An Autonomous Multi-UAV System for Search and Rescue

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ABSTRACT

This paper proposes and evaluates a modular architecture of an autonomous unmanned aerial vehicle (UAV) system for search and rescue missions. Multiple multicopters are coordinated using a distributed control system. The system is implemented in the Robot Operating System (ROS) and is capable of providing a real-time video stream from a UAV to one or more base stations using a wireless communications infrastructure. The system supports a heterogeneous set of UAVs and camera sensors. If necessary, an operator can interfere and reduce the autonomy. The system has been tested in an outdoor mission serving as a proof of concept. Some insights from these tests are described in the paper.

Categories and Subject Descriptors

I.2.9 [**Artificial Intelligence**]: Robotics—*autonomous vehicles*

General Terms

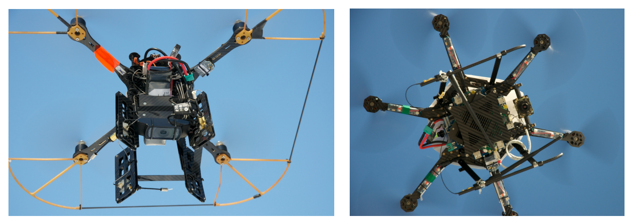
Design, Experimentation

Keywords

Unmanned aerial vehicles; UAV; search and rescue; system architecture; aerial communication; video streaming

1. INTRODUCTION

Autonomous unmanned aerial vehicles (UAVs) are used with increasing interest in civil and commercial applications. Our work focuses on search and rescue missions. Here, small-scale UAVs as shown in Figure 1 can be equipped with imaging sensors for aerial photography to support rescue people. Due to the limited flight time of such UAVs (a few ten minutes) and the fact that search and rescue missions are time critical [5], the use of multiple UAVs rather than one UAV plays an important role. This also raises the demand for reliable wireless networking between the UAVs and communication to the base stations.



(a) AscTec Pelican (b) AscTec Firefly

Figure 1: Different types of UAVs equipped with cameras which are used for our search and rescue mission.

Our multi-UAV system should be autonomous; this means that it can plan and execute different operations with little or no human interaction, and it can change its behavior in response to unanticipated events during the operation [15]. Task-based control of systems with higher degrees of autonomy can mitigate cognitive overload and reduce workload [10]. Different levels of decisional autonomy exist for a multi-UAV system [11]. In different applications, different levels of autonomy may be needed. For instance, in aerial image mosaicking, each individual UAV will move to a set of pre-planned way-points which can be implemented in a centralized manner [17, 16]. In addition, a user can manually define a point on a map to be visited. On the other hand, in a search scenario (e.g., a target on the ground to be detected) we expect each individual UAV to sweep the area and detect the target in an autonomous manner with minimum human intervention.

Based on the structure of decision-making, a system can also be categorized from centralized to distributed [8]. In a centralized system, a central processor or entity directly controls the flow of information and operation of the individual units. Contrarily, in a distributed system, the decisions are made over different entities while they communicate and

DroNet'15, May 19, 2015, Florence, Italy.

http://dx.doi.org/10.1145/2750675.2750683.

coordinate their actions by passing messages. In large and complex systems, such as multi-UAV systems, we may have a combination of distributed and centralized tasks and decisions for different phases.

In the scope of the SINUS[1] project, we aim to set up a search and rescue (SAR) mission [7] by using an autonomous multi-UAV system. The goal of such a mission is to locate a target such as a person or an object of interest using on-board sensors. Once the target is identified, a video stream showing the target is sent to first responders. To stream the video over a large distance, multiple relaying UAVs might be necessary. UAVs reposition to form a chain of relays. After achieving the required formation, a video of the detected target is transmitted either through the other UAVs acting as relays, or directly to the base station and first responders. We summarize such missions into the following phases:

1. **Pre-planning**: The human operator defines the search region at the control base station. The optimal flight paths for all UAVs are computed to reduce the required time to search the area. Generated plans including the way-points are sent to individual UAVs.

2. **Searching**: The UAVs autonomously follow their predefined way-points while scanning the ground. The detection, collision avoidance, and frequent image transfer are active at this phase.

