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MUAVET – an experimental test-bed for autonomous multi-rotor applications

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Abstract. Multi-rotor flying vehicles (referred as UAVs here) are well suited for many applications, including patrolling, inspection, reconnaissance or mapping and they are already used in many cases. In most cases they are used in manual mode, mainly due to legal issues, but autonomous methods and algorithms for UAV navigation are under extensive development nowadays.
This article describes a test-bed system for development of the fully autonomous multi-UAV systems called MUAVET (Multi-UAV Experimental Test-bed). The system incorporates several UAVs, communicating with the base station, able to be controlled either locally from the onboard-running control application, centrally from the base station, or by any combined approach. The system provides basic safety features and autonomous/automatic functions which significantly reduce the risks of crash or loosing the UAV, even in case of wrong command from the user application. The function and the performance of the MUAVET system is demonstrated in the search-and-rescue scenario of multiple UAVs searching for the visually-marked ground objects placed in the designated area and cooperating with the autonomous ground vehicle supposed to reach the found targets on ground.

1 Introduction

Unmanned aerial vehicles (UAVs) are widely and commonly used nowadays for the tasks, where manned airplane or helicopter utilization is not efficient, economic, or possible. Majority of these tasks are focused on the inspection or monitoring of the specified area of facility from the air. The mapping of the area is another significant area of the UAV utilization. Mainly due to the actual legislative restrictions, most of the operations are remote controlled. This is demanding for the need of sufficient number of trained pilots, especially in multi-UAV tasks, as well as stress laid on individual pilots during the flight.

Current level of UAV development is prepared for the fully autonomous operations, which can significantly simplify the mission setup and reduces the necessary personnel requirements. As a result, the cost of the mission may be decreased. A fully autonomous UAV system has to be safe in the first place. This means mainly that risk of accidental crash of the vehicle or flight in the unintended direction is minimized as much as possible.

This article is focused on multi-rotor unmanned helicopters, able to take-off and land vertically and stay on the position in the air. These vehicles have typically lower cruise speed and significantly lower flight time on single charged battery than fixed-wing vehicles. Multi-rotor UAVs are optimal for smaller area operations, where total flight trajectory length does not exceed few kilometers. The significant advantage of multi-rotors is that they only need sufficiently flat terrain for take-off and landing, but no extra equipment or runway.

The topic of this article is a description of a test-bed system for evaluation of methods and algorithms for the control of multiple UAVs. Similar systems were built in the past, like the Multi-vehicle Experimental Platform for Distributed Coordination and Control built by H. How's team, used e.g. in [9]. This test-bed consists of several fixed wing planes, ground rovers and blimps. The system addresses the issues of distributed command and control algorithms, network topologies, resource allocation, fleet autonomy and human-in-the-loop operation control. Most past or existing UAV test-beds with multi-rotor UAVs are small-scale and indoor. The test-bed used at the GRASP laboratory [7] uses several AscTec Hummingbird quad-rotors controlled under Vicon [3] motion capture system used as a ground-truth localization system. The size of the test-bed arena is approximately $5 \times 4 \times 3.5m$. Basic UAV control regulators are provided on different levels, allowing UAV control by variously skilled users and different methods. System provides basic functions like initial positioning of UAVs or collision avoidance. There is also a simulator as a part of the system. Another example of the similar test-bed system is mentioned in [8]. There are also software-based simulated testbeds available, like the OpenUAV system presented in [10], providing cloud support and allowing users to use it without difficult initial setup. The OpenUAV project is provided as an open-source. As the simulated environments can not cover the richness and all possible complications of the real world, they can significantly help to solve the basic problems before transfer to the hardware platform.

This article describes a design and development of the test-bed system called MUAVET (Multi-UAV Experimentation Test-bed), intended for testing of autonomous methods and algorithms for control and coordination of multiple UAVs fulfilling the common mission. It is an outdoor system with the expected operation area up to $1km^2$. The main requirements which affected the system design were

- low cost and usage of off-the-shelf components,
- maximal safety (automatic detection of dangerous situations and response to prevent damage),
- scalability for up to tens of UAVs and
- simple but flexible API for user application development.

