Designing Multi-Agent Swarm of UAV for Precise Agriculture

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Abstract. The paper proposes multi-agent technology and a prototype system with together-acting UAVs for joint survey missions. The prototype makes it possible to connect UAVs in a united swarm, proposes coordinated flight plans and adaptively re-configures plans due to disruptive events. The approach to organization of program agents within a prototype subsystem is described. A series of simulation experiments and several flight tests were conducted to evaluate the effectiveness of the distributed scheduling mechanism. The aim of the current and future developments is creation of complex solutions for coordinated management of UAVs for precise agriculture.

Keywords: Unmanned aerial vehicle, UAV, drone, swarm, multi-agent system, coordinated control, swarm intelligence, survey mission, crops monitoring, precise agriculture.

1 Introduction

More than 10 million acres were mapped by unmanned aerial vehicles (UAVs or drones) in 160 countries on 7 continents in 2016. This generated an estimated $150 million in economic value for the commercial drone industry [1]. Large and small companies are not only integrating commercial drones into day-to-day processes, but also relying on the data from drones. Drone application brings significant time and cost savings over traditional data capture methods.

The main advantages of using drones are achieved when used in time-critical missions or during monitoring of large areas [2]. One of the top drone adoption leader industries is agriculture (see Fig. 1). Drones make it possible to capture on-demand aerial imagery of fields. This means the user can analyze drone map data to understand the health of crops, spot problem areas, and take action quickly to remedy any issues before they spread.

There is a variety of crop management decisions business can make based on drone imagery to help increase the financial potential. Drones are changing agriculture. The insights provided by the average drone and standard camera can prove to be the best investment in season.

Fig. 1. Top drone adoption leaders in 2016 by blog.dronedeploy.com.

However, there are some key issues not resolved for drone industry at the moment:

- no real Intelligence Inside UAV;
- difficult to manage several UAVs;
- time consuming if several UAVs;
- no flexibility or rescheduling;
- conflicts and accidents;
- human factor.

For example, there is lack of software to manage a group of UAVs to reassign tasks in case of failure of one UAV, addition of a new area, or addition of a new UAV to the group. Most of the existing software solutions are designed for planning only one UAV mission. On the other hand, drone group management software would use available UAVs resources in the most efficient way (battery or fuel supplies, time resources, hardware/computing resources of UAVs). In addition, quick reallocation of tasks between the drones during mission execution would reduce mission completion time. Thus, the development of such systems of automatic control of drones groups will allow timely receiving detailed information on crops, reduce the costs of plant protection and increase yields.

In this paper, we discuss our work on developing multi-agent technology and prototype for UAV swarm control. The next section describes some known developments for managing drones groups. The problem statement is described in Section III. The prototype development aspects, high-level description of planning algorithm and criteria are outlined in Section IV. Results are presented and discussed in Section V, conclusions and future work in Section VI.

2 The concept of swarm

Swarms in Nature are societies of simple insects. But at the same time, the phenomenon is that when working together in coordinated manner swarms are able to demonstrate intelligence, flexibility, efficiency, performance, reliability (see Fig.2).

Fig. **2.** Different swarms and behavior

There are several research projects aimed to propose swarm intelligence in aerial management. For example, DARPA: HART (Heterogeneous Aerial Reconnaissance Team) autonomously manages a large mix of manned and unmanned aircrafts and sensors and distributes streaming video, surveillance and reconnaissance information to warfighters in the field. The system can either dynamically retrieve, in near-real time, the required information from a catalog of geo-registered images or direct manned/unmanned aircraft systems and/or sensors to collect updated intelligence, surveillance and reconnaissance information. The HART system has recently completed testing and is in the final stages of preparation for fielding. Adoption of HART is under active consideration by all military services [3].

Another example is DARPA: CODE (Collaborative Operations in Denied Environment) project. The CODE program seeks to help military's unmanned aircraft systems conduct dynamic, long-distance engagements of highly mobile targets. CODE-equipped UASs would perform their mission by sharing data, negotiating assignments, and synchronizing actions and communications among team members and with the commander. CODE's modular open software architecture on board the UASs would enable multiple CODE-equipped unmanned aircraft to navigate to their destinations and find, track, identify, and engage targets under established rules of engagement. The UASs could also recruit other CODE-equipped UASs from nearby friendly forces to augment their own capabilities and adapt to dynamic situations such as attrition of friendly forces or the emergence of unanticipated threats [4].