3. **Detection**: Upon detection of a target, the detecting UAV hovers while the other UAVs form a new formation for communication relaying.

4. **Repositioning**: The UAVs switch mode from searching to propagating. They change formation and set up a multi-hop link to allow viewer base stations to evaluate the situation. The location of the target is indicated at the viewer base station.

5. **Streaming**: The UAVs surveil the target by propagating videos or pictures until ordered back to the control base station.

In this paper we introduce an architecture for SAR scenarios, which provides flexibility to change the decision-making and autonomy level based on the application and user demand.

There are many projects that envision employing UAVs for SAR purposes. Each project focuses on development of certain aspects of the system development. For instance, COMETS employs heterogeneous (in type and capabilities) UAVs to aid first responders in localizing and monitoring wildfires [1]. CLOSE-SEARCH focuses on performing SAR operations in unknown terrain [2], while SHERPA aims to specifically focus on performing such operations in alpine regions [4]. SUAAVE considers dangerous terrain, and emphasizes on time criticality in acquiring imagery for SAR operations [14]. On the other hand, RESCUECELL focuses on logistics and considerations for transport of a UAV system to disaster struck areas [3]. However, none of these projects focus on a complete system integration considering all the system modules coordination, communication and sensing. This has been the aim of the SINUS project.

[1]Self-organizing Intelligent Network of UAVs (uav.lakeside-labs.com)

2. CHALLENGES

With the rising interest toward using multiple UAVs for civil applications, different architectures to coordinate the simultaneous flights of UAVs [6, 13] are suggested. The architecture design varies based on the application, expected quality-of-service (QoS), and type of UAVs. In our system, we may have a heterogeneous set of UAVs and sensors, and failure of one UAV will not affect the whole mission. To allow easy deployment of the system, human intervention shall be minimized. Unlike other works [6, 9], we do not merely rely on a centralized base station control for navigation or coordination. Each UAV is capable of performing detection independently. At the same time, we expect all UAVs to be able to share their metadata (e.g., locations, states, and images) with a direct communication among themselves. To fulfill these expectations, we need a reliable wireless communication infrastructure.

Imagine a scenario where QoS demands are such that a high resolution of captured aerial images or a video of the target is required. In order to transfer such data, we need to be able to estimate the required bandwidth, the throughput versus range relationship for the considered technology, current and future UAV positions, and at the same time, guarantee the reliable transmission of the data to the first responders in a timely manner. To summarize, here are some challenges and the corresponding features that distinguish our work from others:

- For a multi-UAV system to be robust, it needs to be fault tolerant, such that the failure of one device does not deem the mission unsuccessful.

- For search and rescue scenarios, time is critical and we need also to satisfy some specific QoS requirements in terms of visual quality and robustness.

- The small scales of our UAVs with a maximum payload of approximately 500 g limit available processing power, communication equipment, and sensors.

To address these challenges, we introduce the feature of *distributed decision making* in our system. This, in turn, requires the implementation of distributed communication rather than a centralized communication, in order to reduce the traffic and increase the response time and robustness. Having distributed communication ensures that the UAVs can communicate with each other directly and not necessarily all the traffic is sent through the base station. We also introduce, in our system, an autonomous control for navigation and detection, and a distributed control for collision avoidance of the UAVs. Though, if a distributed structure is not applicable or it does not improve the system performance (e.g., pre-planning), decisions are made in a centralized manner. In the next section we explain our multi-UAV system architecture in more detail.

