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Universal Ground Control Station for Heterogeneous Sensors

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***Abstract*—Today, a wide range of sensors and mobile systems – both aerial and ground-based – are available for surveillance and reconnaissance tasks. For example, they provide first responders with current information about the situation at the operation site. In many cases those systems have their own dedicated control and exploitation station. The joint control of heterogeneous sensors and platforms, as well as the exploitation and fusion of heterogeneous data is a challenge. The surveillance system AMFIS presented in this paper is an integration platform that can be used to interconnect system components and algorithms. The specific tasks that can be performed using AMFIS include surveillance of scenes and paths, detection, localization and identification of people and vehicles as well as collection of evidence. The major advantages of this ground control station are its capability to display and fuse data from multiple sensor sources and the high flexibility of the software framework to build a variety of surveillance applications.**

Keywords - ground control station; sensors; unmanned aerial vehicles; security; surveillance; disaster management

I. INTRODUCTION

This paper presents a generic surveillance system and its control station called AMFIS. AMFIS is a component based modular construction kit currently under development as a research prototype. It has already served as the basis for developing specific products in the military and homeland security market. Applications have been demonstrated in exercises for the European Union under the PASR program (Preparatory Action for Security Research), German Armed Forces, and the defense industry. The tasks that have to be supported by such products are complex and involve among other tasks, control of sensors, mobile platforms and coordination with a control center.

The surveillance system AMFIS [1] is an adaptable modular system for managing mobile as well as stationary sensors. The main task of this ground control station is to work as an ergonomic user interface and a data integration hub between multiple sensors mounted on light UAVs (unmanned aerial vehicles) or UGVs (unmanned ground vehicles), stationary platforms (network cameras), ad hoc networked sensors, and a superordinated control center.

The AMFIS system is mobile and portable, allowing it to be deployed and operated anywhere with relative ease. It can supplement existing stationary surveillance systems or act as a surveillance system on its own if no preexisting infrastructure is available. The sensor carriers in this multi-sensor system can be combined in a number of different setups in order to meet a variety of specific requirements. At present, the system supports optical sensors (infra-red and visible) and alarms (PIR, acoustic, visual motion detection). There are plans to add support for chemical sensors in the future.

AMFIS has established standardized interfaces and protocols to integrate and control different kinds of sensors. This “plug and sense” approach allows the seamless integration of new sensors with a minimal effort. If necessary, all sensor data is automatically converted by dedicated services to a format usable by the ground control station.

After a short survey of related work an overview of the application scenarios is presented, followed by a detailed description of the apparatus in Section IV. Sections V and VI outline selected services and introduce a commercial flight platform modified to reach a higher level of autonomy and extending the ground control station presented in Section IV. Finally, in Section VII some first practical results are shown.

II. STATE OF THE ART

To the best of our knowledge, the combination of heterogeneous sensors and sensor platforms (ground, air, water) in an open homogeneous system allowing the fusion of various sensor data to generate a complex situation picture is quite a unique project. The integration of different sensors into one system has already been realized in previous systems but mainly in order to create specialized individual solutions tailored to individual customer requirements. Many projects deal with the development of supervision systems, new sensor platforms or control of sensors. The combination of these innovative supervision and reconnaissance attempts to one modular system has not yet been done.

Systems similar to AMFIS are the ground stations of the French company Aerodrones [2] and the American company AII [3], both developed as stand-alone control stations for multiple airborne drones. Another example is the product of the US company Defense Technologies [4], which focuses on military standardized interfaces to control different sensor platforms on the ground, in the air and in the water.

In contrast to AMFIS, Aerodrones and AII deal exclusively with airborne sensor platforms. Defense Technologies does not commit itself in the kind of used sensor platforms and is therefore more similar to AMFIS.

AII and Defense Technologies are concentrating on military solutions while AMFIS is mainly intended for civil applications.

III. Application Scenarios

The security feeling of our society has significantly changed during the past years. Besides the risks arising from natural disasters, there are dangers in connection with criminal or terroristic activities, traffic accidents or accidents in industrial environments.

Even though a lot of effort is put into protecting threatened or vulnerable infrastructure, most threats cannot be foreseen in their temporal and local occurrence, so that stationary in situ security and supervision systems are not present. Such ad hoc scenarios require quick situation-related action.

Possible scenarios that deal with these specifications are the supervision of big events or convoys for security reasons, natural and man-made disasters such as earthquakes or major fire control but also intrusion of unauthorized persons into sites and buildings, e.g., to take hostages or place explosives.

Especially in the civil domain, in case of big incidents there is a need for a better data basis to support the rescue forces in decision making. The search for buried people after a building collapses or the clarification and location of fires at big factories or chemical plants are possible scenarios addressed by our system. Only in the minority of cases the rescue forces can rely on an already available sensor infrastructure at the incident site. If there were sensors available, there is a significant chance they will be destroyed or at least partially corrupted. A transportable sensor system to be used remotely at the site of the event is proposed to close this gap.

The micro UAVs used in AMFIS can deliver a highly up-to-date situation picture from the air during a conflagration in a chemical factory or a similar scenario. Ground robots can enter the building in parallel to the fire-fighting work and penetrate areas, which are not yet accessible for the fire fighter and search for injured people or unknown sources of fire without endangering human life. Additionally, the mobile sensor platforms can be complemented by stationary systems. These can be temperature sensors for the fire aftercare or the measuring of the fire development and expansion or vibration and motion sensors to use in a collapsed building. These sensors can be used to prevent or at least to warn of any further structural changes in a collapsed building by detecting vibration and movement in the debris. The UAVs or ground robots can also act as platforms to deploy sensors at points of interest.