The basic navigation of the UAVs is Global Navigation Satellite System (e.g. GPS) based.

The designed system is indented for experimental and evaluation purposes only. It is not expected to be used in real situations.

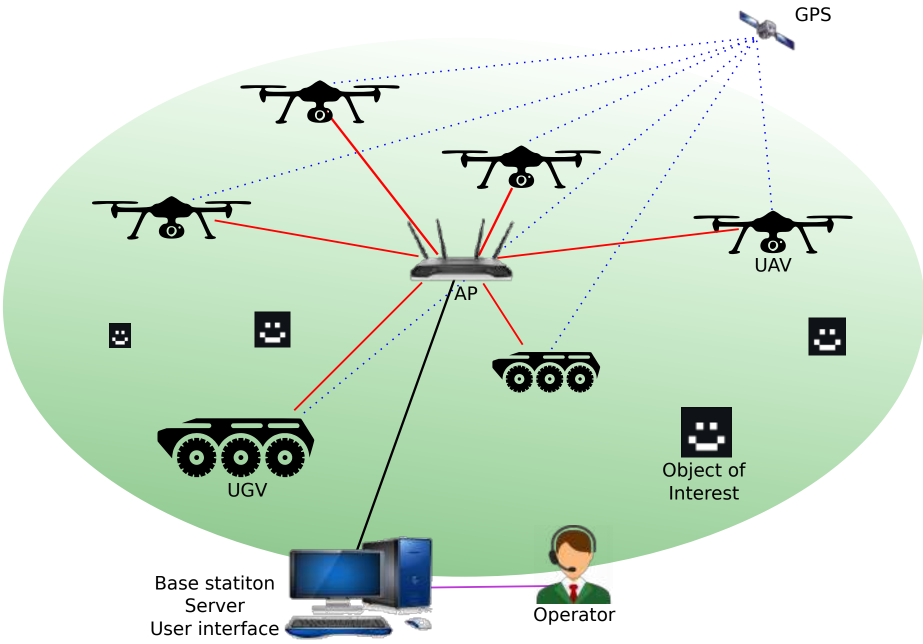


Fig. 1: MUAVET system overview (from [5]).

2 System description

The overview of the MUAVET system is depicted in figure 1. There is a base station containing server computer, wireless communication access point and an user interface. Several UAVs and ground vehicles (UGVs) are connected to the server through the access point.

The MUAVET system consists of hardware and software part. The software part is designed as independent on the hardware, so any UAV (or possibly other robot) may be integrated after proper interfacing.

2.1 Test-bed hardware

The hardware used for the demonstration and evaluation was selected with regard to minimal cost and sufficient necessary abilities. One of the most important factors is possibility of controlling the UAV flight controller from the installed on-board computer.

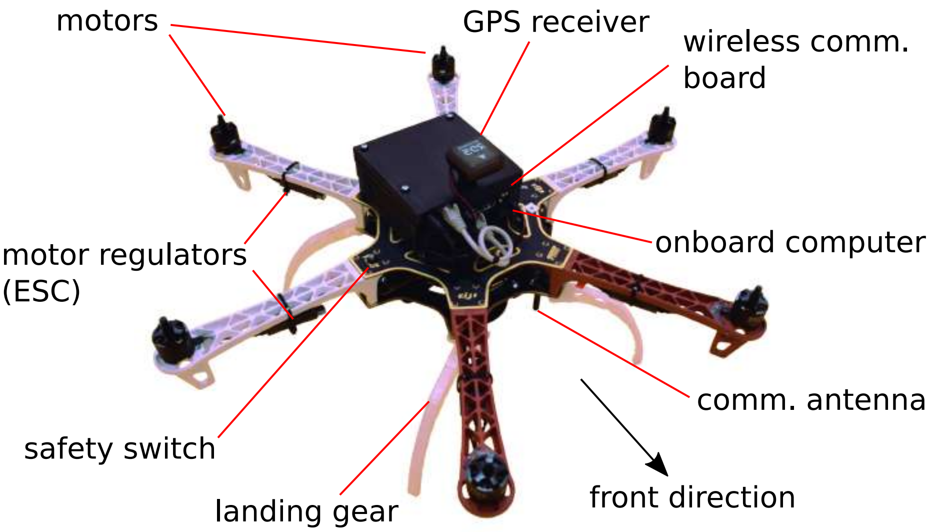


Fig. 2: MUAVET test-bed hexa-copter with propellers dismounted (from [5]).