3. SYSTEM ARCHITECTURE

For the SAR example, the architecture design is supposed to handle the five phases explained in Section 1. Figure 2 shows the main components of our system. We distinguish two types of base stations. A *viewer base station* allows to connect to the system to receive sensor data. Multiple viewer base stations may exist providing visual feedback of the ongoing mission execution (e.g., current UAV positions

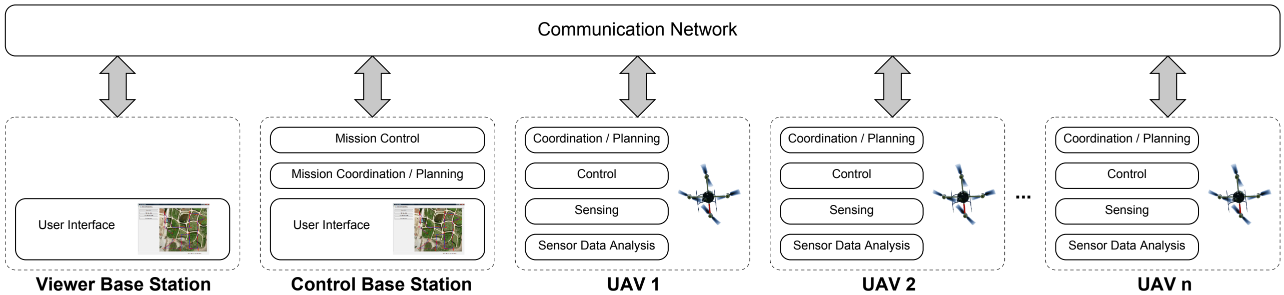


Figure 2: System components.

overlayed on a map, received images, battery level and other status). A single *control base station* controls various aspects of the system. The UAVs and the base stations communicate over a wireless network. At the control base station, initial mission parameters such as mission area, number of UAVs to use, etc. are defined by the user via a user interface. The user can also supervise the mission execution and interact with the system at this base station.

For the implementation the middleware ROS (Robot Operating System) is used, which enables a flexible and modular design of the system. It uses TCP to exchange messages between modules and offers different message exchanging paradigms (e.g., publish/subscribe or service calls[2]).

3.1 System Modules

Figure 3 illustrates the main components of the architecture and their dependencies.

Coordination / Planning: This module exchanges information to provide high level coordination with the base station or with the *Coordination / Planning* module of other UAVs. High level coordination means cooperative generation of plans (a plan is a sequence of simple actions) for all UAVs or a subset of UAVs for performing a certain mission task. Such tasks are: *search an area for a target* or *form a relay chain*. The generated plans are sent to the *Plan Execution* module. The module also receives information from other modules to react to situations that need further coordination and replanning, such as detection of a target (feedback from *Image Data Analysis* module), failure to stream a video with a desired quality (feedback from *Streaming Control* module), or low battery (feedback from *UAV Control* module).

Plan Execution: This module is responsible for the plan execution and the low level coordination with the base station or the *Plan Execution* module of other UAVs. Low level coordination means synchronization of the executed plan with the plans of other UAVs (e.g., for collision avoidance). It controls the behavior of other modules by sending control commands.

UAV Control: This module receives control commands (e.g., *go to way-point*) and forwards them to the *UAV Hardware Interface*. Telemetry and state information of the UAV are forwarded to the *Coordination / Planning* module. This module depends on the model of the UAV since it communicates directly with the UAV hardware but offers a generic interface to other modules of the system.

[2]wiki.ros.org

WIFI Control: This module receives commands that change the behavior of the underlying wireless network module (e.g., force the route of packets along a chain of relaying UAVs). It delivers information about the current connection quality to the *Streaming Control* module in terms of packet acknowledgment times which is the delay between the sending of an IEEE 802.11 packet and the receipt of its acknowledgment.

Streaming Control: This module receives commands from the *Plan Execution* module (e.g., start or stop streaming), but it is also able to autonomously change the quality of the streamed video to account for changes in the connection quality. It sends information about the quality of the video stream to the *Coordination / Planning* module. Adjustment of the stream quality can be done based on the link quality which is related to the acknowledgment time of IEEE 802.11 packets [12].

Image / Video Streaming: This module encodes or recodes the acquired images or the video based on the commands from the *Streaming Control* module and streams a video to the base station.

Image Data Analysis: This module analyzes the captured images and provides the result to the *Coordination / Planning* module.

Image / Video Acquisition: Depending on the camera model, different implementations of this module can be used that offer images and videos via a generic interface to other modules.

The information exchanged with other UAVs or the base station as well as the video stream are sent through the WIFI module to the wireless channel which is not explicitly depicted in the figure.