Besides the system's capability of ad hoc deployment during disasters or accidents, AMFIS can also be used as a versatile protection and supervision system. Premises or vulnerable infrastructures can be monitored with all types of sensors and actuators. Equipping the perimeter with motion detectors and cameras is a typical setup. In addition, mobile ground robots can patrol the area and respond to events. Other tasks that can arise are the detection of danger potential, the supervision of scenes and ways or the localization, tracking and identification of people and vehicles.

When several sensor systems and platforms are used in a complex scenario at the same time, conventional control systems designed as single use- and controlling-systems quickly reach their limits. First of all, every subsystem needs its own console and a specially trained operator due to the fact that each system has its own interface. Secondly the fusion and synchronized filing of sensor and status data from different systems is not an easy task.

The control of the individual sensors and platforms from the situation center is hardly practicable on account of the complexity, delay in the data transfer and distance to the place of action (often several kilometers).

As a connection between the sensors and the situation center an authority directly on the site of the event is necessary, which processes the reconnaissance missions independently. That includes steering sensor platforms, controlling sensors as well as filtering and densification of sensor data so that only information relevant for decisions like situation reports, alarms and critical video sequences are transmitted in an appropriate way to the situation center.

An analysis of the demands in complex scenarios incorporating micro UAVs has shown that at least two operators are necessary on the ground control station to deal with the requirements and problems arising from such a scenario. One operator is exclusively responsible for the control and supervision of the mobile sensor platforms. The second operator looks after the evaluation of the sensor data streams and the communication with the situation center.

According to a recent Frost & Sulivan report [5] micro UAVs are already used in vast and diverse civil applications. Some of the tasks that can be supported with UAVs in general include but are not limited to: enhancing agricultural practices, police surveillance, pollution control, environment monitoring, fighting fires, inspecting dams, pipelines or electric lines, video surveillance, motion picture film work, cross border and harbor patrol, light cargo transportation, natural disaster inspection, search and rescue, and mine detection.

Figure 1. A team of micro UAVs

Obviously some of these tasks are not suitable for single micro UAVs due to their limited operating range and payload. With groups or swarms of micro UAVs (Figure 1) it is possible to realize scenarios that are inefficient or even not feasible with a single micro drone. Some situations where cooperating MAVs (micro aerial vehicles) add value include:

- A wider area has to be searched. A team of MAVs can increase coverage and reduce the time required.
- A UAV loses connection to the ground control station because it moved too far or the signals are blocked by an obstacle. In a group of UAVs, one of them can be "parked" in reach of the ground control station and act as relay station.
- Several intruders enter the site. They later split up, each taking different directions. A single drone would have to decide, which person to follow, while a swarm of UAVs can form subgroups and track each intruder individually.
- The duration of surveillance exceeds battery life time. In a team, assignments can be planned accordingly and another UAV can take over the task of an out-of-battery drone.
- A threat has to be monitored with different sensor types. For example, an intruder who is tracked visually suddenly places an object. Besides the visual sensor some CBRNE (chemical, biological, radiological, nuclear, and explosive) detection devices are needed. Since the payload of a single quadrocopter is very limited, a swarm could carry different sensors.
- Multi-sensor capability can also be used to visually control the action of different drones. For example an infrared sensor equipped UAV could be employed by the operator located at the ground control station to navigate a chemical sensor equipped micro UAV through a dark building.

These use cases illustrate that there is a need for the coordinated use of micro UAVs. The combination with other sensor platforms, such as UGVs (unmanned ground vehicles) or stationary sensors, adds further value to the system.

IV. System Overview

In order to be adaptable to a wide range of different requirements and applications, AMFIS was developed as a mobile and generic system, which delivers an extensive situation picture in complex surroundings - even with the lack of stationary security technology. In order to achieve maximum flexibility, the system is implemented open and mostly generalized so that different stationary and mobile sensors and sensor platforms can be integrated easily with minimal effort (Figure 2), establishing interoperability with existing assets in a coalition such as UAVs.

The system is modular and can be scaled arbitrarily or be adapted by choosing the modules suitable to the specific requirements. Because of the open interfaces, the accumulated data can be delivered on a real-time basis to foreign systems (e.g., command and control systems or exploitation stations, cf. Figure 3).

The AMFIS system can be divided into a mobile ground control station, which can control and coordinate different UAVs, land vehicles or vessels (sensor platforms), as well as stationary autonomous ad hoc sensor networks and video cameras. Depending on the used sensors and sensor platforms, the system is extended with suitable broadcasting systems for the transmission of the control signals and the sensor data (e.g., video recordings.)