The test-bed hardware is based on the DJI F550 hexa-copter frame [2] with motors installed (see Fig. 2). The frame is further equipped with the 3DR Pixhawk mini flight controller, providing good stability, flight performance and sufficient adjustability and configurability. This flight controller is running on the open-source Pixhawk firmware [1].

The PC-level computer (Intel NUC) is installed as the UAV on-board computer. This brings sufficient power on-board, suitable even for camera image processing applications. Additionally, the on-board code update and development is easy and fast. The presence of PC on-board also allows easy connection of various devices or sensors using standard interfaces.

Since the longer-range communication with the base station is required, an extra wireless communication module was installed on-board. This module is based on Mikrotik Routerboard IEEE802.11/bg WiFi with external antenna. The communication range in the open space was successfully tested up to 1 kilometer, which is over expected operation range of the UAV.

The main sensor installed on-board the UAV is a camera. The global-shutter camera was installed due to possible vibrations, which usually significantly distort image of rolling-shutter cameras, rendering their output unusable for machine processing. For the demonstration purposes, the visual pattern detector method based on AprilTag [11] library was installed, giving the UAV ability to autonomously recognize artificial marks placed on ground.

The table 1 summarizes the basic parameters of the UAV.

The second hardware part of the MUAVET system is a base station. Main components of the base station include a server computer and a wireless access point with an antenna. For field experiments, battery operation of the base

Parameter	Value
Frame weight	480 g
Total take-off weight	1200 g – 2400 g
Diameter incl. propellers	800 mm
Max. ascend velocity	8.0 m/s
Max. cruise velocity	20.0 m/s
Max. horizontal acceleration	15 m/s^2
Primary battery	4-cell (14.8 V), 6750 mAh
Max. flight time	approx. 15 min

Table 1: UAV basic parameters

station is advantageous. The possible extension of the base station includes a RTK GNSS base station for centimeter-level positioning of UAVs. A computer with the display and input device is typically part of the base, forming the system user interface and serving as a platform for executing user applications.

2.2 Software architecture

The MUAVET system is designed as a centralized system with the base station computer (server) as a central element providing connection between UAVs and user control applications, as seen in Fig. 3.

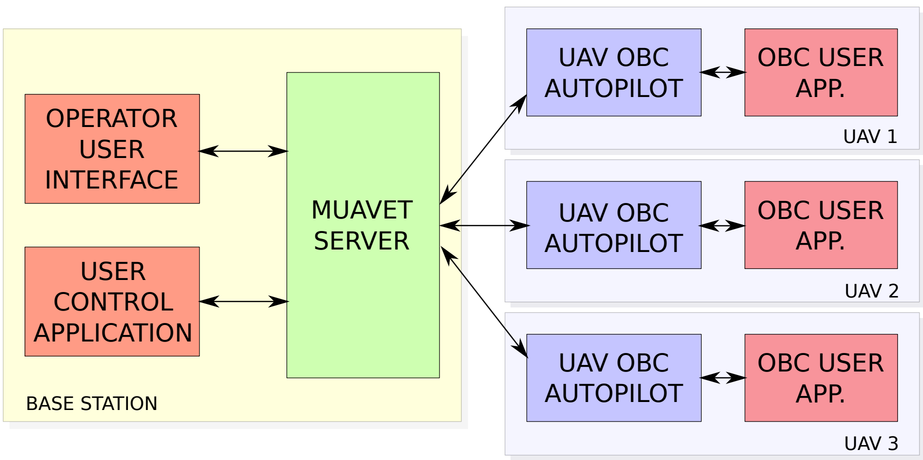


Fig. 3: MUAVET software structure (from [5]).

This approach was selected regarding the following advantages:

- central computer can permanently monitor states of all UAVs,
- user application connects to the single fixed point (server socket) and

– server can filter messages sent by user to UAVs in order to prevent communication channel overload.