3.2 Communication Infrastructure

For the establishment of a reliable distributed multi-UAV system, it is necessary to consider the demands posed by such a system in terms of networking of the UAVs and base stations. An aerial network in three dimensional space would benefit from antennas with nearly isotropic radiation intensity patterns. Also, to enable distributed online decision making, it is necessary to have real-time communication amongst the devices. In adaptive application scenarios, like SAR, where the mission tasks vary dynamically, such communication may be required to disseminate information (e.g., detection message) and tasks (e.g., traffic generation and information relaying) in the network. Also, as mentioned previously, SAR is a time-critical application where a continuous connectivity to ground personnel is mandatory.

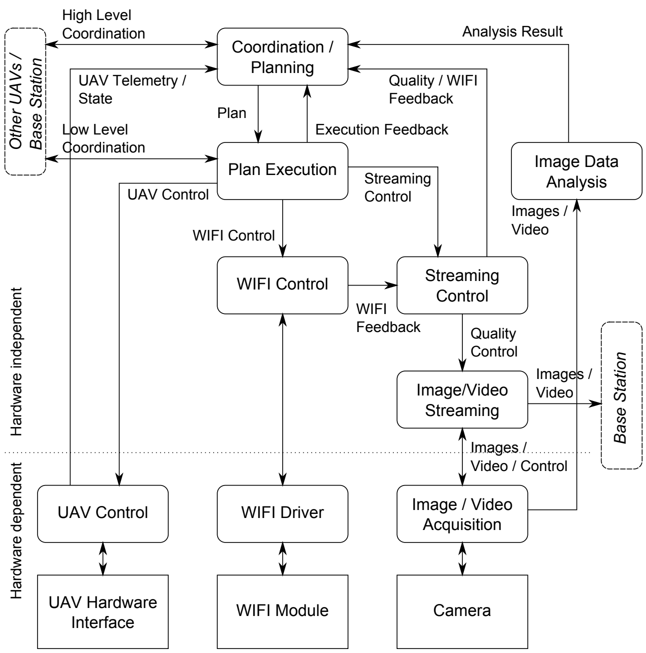


Figure 3: Modules on a UAV.

Thus, a persistent network connectivity is desirable to propagate information more efficiently in time.

All these requirements are addressed in the SINUS system using off-the-shelf wireless technology. An antenna structure in the shape of a horizontal equilateral triangle is introduced, which uses three Motorola ML-5299-APA1-01R dipole antennas, to provide isotropic coverage [19]. This antenna structure is mounted at the base station (see Figure 4), as well as on the UAVs. The requirement for peer-to-peer connectivity between the devices is addressed using an adhoc network. The standard IEEE 802.11s mesh technology is used for this purpose. A performance analysis was performed in [18] comparing the network characteristics of such a multi-hop ad-hoc network with infrastructure mode, to examine the strengths and weaknesses of each mode. The work exploits relaying to establish connectivity for out-of-range nodes. WLE300NX 802.11abgn mini-PCIe modules are used as network interfaces. 5.2 GHz 802.11a links are employed to avoid interference with the 2.4 GHz remote control (RC) links.

3.3 Detection and Video Streaming

Each UAV is running a detection algorithm on-board that scans in real-time the captured images and searches for specific features or patterns (e.g., color, text or shape). See Figure 5 for a sample color-based detection. Features or patterns are extracted by using the existing image processing tools which are embedded by OpenCV in all UAVs. This way, we avoid the extra traffic and delay of sending the images to the base station and also we avoid a centralized decision making. However, for monitoring purposes, images with a frequency of 1/5 Hz are transferred to the base station (see Figure 6).

