ones that are expected to be covered are yellow and for UAVs without communication a red color is given because sensed data cannot be sent to the GCS. Coverage areas are circular because surveillance UAVs typically 'circle around' their assigned waypoint. The radius depends on the UAV altitude and the field-of-view of the on-board camera.

Locomotion is present in the display in the form of movement of UAV icons on the map. Furthermore, collaboration of UAVs can be detected through the relay status and communication information (i.e., (dashed) relay communication range circles). Separation between UAVs is shown through coloring the icons and labels on an altitude tape on the right-hand side. UAVs that fly at unique altitudes are colored gray; UAVs that fly at the same altitude but with sufficient horizontal separation are colored blue. In case of a separation conflict, the involved UAVs are colored red, and lines between the UAV icons to depict conflicting pairs. Group labels are used on the altitude tape to indicate that UAVs are located at (approximately) the same altitude. This grouping of labels is also needed to prevent a cluttered altitude tape and thus to keep the design scalable. Once a group label is clicked, the involved UAV icons become yellow (indicates the relation with the selected altitude label group) and individual labels are shown on the left side of the altitude tape.

Generalized Function The mission flight plan is indicated on the map using waypoints which contain labels indicating which UAV they belong to. The generalized function of communication is represented in the interface by a small communication icon, as shown in Figure 3, included in the UAV icons. This icon was designed to match the human mental model of the information it represents: three full (blue) bars for high signal reception, less bars when signal reception decreases, and a cross in case of complete communication loss.

Physical Function Aircraft icons are used to show the status of UAVs on the map. Apart from the communication status icon these contain information about heading (attitude is irrelevant because autonomous navigation capabilities were assumed), position and battery status. The latter is shown in a way that matches the operator mental model: a high battery level corresponds with a full green icon, a low level with an (almost) empty red icon, Figure 3.

The communication area is indicated using outer boundary circles. The maximum communication range of the UAVs is assumed to be equal to that of the ground station, so communication is possible when the UAV is located within the circle. The communication area of the ground station is displayed around a "home" icon, indicating the GCS position. In case a UAV has been assigned a communication relay task, an extra range circle is drawn around it, extending the area in which communication with the GCS is still possible.