Even though the system is designed as centralized, UAVs do not need permanent connection to the server for the safe operation. The control system of the UAV is designed as semi-autonomous, which means an UAV can fulfill the assigned task even without the active server connection. Only consequence of the lost connection is the actual inability to send new command and monitor actual state from the base station. However, since the commands are re-transmitted until acknowledgment, the UAV will get the command as soon as the connection is re-gained.

API function	**Description**
Arm	enable activation of UAV motors (*)
Disarm	disable UAV motors (*)
Takeoff	start the motors and take-off to pre-defined height
LandOnPosition	fly to specified position and land there
Land	land on the current position
HoldPosition	stop moving and hold current position
FlyTo	fly to specified position and stop there
FlyTrajectory	fly through specified list of way-points
TrajectoryPause	stop while flying through the waypoints
TrajectoryContinue	continue paused flight
EnableLocalControl	enable / disable control from the on-board computer (*)
SetFlyVelocity	set a cruise velocity of the flight
SetMaxTiltAngle	set the limit for the allowed tilt angles
RequestCameraImage	start camera image capturing

Table 2: API functions used to control an UAV from user application. Functions marked with (*) are provided for increased safety of the system and prevention of unintended UAV action.

The UAVs in the MUAVET system are controlled by the user applications, which may be running on base station or on-board the UAV. The on-board application can provide fully autonomous control without permanent server connection. Base-station application is advantageous in situations, where more UAVs need to be controlled simultaneously and connection losses are not expected. The application programming interface used by the user application is same on the server as well as on-board, so the same application may transferred from base to UAV or vice-versa with minimal or no modification needed. From the obvious reason, controlling of another UAV from on-board computer of second UAV is not possible. The user API allows to control the UAV using the functions listed in the table 2. The UAV measured data and telemetry is provided to the user application using the callback function mechanism.

Communication between UAVs is possible through the base station access point, as long as both communicating UAVs have an active connection. An advanced mode of direct communication between UAVs is possible by configuring the wireless modules in mesh mode.

Data sent between the UAV and the base station are handled differently, based on the data nature. These data may be basically divided into commands (sent to UAV) and sensor data (sent from UAV). The sensor data are sent continuously with the period given by the speed of measurement or defined requested period of sending. Typically, only the most recent data are important. This means, that in case of short loss of connection, some data may be lost without much trouble, as long as most recent data are received when connection is re-gained. For this reason, the connection between base station and the UAV is based on UDP protocol, which does not provide secure delivery. The advantage of this approach is communication overload prevention in such situations.

The UAV commands, on the other hand, has to be safely delivered, since the command is sent only once by the user application. Since the commands are sent over the same UDP protocol, the acknowledge and re-transmit mechanism is implemented in the base station server, ensuring the secure command delivery. Moreover, this mechanism is improved in a way to prevent overloading of the communication when user tries to send commands faster than what is possible to actually send. When a new command is sent by the user, it cancels the previous command of the same type, so for example the pending command to "fly to requested position" may be overridden by a newer "hold position" command, so the previous command is not delivered to UAV since it is already obsolete.

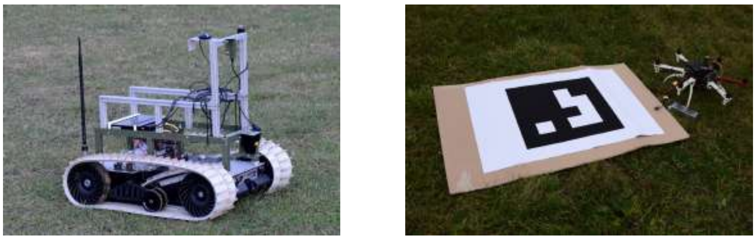
Several safety features and mechanisms are implemented on different levels of control. These levels include mainly the firmware in the flight controller HW module and the autopilot software running on-board the UAV PC. Since the on-board PC or its control application may fail, some basic safety functionalities are included in the flight controller. These include dangerous discharge of the battery, leaving an operation area in defined radius from the take-off position, or loss of the control commands from the PC, which may indicate PC or application failure. Since the activation of the safety mechanisms on the flight controller is not expected under normal conditions, the reaction results in imminent landing.