After detection, the UAVs will shape a new formation and the detecting UAV will start to stream a video to the base

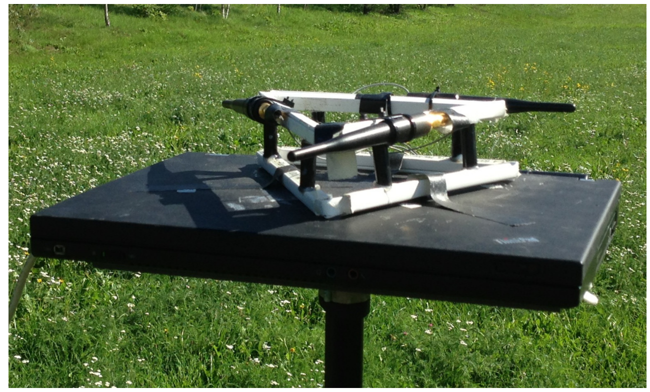


Figure 4: Base station with triangular antenna setup.

Figure 5: UAV detects the person by the red color of the jacket.

station. At this level, the data flow is enforced through the relaying UAVs so that the quality of the stream remains intact. At the moment only one detected target can be handled by the system at the same time.

4. DEMONSTRATION AND DISCUSSION

4.1 Search and Rescue

For the SAR demo we use four UAVs, two of each type depicted in Figure 1. The Fireflies are equipped with Bluefox color cameras from Matrixvision and Mastermind processor boards, and the Pelicans are equipped with $C920$ webcams from Logitech and Atom processor boards. On all the UAVs and the base station, Ubuntu 12.04 was installed, and all were equipped with a Compex WIFI module, which can be operated in 802.11s mesh mode.

All four UAVs start the mission from their base positions, and follow their pre-planned way-points. Five way-points are preplanned for each UAV to sweep the whole area (see Figure 6). The start of the mission till the video streaming lasts 120 seconds. The mission continues with real-time streaming as long as enough energy remains. The maximum flight speed of all UAVs is set to 5 m/s. Throughout our experiments the communication delays are measured to be below 5 ms, which is quite satisfactory for our purposes.

Demo phases \ Decision-making	Planning	Navigation	Collision Avoidance	Detection	Image/Video Streaming
1: Pre-planning	C (BS)	-	-	-	-
2: Searching	-	A	D	A	A
3: Detection	C (DU) / D	-	-	-	A
4: Repositioning	-	A	D	-	A
5: Streaming	-	-	-	-	C (DU) / D

Table 1: Distributed (D) vs. Centralized (C) vs. Autonomous (A) tasks. Centralized tasks are coordinated either by base station (BS) or by detecting UAV (DU).

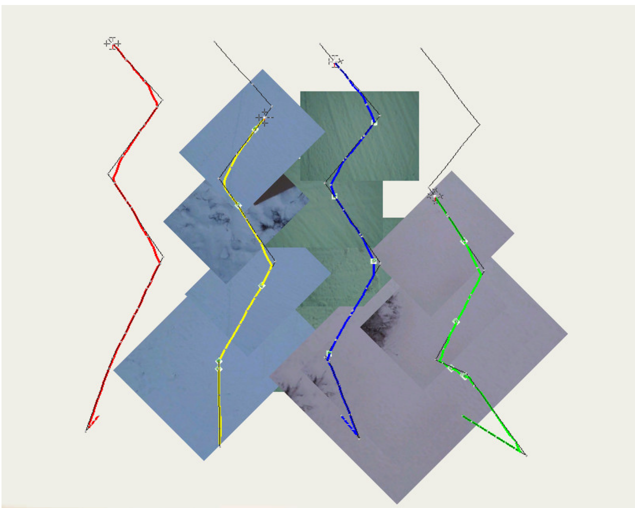


Figure 6: Visualization of mission execution.