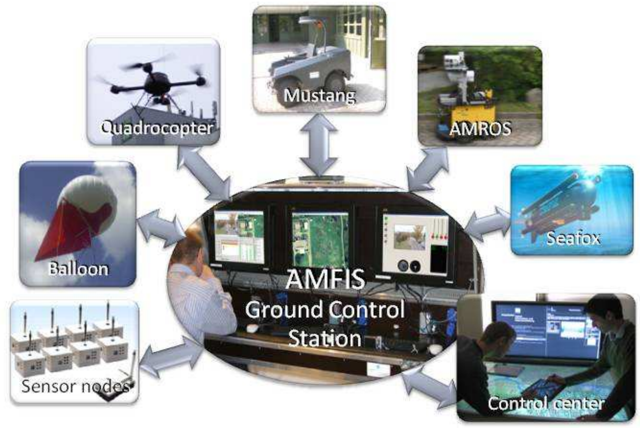

Figure 2. The AMFIS ground control station serves as integration platform for various sensors and vehicles

By the universal approach, the system is able to link with a wide range of sensors and can be equipped with electric-optical or infrared cameras, with movement dispatch riders, acoustic, chemical or radiation sensors depending on the operational aim. If supported or even provided by the manufacturer, these sensors can be mounted on mobile sensor platforms or be installed in fixed positions. The only requirement such sensors have to fulfill in a mobile scenario is that they work properly without the need for any pre-existing infrastructure.

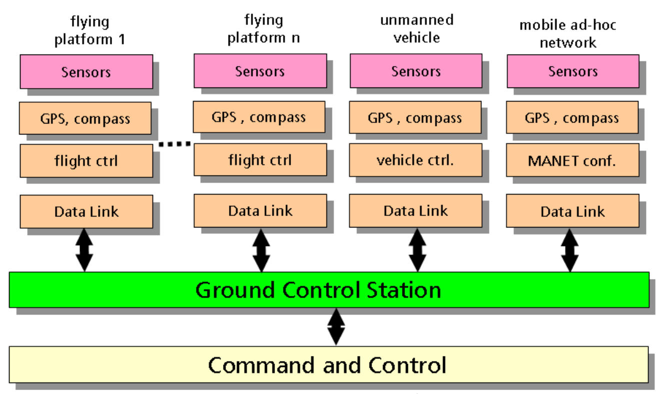

Figure 3. AMFIS interfaces

The AMFIS system is scalable and can be extended to any number of workstations. Due to this fact several sensor platforms can be coordinated and controlled at the same time. The most different sensor platforms can be handled in a similar manner by a standardized pilot's working station that in turn minimizes the training expenditure of the staff and raises the operational safety. The user interface is automatically adapted according to the sensor or sensor platform at hand by using standardized descriptions.

Data fusion is one of the most important tasks of a multi sensor system. Without merging the data from different sensors the use of such a system is very limited. Linking data of sensors that complement each other can generate an entire situation picture.

All information gathered during the operation is immediately available to the crew of the ground control station, in which a GIS-supported, dynamic situation picture plays a central role. At the same time all received data is archived and stored into databases, e.g., a CSD (Coalition Shared Data) [6] or SSD (SOBCAH Shared Data) [7]. This serves the perpetuation of evidence and allows an additional subsequent analysis of the events.

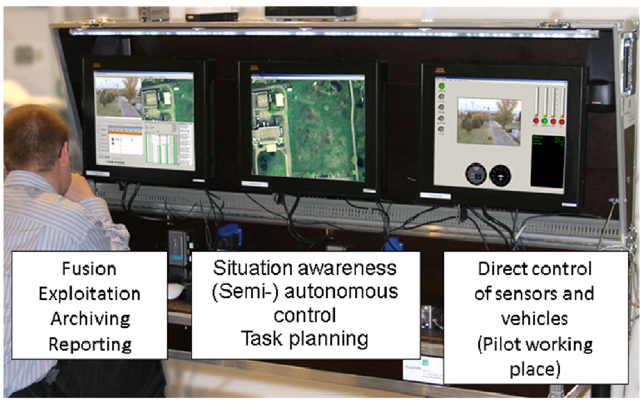

Figure 4. The AMFIS ground control station and its user interface

The open interface concept supports the integration of AMFIS in existing security systems so that data can be exchanged on a real-time basis with other guidance, supervision or evaluation systems. Mission planning, manual and automatic vehicle guidance, sensor control, local and temporal linking (coalescence) of sensor data, the coordination of the people on duty, reporting and the communication with the leading headquarters in the situation center belongs to the other tasks of a reconnaissance system.

Combination of sensor events and appropriate actions are implemented by predefined rules with an easy to use production system for situation specific adaptations.

A. *User Interface*

The user interface of the AMFIS ground control station at Fraunhofer IOSB consists of three workstations (Figure 4). Basically, the system is designed such that each display can be used to interact with each function allocated by AMFIS. The standard setup consists of two workstations with one operator each, and one situation awareness display in between that supports both operators. The duties of the two operators can be divided into sensor and vehicle control, called pilot working place, and data fusion, archiving, exploitation and coordination tasks.

The user interface of the latter working place primarily provides a function for the visualization of sensor data streams. Therefore the operator gains access to the accumulated data. His task is to obtain and keep an overview of the situation and to inform the higher authorities about important discoveries. He provides the associated data so that external systems or personnel can utilize that information. It is incumbent on him to mark important data amounts and to add additional information when necessary. Furthermore, he is the link to the pilot and coordinates and supports the pilot in his work. The analyst as well as the pilot relies on the central geographical information system-supported situation representation that provides an overview of the whole local situation. The geographical relation is established here and the situation and position of the sensors and sensor platforms can be visualized. This includes for example, the footprints of cameras or the position and heading of UAVs or UGVs.