Safety mechanisms implemented in the autopilot control application running on the on-board PC should be activated sooner than the corresponding mechanisms in the flight controller. When a battery is discharged under a defined safe level, the UAV is ordered to return to the take-off position and land there. During this return flight, user can not override the UAV operation by a different command, with the exception of imminent landing. The short-term loss of the connection between the base and the UAV is allowable. When the connection is lost for longer period, the UAV interrupts the current operation and returns to the take-off position. In this case, the user may send new command to the UAV and interrupt the return when connection is re-gained.

Additionally a basic collision avoidance is implemented, preventing collision between two UAVs. When an UAV presence is detected in a expected trajectory of a second UAV, the second UAV flight is paused, holding the UAV on the current place until the first one clears the way. The collision avoidance mechanism is designed only as a last chance to prevent accident and may cause deadlock between two UAVs. Therefore, the flight trajectories should be planned as collision-free by the user applications in the first place. Since the UAVs do not have sensors for detecting obstacles physically, the collision avoidance is realized only by evaluating UAV positions and velocities. Collisions avoidance with fixed obstacles is possible by adding positions of the known obstacle boundaries to the collision avoidance subsystem, so UAVs are not allowed to fly into these areas.

3 Experimental evaluation

For the purpose of the system functionality and performance evaluation, the search & rescue - type of experiment was performed. In this experiment, the ground vehicle (UGV, see Fig. 4a) was integrated into the system to demonstrate the scalability and possibility to integrate different types of robots. The UAVs divided the whole operation area into several sections depending on the number of UAVs and selected method of coverage. The algorithm for the area division and the trajectory planning was provided by our partners from King Abdulaziz University [4]. Each of the UAVs then executed a trajectory providing full coverage of the assigned area, considering the height above the ground and camera field of view. There were several visual marks placed in the area (see Fig. 4b), representing the objects of interest.



(a) (b)

Fig. 4: (a) Cameleon UGV used in the experiment. (b) Visual target used as an object of interest.

The mission execution was controlled by a central application commanding all UAVs and the UGV through the system user API. This setup allowed easy time synchronization of all controlled vehicles. The detected and localized position of the installed objects were reported to the mission control application, which ordered the UGV to visit the places of the object positions in the order of detections. The resulting trajectories are visible in the figure 5.

The 3 used UAVs flew total distance of 4271m, including the paths from the base to the starting position and return to land. The total covered area was about $200 \times 200m$ and the time of search mission was about 640s. The positions

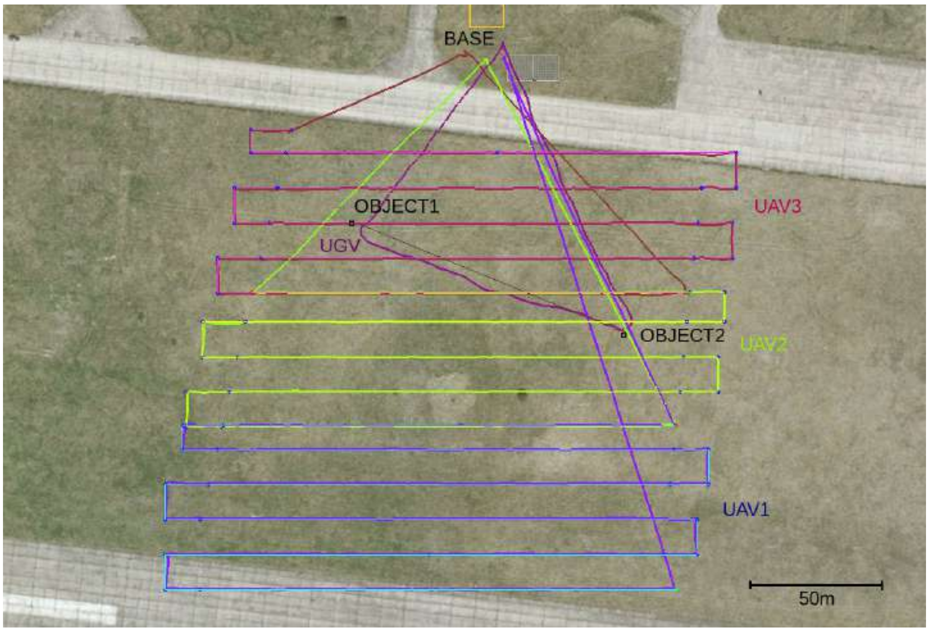


Fig. 5: Search and rescue experiment UAV and UGV trajectories (from [6], modified).

of all robots in time are plotted in the figure 6. The cruise speed of all UAVs was set to $3m/s$.