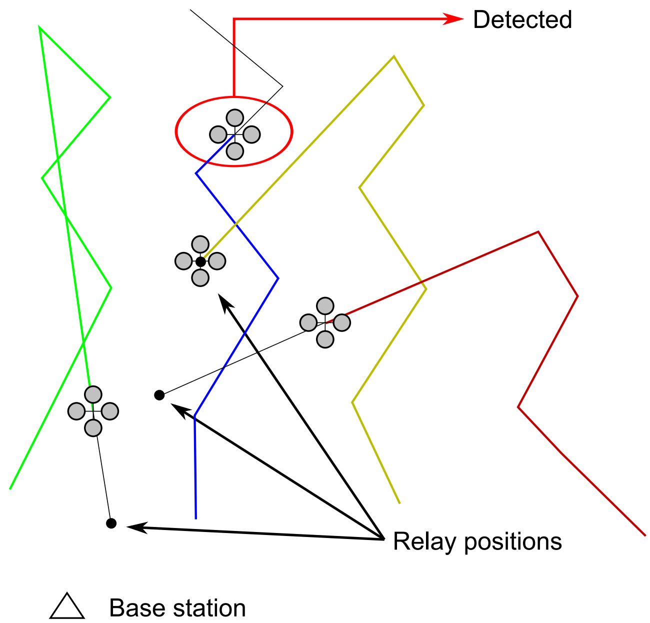


Figure 7: Repositioning phase: after a UAV (blue in this sample) detects a target, the other UAVs fly to their calculated relay positions.

However, GPS delays of 1 to 2 seconds have been noted, and therefore a 10 m positioning error has been taken into account for safety reasons.

Although pattern recognition has also been tested, in our demo the red color is used for detection (see Figure 5). In our test mission, the detection happens approximately 100 m away from the base station. We have set the minimum relay distance parameter to 30 m, which means for distances less than 30 m, a relay is not necessary and the video can be transmitted directly to the base station. However, for a distance d greater than 30 m, the number of relay positions is calculated by $\lfloor d/30 \rfloor$. This distance is chosen based on the size of the mission area and the number of available UAVs.

Figure 7 visualizes the repositioning phase after the detection. The blue UAV detects a target and the other three fly to their relay positions. After repositioning, a video is streamed to the base station through the three UAVs (shown in red, yellow, and green). The transmitted video and a demo video of the whole mission is available on our website.[3]

4.2 Distributed vs. Centralized Decisions

Our demo is comprised of different phases and each phase has its own tasks. The decision-making implementation for these tasks could be in a centralized or distributed manner. In Table 1 different tasks are categorized based on their implementation in different phases of the demo. Centralized tasks are coordinated either by the base station (BS) or by the detecting UAV (DU), while the distributed tasks are performed independently on all individual UAVs. Autonomous tasks are executed by the UAVs independently without high level coordination. A centralized and a simple distributed method have been implemented to find an assignment of UAVs to relay positions. In the centralized version the detecting UAV calculates an assignment and sends the result to the other UAVs which navigate to their assigned positions. In the distributed version the UAVs assign themselves to a position and announce this to the other UAVs. If there is a conflict, the UAV with the lower ID number (a unique ID number is assigned to a UAV at the beginning of the mission) resigns this position and claims a new one. This is repeated until the UAVs agree on an assignment. The position of the detected target is sent to all UAVs by the detecting UAV, and the coordinates of the actual relay positions can be calculated by the UAVs independently. In the streaming phase the UAVs have to configure their wireless modules to send the video to the next hop in the relay chain. Depending on whether the planning in the detection phase

[3]uav.lakeside-labs.com/media/video-clips

is done centralized or distributed, determination of the next hop is done by the detecting UAV or the UAVs depending on the agreed assignment. The collision avoidance routing is executed by every UAV and uses the GPS positions which are exchanged by the UAVs for this purpose.

5. CONCLUSIONS

In this paper we describe an architecture to build an autonomous system of small-scale UAVs to use in search and rescue missions. Since different levels of autonomy and different levels of centralization may fit different applications, we described a system which can be adapted to different scenarios. Such a system can be adjusted to different levels of autonomy based on operator demand. Individual nodes (e.g., UAV or base station) can simply join or leave the network without affecting the ultimate goal of the mission. This characteristic makes our system robust to individual failures and also expandable to add new types of UAVs, and even other types of robots (e.g., ground robots). Whenever necessary, an operator is able to interrupt the mission or adjust the mission plan with the GUI available at the control base station. The architecture has been tested successfully in a real outdoor mission by using a heterogeneous set of UAVs and sensors.

Acknowledgments

The work was supported by the ERDF, KWF, and BABEG under grant KWF-20214/24272/36084 (SINUS). It has been performed in the research cluster Lakeside Labs.

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