The pilot's workstation is designed to control many different sensor platforms. It is not clear from the start, which sensor platforms will be used in the future and it is also not clear, which situation information will be provided by the different systems, or which information is needed to control the future platforms in a proper way. For this purpose the pilot workstation provides a completely adaptable user interface, which allows selectively activating or deactivating the required displays. For example, an artificial horizon is completely useless in order to control a stationary swiveling camera but very helpful for controlling an airborne drone. The surface can be adapted to the particular circumstances and is configurable for a wide range of standard applications. No matter what sensor platform the user is currently controlling or supervising, the task is the same. He does not have to switch between different proprietary control stations. The user interface is identical except for individual volitional or necessary adaptations.

B. *System and Software Architecture*

The physical sensors and sensor carriers are mapped logically to the so-called sensor web. This is a tree structure describing the real-world entities: The root node, the sensor web itself, connects to different sensor networks, each representing a number of similar sensor carriers, for example a team of UAVs. Each of those sensor networks is made up of one or more sensor nodes, equal to a physical sensor carrier (e.g., a single UAV), which in turn contain numerous sensors (e.g., camera, GPS receiver, etc.). The sensor web is permanently stored in a database, from which an XML file is generated at runtime by the central message hub of the AMFIS ground control station, the Connector.

The standard communications protocol within AMFIS is based on XML messages transported via TCP socket. To ease the use of this protocol, implementations exist in various runtime environments (e.g., .NET, Java), encapsulating the XML-handling and offering the user an object-oriented view of the messages. When a client application connects to the Connector, it first receives the aforementioned XML-version of the sensor web followed by a steady stream of XML messages, each containing metadata (e.g., sensor values, commands, etc.) originating from or destined to one of the sensors in the sensor web.

A client application can be anything from a GUI application to a low-level service:

- The various GUI applications of the user interface, most importantly the analyst's interface, the situation overview and the pilot's interface. Those applications offer a visual representation of received metadata to the user, for example by displaying the current geographical locations of the various sensor carriers in the map, and transmit commands to the sensor carriers, for example a user-generated waypoint for a UAV.
- A number of services running in background, notably the video server, offering time shifting and archiving for both video and metadata (more on video management within AMFIS see below), the rules engine, the flight path planning tool and the multi-agent system, all supporting the user by automating certain processes (see Section V).
- Drivers for various sensor carriers, for example a dedicated control software for UAVs, which translates high-level flight commands like waypoints into the proprietary RS232-based control protocol of the respective drone, and in turn generates metadata XML status messages containing the current position, heading, remaining flight time etc.
- Interfaces to third-party applications or networks, for example superior command centers.

The current implementation of the communication protocol is strictly multicast-based: Every message sent to the Connector is relayed to every connected client application, leaving it to the respective application to decide what to do with it. For future versions, a subscription-based model is planned.

The protocol relies on lower-level protocols such as TCP to ensure delivery of the messages. Since most of the messages contain live status data, they are transferred in a fire-and-forget manner, thus eliminating possible race conditions within the Connector.

While all metadata – be it sensor values, commands or user-generated textual comments – is transmitted via XML, the extensive amount of video data accumulated by the various cameras has to be processed and stored by other means. A central application within AMFIS is the video server, which receives and records all available network video streams along with incoming XML messages. Since the analyst's interface heavily relies on the capability to go back in time and review critical situations, the video server serves the dual purpose of both recording the video streams for later archival as well as providing time shifting-enabled streams to other clients. If required the video server can store (and later play back) the accumulated data using a standard MySQL database.

In order to interface with third-party systems, it can become necessary to transcode available data into another format. Upon request, the video server can spawn a so-called transcoder process, multiplexing video and metadata into a single stream to be transmitted to a remote command center. To receive incoming commands from a command center, an XMPP client (Extensible Messaging and Presence Protocol, formerly Jabber [8][9]) has been implemented, which seamlessly integrates into the AMFIS ground control station.

Figure 5 shows a logical representation of the AMFIS system.

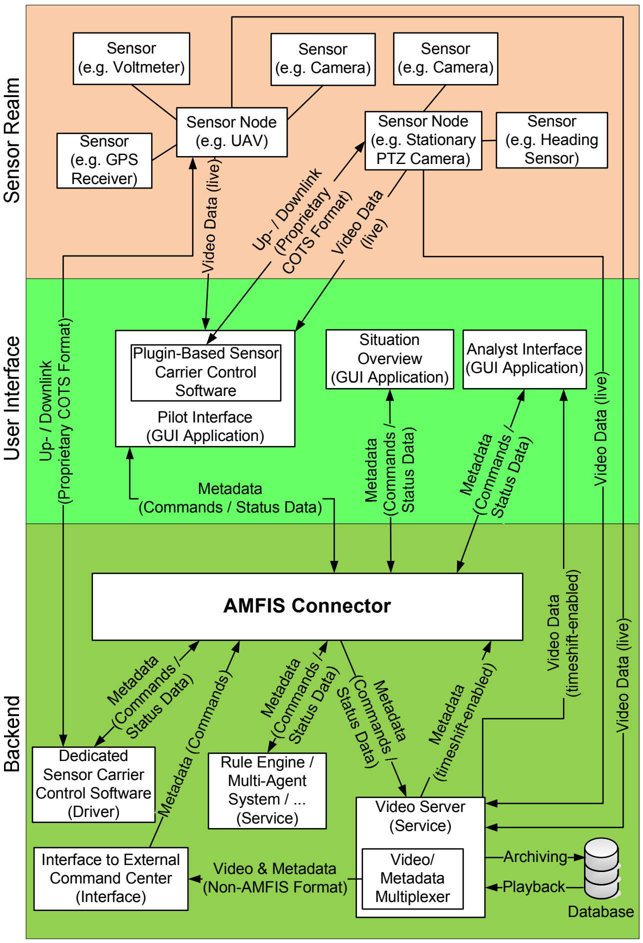

Figure 5. AMFIS system overview

V. AMFIS SERVICES

In addition to being an integration platform, AMFIS offers a number of support services related to surveillance and reconnaissance tasks. Those services facilitate resource planning, sensor and vehicle coordination, sensor data exploitation, and training. Three of these services, i.e., rule-based event response, photo flight and simulation, are described in the following paragraphs.