This experiment successfully demonstrated ability to simultaneously control several UAVs and coordination between air and ground robots. The precision of the real flight trajectory error from the planned trajectory and the precision of the ground object detection corresponds to the achievable precision of the common GNSS system (typ. error 1–3 m [12]).

4 Conclusion

In this article, the multi-UAV experimental test-bed MUAVET was presented. The test-bed is able to execute experiments and tests with multiple coordinated UAVs. A skilled pilot is not needed for the usage of the system. The UAVs are controlled using a simple API either from the centralized application running at the base station computer, or by autonomous control application which may run on-board. Alternatively, the both control approaches may be combined, so the UAV may be autonomous and commanded by higher-level command from the base. The UAV may be controlled on different levels of control, while the basic mode is the control by GPS way-points which UAV flies through using the defined velocity.

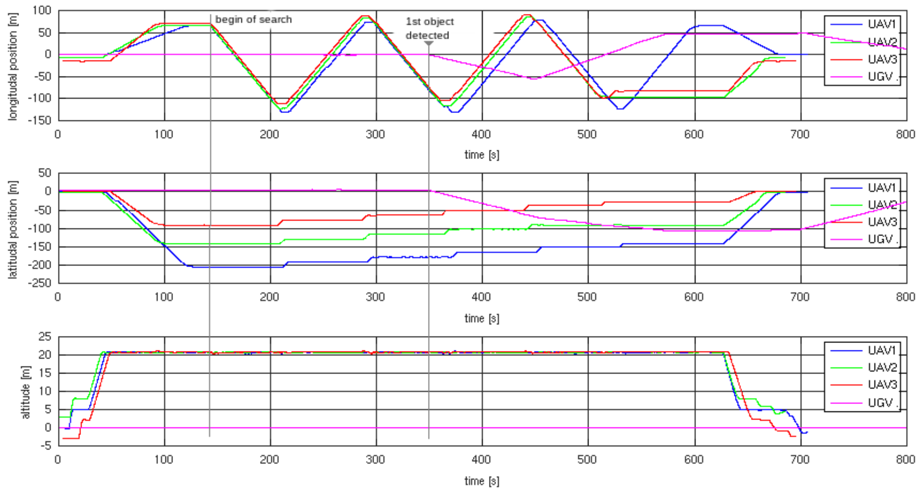


Fig. 6: Position of all robots in time.

The UAV telemetry is transmitted to the base in a way which does not overload the communication channel in case of worse wireless connection. When the communication to the UAV is lost for short period, actual data transferred to the base may be lost, but the UAV may still continue the mission since it is designed as autonomous. Commands sent from the base to the UAV are acknowledged and re-transmitted if necessary, so they can not be lost permanently.

The system safety is a primary objective and also one of the biggest challenges. Dangerous situations and common faults are permanently automatically evaluated on-board the UAV. These include mainly discharged battery state or loss of the connection to the base for the longer period. In such dangerous cases, the UAV selects one of the possible options, depending on the actual level of danger, typically return to the take-off position and land or land immediately on the current place. These safety mechanisms are implemented on different HW/SW levels, so in case the software running on-board the UAV PC fails, the low level flight controller is able to handle the situation.

After the individual UAVs were properly tested and calibrated, no accident occurred during the tens of experimental hours in the air and more than 30 individual starts even in worse weather conditions. Even though there are many safety mechanisms implemented, the system has still to be considered possibly dangerous and constant supervision is needed during the flight. One reason is dependence of the navigation system on the available GNSS systems (e.g. GPS), which may occasionally fail to provide sufficiently precise position, as reported by several users of similar UAV systems. The solution of the better independence on the satellite navigation systems is one of the future directions of the further system development.

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