A. *Rule-Based Event Response*

This service is a support system for the automatic combination and selection of sensor data sources in a surveillance task. Autonomous reactions, e.g., responding to an intrusion alert triggered by a motion detector, are very important during a surveillance scenario. Therefore a solution was developed, which grants users an easy, powerful and versatile platform for defining reactions.

The implementation is universal so that the support system can be adapted to several scenarios at different individual sites. This is accomplished by the use of rule sets, which are created site and task specific. These rules contain work flows which are pushed if a certain predefined event occurs. Thus, for example, a watchman can be automatically informed or a UAV can be sent off for reconnaissance of a defined area without any user interaction.

The support component in AMFIS is implemented with the Drools rules engine [10] using production rules for representing procedural task knowledge. The engine uses the Rete algorithm, which repeatedly assesses the current situation and selects the rules to execute. Drools is open source and contains a well developed rule language.

The rule language is based on the when-then schema (Figure 6). Additionally, Boolean logic, methods of compiled Java source code and their return values can be used.

```
rule "rule"
    when
            sensor triggers alarm
            <additional preconditions>
    then
            camera turns to sensor position
            drone flies to sensor position
end
```

Figure 6. Layout of a rule

The integration of the rule-based event response application into the AMFIS system is depicted in Figure 7.

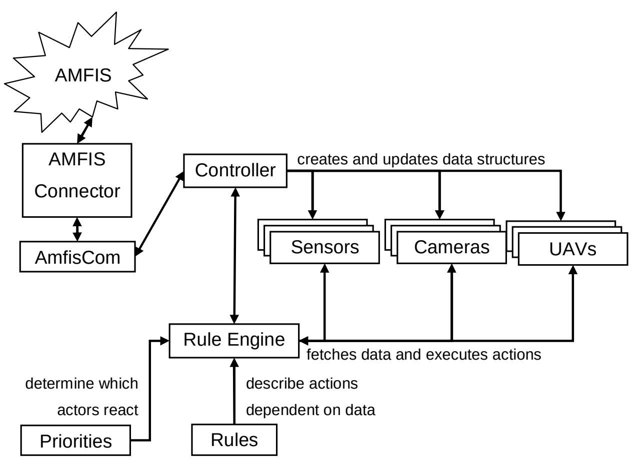

Figure 7. Integration of a rule engine

The rule engine uses AmfisCom, a communication library for interfacing the AMFIS Connector (cf. Section IV.B) to establish a connection to the Connector Service, the message hub of AMFIS, and receives data. Data structures containing e.g., positions and IDs of sensors, cameras and UAVs are created and updated with the received data. When there is an alarm message it can be assigned to its corresponding sensor through the unique ID. After this initialization phase the rule interpretation starts. When a rule becomes applicable messages are sent to the corresponding assets (cameras, UAVs, etc) to change their positions accordingly. Furthermore, every camera has a priority list of targets. Before the message is sent, this list is evaluated. Only if the new target has at least the same priority as the current target, the camera pans to the new target.

Additionally, a tool providing a graphical user interface has been developed. It facilitates the definition of rules and the creation of priority lists for cameras. The rules can be assembled by clicking and saved as XML file. These files are editable by the user at any time. Furthermore, the rule engine can import these files and convert the content into the specific rule language.

B. *Photo flight*

The photo flight service assists the operator in obtaining an up-to-date situation picture of a site. One or more UAVs with camera payloads fly to defined waypoints and capture high resolution still images. These images are later combined to a mosaic. The photo flight service manages the available assets (i.e., UAVs and payloads) and automatically calculates flight paths based on a user-defined area of interest.

In the flight path planning tool, the user can define any polygonal shape on the map. He then selects one or more UAVs from a list of available drones, which is distributed by the AMFIS Connector. The Connector provides the necessary information about all drones and their current payloads. For each selected UAV the user is requested to enter some variable parameters like desired photo flight height or safety height. The safety height parameter is an additional safety feature that defines individual cruising heights in order to prevent collisions between UAVs.

After that, the operator can start the photo flight or add/remove additional drones to/from the list. Once all necessary information has been entered correctly and the "Calculate" button is clicked, the planning algorithm starts and shows the resulting flight path on the map (Figure 8).

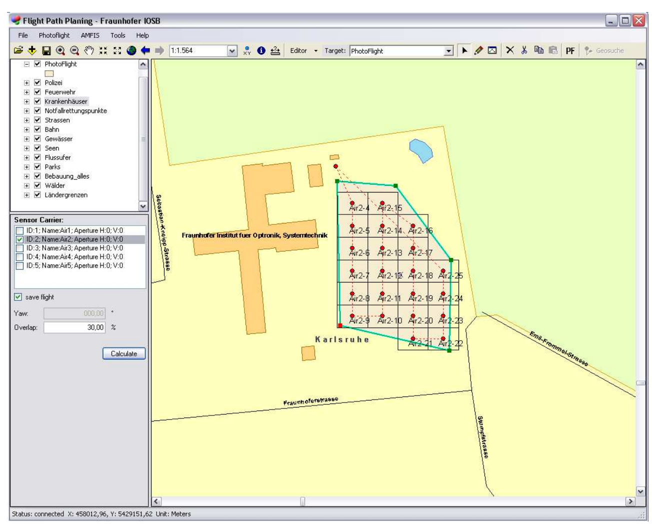

Figure 8. GUI of the flight path planning service

Additionally, the flight path planning service offers the possibility to export the calculated waypoints in an AMFIS specific file format or upload the points directly to the respective UAV using the Connector.

C. Simulation

In order to assess different cooperation strategies for teams of UAVs and other assets, a simulation tool has been developed. The tool is also useful when it comes to training and briefing of the operators. Modeling and visualization of scenarios was done using a computer game engine with corresponding editing tools. An interface between AMFIS and the engine has been implemented. It allows full control of the virtual entities as well as feedback from the virtual world. The simulation tool is fully integrated into the AMFIS ground control station allowing seamless combination of virtual and real assets. Virtual vehicles can be monitored and controlled analogous to real assets through the AMFIS situation map, whereas real UAVs can be displayed in the virtual world next to simulated components.

Figure 9. The AMFIS simulation component

An example scenario that simulates an intrusion has been realized (Figure 9). Besides the UAVs and the actors in the scenario, sensors have also been modeled. Different kinds of sensors such as motion detectors, cameras, ultra sonic or LIDAR (light detection and ranging) sensors can be modeled with their specific characteristics. The simulation tool can determine if an object lies within the range of a sensor. This helps evaluate and optimize the use of different sensing techniques.

The intelligence of team members is implemented in software agents as described in Section VI.C. They interface with the simulation engine using the same control command interface as the actual quadrocopters. This subsequently can allow the simulation to be transferred to the real world without changes to the agents.

VI. AUTONOMOUS SENSOR PLATTFORMS

AMFIS as an open and generic system supports the simultaneous operation of a large number of sensors and sensor platforms. While the handling of single platforms is already well understood, control and coordination of several mobile platforms can be a challenging task.

For this purpose one of the research focuses lies on the improvement of the application of multiple miniature UAVs. Our approach is to increase the level of autonomy of each drone. Therefore a vast amount of effort has been put into the selection of the flight platform. Such a platform preferably comes with a range of sensors and an advanced internal control system with autonomous flight features, which minimizes the regulation need from outside. When it comes to flying autonomously, the system has to be highly reliable and possess sophisticated safety features in case of malfunction or unexpected events.

Figure 10. Sensor platform AirRobot 100-B

Other essential prerequisites are the possibility to add new sensors and payloads and the ability to interface with the UAV's control system in order to allow autonomous flight. A platform that fulfils these requirements is the quadrocopter AR100-B by AirRobot. It can be both controlled from the ground control station through a command uplink and by its payload through a serial interface.

A. UAV Control Hardware

To support the pilot at his work at the ground control station and to give him the possibility to supervise multiple flying sensor platforms at the same time, several steps are necessary. The first step is to enhance the hardware in order to reach a higher level of autonomy. Therefore, a payload was developed, which carries a processing unit that can take over control and thereby steer the quadrocopter.

Due to space, weight and power constraints of the payload, this module has to be small, lightweight and energy-efficient. On the other hand, a camera as a sensor system should not be omitted. An elegant solution is the use of a "smart" camera, i.e., a camera that not only captures images but also processes them. Processing power and functionalities of modern smart cameras are comparable to those of a PC. Even though smart cameras became more compact in recent years, they are still too heavy to be carried by a quadrocopter such as the AR100-B. In most applications, smart cameras remain stationary whereby their weight is of minor importance. However, a few models are available as board cameras, i.e., without casing and the usual plugs and sockets (Figure 11). Thus, their size and weight are reduced to a minimum. The camera that was chosen has a freely programmable DSP, a real-time operating system and several interfaces (Ethernet, I²C, RS232). With its weight of only 60g (without the lens), its compact size and a power consumption of 2.4W, it is suitable to replace the standard video camera payload.

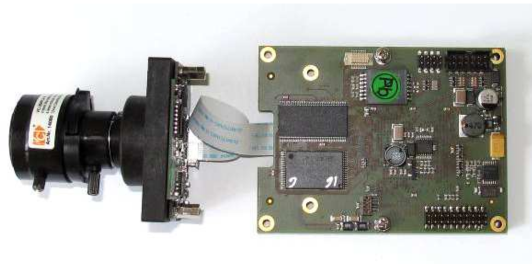

Figure 11. A programmable camera module controls the UAV

The camera can directly communicate with the drone's controller though a serial interface. The camera receives and processes status information from the UAV such as position, altitude or battery power, and is able to control it by sending basic control commands or GPS-based waypoints.

A drawback of the board camera is its lack of an analogue video output thus rendering the quadrocopter's built-in video downlink useless. Image data is only available through the camera's Ethernet interface. To enable communication between the smart camera and the ground control station, a tiny WiFi module was integrated into the payload. The WiFi communication link allows streaming of live video images, still shots and status information from the UAV to the ground control station. Furthermore, programs can be rapidly uploaded to the camera during operation.

Currently, the above enhanced UAVs are able to perform basic maneuvers, such as take-off, fly to position, and landing, all autonomously. Furthermore, a software module was implemented, that calculates the footprint of the camera, i.e., the geographic co-ordinates of the current field of view. In the future we will also use the camera's image processing capabilities to generate control information. As a safety feature, it is always possible for the operator to override autonomous control and take over control manually.

B. Communication Infrastructure

For a single UAV communication usually consists of two dedicated channels, an uplink channel for control commands and a downlink channel for video and status information. In present UAVs, each of these channels has its own communication technique in a special frequency band. In complex scenarios that require multiple UAVs there has to be twice as many RF channels as UAVs used. These channels are all point-to-point connections, which, if at all, see the other UAVs only as interferer. There is no channel between two UAVs; all communication goes via the base station.

Besides this direct control of UAVs, there is a more abstract way, which can use the benefits of an intelligent payload. The group of UAVs receives complex tasks, which they will fulfill autonomously. This kind of control however brings the standard system with up- and downlink to its limits because it poses demands, which cannot be fulfilled with the standard communication:

- No interference between communication of multiple UAVs (ideally: use of multihopping)
- Adding UAVs to the swarm must not require a new RF channel
- Opening of data channels to transmit the results to the base-station
- Opening of control channels to transmit any kind of commands to the UAV
- Sending broadcast messages to all UAVs
- Opening direct communication channels between UAVs

In addition to the new demands, the standard requirements for UAVs still must maintain the following:

- Monitor the status of every UAV in the air
- Manual control of every UAV as fallback function

To fulfill these needs the (video-) downlink is replaced by a module capable of using networking communications. In our prototype we use a WiFi module because of its high data rates and good range, though other technologies might be feasible too. The UAV's uplink channel is retained as fallback control option in case of an emergency.

With the WiFi network, we implemented a communication solution that meets the demands listed above. This solution differentiates between UAV and base-station, i.e., the ground control station. There is only one base-station within the network. A base-station monitors the status of every UAV assigned to it. It also acts as gateway to other system components.

Our communication setup uses four types of channels (cf. Figure 12):

- Broadcast channel
  a channel, which offers random access to every subscriber in the network
- Control channel
  a dedicated channel between a UAV and the base-station to transmit status information from the UAV and to receive commands from the base-station
- Data channel
  a dedicated channel between UAV and the base-station to send results of task i.e., images
- Co-op channel
  this channel is opened between two UAVs if one of them needs assistance to finish a task

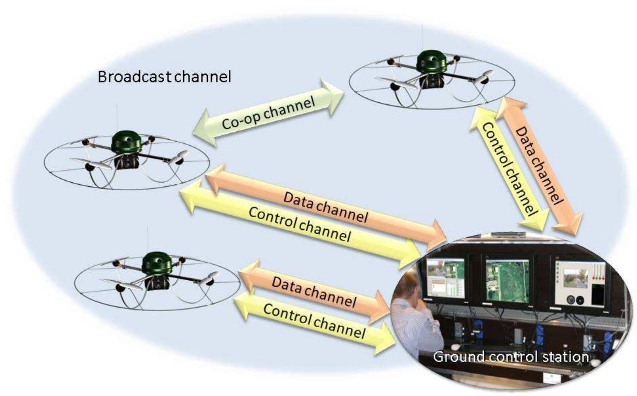

Figure 12. Communication channels between UAVs and the ground control station

1) Broadcast channel

The broadcast channel is mainly used for initializing the other channels. If a UAV is not assigned to a base-station it will look for a base-station on this channel. Also if a UAV needs assistance to finish a job, e.g., when its battery runs low or it needs a UAV with another sensor, the UAV calls for assistance on this channel. Through the broadcast channel it is possible to reach all UAVs with a single message. If a UAV, for example, detects an obstacle it can inform all other UAVs in the group. Another main feature of this channel is communicating new tasks. When this task is transmitted to the whole group instead of a single UAV, the decision regarding which UAV best fits the needs for this task can be done by the group.

2) Control channel

The control channel is a dedicated channel between a UAV and a base-station. Over this channel a UAV sends its status as well as an “Alive” Message. These data make it possible to monitor the UAVs in the base-station. The second feature of this channel is a command uplink to the UAV. It can be used to transmit tasks as well as to configure the UAV. Reconfiguring can be done by changing internal parameters of the UAV or by uploading new software modules.

3) Data channel

The data channel sends results (usually video images) to the base-station. The format of the data has to be predefined.

4) Co-op channel

The co-op channel is opened between two UAVs, if necessary. If the UAV has a task, which cannot be done on its own, it seeks a wingman over the broadcast channel. If there is an idle UAV, which can assist, a co-op channel is opened between the two drones. Over this channel the UAV has the possibility to send subtasks to the wingman. After completion, it receives the results over the co-op channel.

Replacing the standard downlink with a networking module is a big step towards autonomy of each UAV. With this adaptive communication solution it is possible to set up an expandable network of UAVs. The implemented channels provide communication links between all subscribers in the net.

C. UAV Control Software

The second step to reaching a higher level of autonomy is based on the development of a multi-agent system to implement team collaboration. An agent-based framework is implemented where the individual entities in a team of UAVs are represented by software agents. The agents implement the properties and logic of their physical counterparts. Their behavior defines the reaction to influences in the environment, such as alarms generated by sensors in the AMFIS network.

An agent is “...any entity that can be viewed as perceiving its environment through sensors and acting upon its environment through effectors” [11]. Incorporating that “An agent is a computer system, situated in some environment that is capable of flexible autonomous action in order to meet its design objectives” [12], a multi-agent system appears to perfectly meet the challenges of realizing an intelligent swarm of autonomous UAVs.

Software agents are computational systems that inhabit some complex dynamic environment, which sense and act autonomously in this environment, and by doing so, realize a set of goals or tasks, for which they are designed [13]. Hence, they meet the major requirements for a suitable architectural framework: to support the integration and cooperation of autonomous, context-aware entities in a complex environment.

The agent-based approach allows a natural system modeling approach facilitating the integration of flight platforms, sensors, actuators and services. The core-agents of the multi-agent system presented in this paper are based on the following three agent classes:

- Action Listener: This agent has two basic tasks: connecting the agent system to the AMFIS ground control station and managing the different Teamleader Agents (see below). The Action Listener receives messages from the AMFIS Connector and sends corresponding commands or data to the relevant Teamleader Agents. Through the Action Listener, the operator can directly task a UAV, bypassing the agents’ logic.
- Teamleader Agent: A team leader agent controls a group of agents consisting of at least one other agent. It co-ordinates higher tasks and assigns sub-tasks to team members, for examples areas they have to monitor. A team leader is always aware of the positions and capabilities of all team members. A team leader itself can be controlled by a superordinate team leader.
- Universal Agent: This agent represents a single UAV. Every drone must be assigned to a team leader. The Universal Agent manages all basic behaviors and data of the UAV it represents. Basic behaviors are for example the direct flight to a waypoint and receiving and handling messages from the team leader.

UAVs in a team can be equipped with different payloads, for example cameras or gas sensors. Therefore, specific agents exist, such as Video Agents and Sensor Agents, which inherit the basic behaviors from the Universal Agent. Additionally, they also have their own specific behaviors. By this separation in universal and specific agents, adaptations of the general behavior or the specific behavior can be made very efficiently, i.e., only one agent has to be modified. For example, if we want to change the behavior to fly to a waypoint we only have to do that in the Universal Agent, not in the specific payload agent.

The communication between the agents of one team is direct. It is not possible to directly communicate with a Universal Agent of another team. Communication to a Universal Agent of another team has to go through the corresponding Teamleaders. A communication between two agents in different teams is usually not necessary, because every team has its own task.

The use of this multi-agent system is not limited to UAVs. As well, it can be applied to coordinate a heterogeneous fleet of ground and air assets.

VII. Results

Figure 13 shows a high-resolution situation picture generated with AMFIS using its photo flight tool presented in Section V.B. The picture is geo-referenced and can be overlaid onto the existing GIS-based, dynamic situation map.

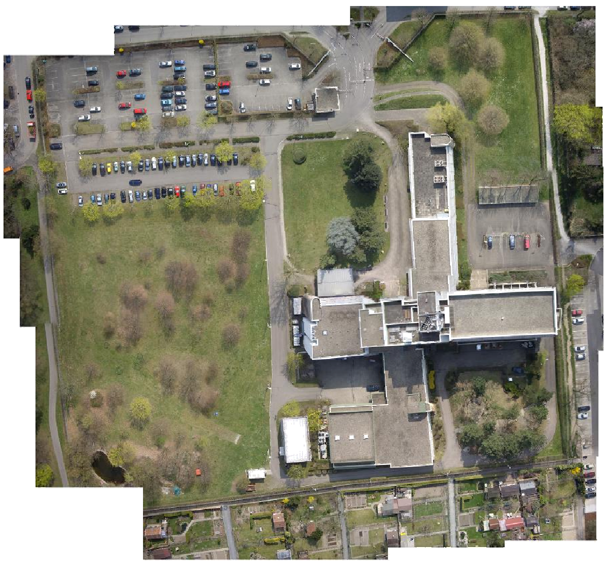

Figure 13. Situation picture generated with the AMFIS photo flight tool (ca. 9500 x 9000 pixel)

Conclusion

The presented surveillance and reconnaissance system AMFIS with its extensions is constantly under development. Due to its generic nature, it forms a rather universal integration platform for new sensors, platforms, interfaces, supporting application programs and customized solutions. The knowledge gained from the participation in various exercises is constantly used to optimize the ergonomics of the work stations and to improve the algorithms for data fusion. The advancement of sensor technology and robotics, increasing processing power, progress in information and network technology provide continuous input for the permanent development and optimization of the AMFIS system.

Presently, the human is still the most important link in the supervision chain. The operator must evaluate the data, which is delivered by the sensors and derive decisions to meet the existing dangers. Lastly, it is a person that is accountable and bears the responsibility for the resultant action, not the supporting machine.

The above introduced duties of the situation analysis and situation response are so versatile and complicated that further research is inevitable to fully automate them. Up to now, humans are still indispensable in their varied roles as head of operations, pilot, analyst, watchman etc. The AMFIS system with its ability to integrate different sensors, sensor platforms and data sources can support and assist people with those tasks.

With the use of the mobile AMFIS system in industry, as well as at authorities and organizations like fire brigade, search and rescue services, and police, the geographical and information data bases can be improved decisively. With the gathered reconnaissance information fused or linked to information extracted from different sources, the task forces deploying the AMFIS system can be better protected and coordinated and decision making in critical situations can be optimized.

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