In its new projects, DARPA aims to research and develop advanced human-swarm interfaces to enable users to manage potentially hundreds of drones simultaneously in real time. Developed computer programs, such as the Low-Cost UAV Swarming Technology (LOCUST) or Micro-Autonomous Systems Technology (MAST), try to provide a way to control Swarms of unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) acting together. The brand new Offensive Swarm Enabled Tactics Program (OFFSET) researches solutions to human-drone swarm communication. As part of drone swarms tactics development DARPA created the Service Academies Swarm Challenge as a collaborative project of the Agency and the three U.S. military Service academies — the U.S. Military Academy, the U.S. Naval Academy, and the U.S. Air Force Academy. The main purpose of the initiative is to encourage students to develop innovative offensive and defensive tactics for drone swarms. In 2017 the initiative held as three-day competition at California Army National Guard post in Camp Roberts and hosted more than 40 Cadets and Midshipmen [5] (see Fig.3)

Fig. **3.** DARPA Service Academies Swarm Challenge, Camp Roberts, California, April 23-25, 2017

Despite a relatively large number of studies of drones for military applications, the authors believe that the use of drones groups is promising for precise agriculture. This is especially true for countries with large areas of crops, as well as lagging in the application of technologies for point spray of fertilizers and plant protection substances. In such a case, regular survey flights by groups of drones can become an indispensable source of operational and more accurate data compared to satellite imagery. However, full automation of the processes of flying over large areas is unthinkable without the development of suitable algorithms and control systems. The authors see this direction as the most promising for the development of this study.

3 Problem statement

Despite military developments for drone swarm management, there is a lag in the application of UAV groups for civilian industries. We believe that some reasons for this lie in the poorly developed approaches to swarm management for precise domains.

For effective management of resource allocation (incl. drones and their subsystems), it is expedient to use scheduling systems. Nowadays these kinds of systems use the following methods of complex problem solving:

- greedy algorithms, based on heuristic business-rules for specific subject areas;
- traditional methods of optimization and linear programming in the area of mixed real-valued, integral-valued and logical variables, the improvement of precise methods of tasks solving, such as "branch and bound" methods, nonlinear programming methods, methods of constraint programming [6];
- metaheuristics (local search, Tabu Search, GRASP algorithms) [7];
- bio-inspired methods: Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Bio Inspired and a similar methods, as well Simulated Annealing (SA), Monte-Carlo method and some others [8]:
- artificial intelligence methods, the use of neural networks and fuzzy logic.

Many scheduling systems are based on centralized and deterministic principles. However, distributed coordination in dynamic networks has attracted an interest of numerous researchers in recent years. As shown in [9, 10], the multi-agent technology methods are the most promising and appropriate for the resource allocation algorithm design.

We consider the following problem statement:

1. there is an area for survey mission that is limited in size and may be identified by boundary points coordinates;
2. topography information about the area is known (terrain heights);
3. several different UAVs are available for the joint mission;
4. technical specification of UAVs and equipment is known (ranges of flight, maximum speeds and altitudes, battery capacity, charging time, camera information, etc.) and they could be different for each UAV.

Required functionality:

1. Management system is able to evaluate coordinated flight plans for each UAV in joint group with consideration of their unique characteristics.
2. Management system is not centralized but works by means of communications of all UAVs in a joint group.
3. Each UAV flight plan is proposed by the Smart UAV Agent located on a single-board computer inside a UAV.
4. Each Smart UAV agent is responsible for coordination and validation of flight plan with other UAVs to avoid conflicts and reduce overall mission execution time.
5. Each Smart UAV is able to react on events, plan and re-allocate tasks adaptively, forecast execution time of mission.

6. Each Smart UAV agent is able to choose and change the role dynamically in real time according to the situation and UAV characteristics.
7. Wireless interaction of UAVs is available directly or through a special drone-connector.
8. Interaction with the Command Center is available to meet the objectives.
9. Usage of knowledge base and multi-agent technology is necessary.

The main expected results are reducing the time for problem solving by up to 3-5 times in comparison with individual managing of UAVs by human operators. We believe it is possible due to the ability of UAVs to communicate over the wireless network and coordinate actions.

4 Prototype development

During the prototype design phase, we have elaborated the following scenario and base scheduling mechanics:

1. Operator sets the initial mission parameters: the boundary points of observation area, selects a mission type, for example, "single flight" or "patrol mission" and determines group members.
2. All UAVs have on board a computer with multi-agent scheduler and are able to share their results wirelessly.
3. Characteristics of the UAVs and their equipment differ and are stored in the knowledge base.
4. For Agents of Regions we introduce Agents of Observation Zones (region is a set of zones).
5. Scheduling is a process of negotiation between Agents of Zones and Agents of UAVs in order to determine the plan of monitoring for the region.
6. If an Agent of UAV decides to take the Zone in plan, it computes the costs and time and shares it with others.
7. If other agents can perform a better plan – the decision is changed.
8. Agents of Zones look for Agents of UAVs in the same manner.
9. After the initial matching each UAV agent and agent of zone are continuing to improve their key performance indicators (KPIs).
10. The scheduling process stops when no agent can improve its KPIs or the time is expired.
11. When a new event occurs – a new task appears or a UAV is unavailable - the process repeats until new balance is found in the schedule.
12. Adaptability is a result of self-organization of UAVs and zones for observation.

A simplified representation of the prototype architecture is shown in Fig.4.

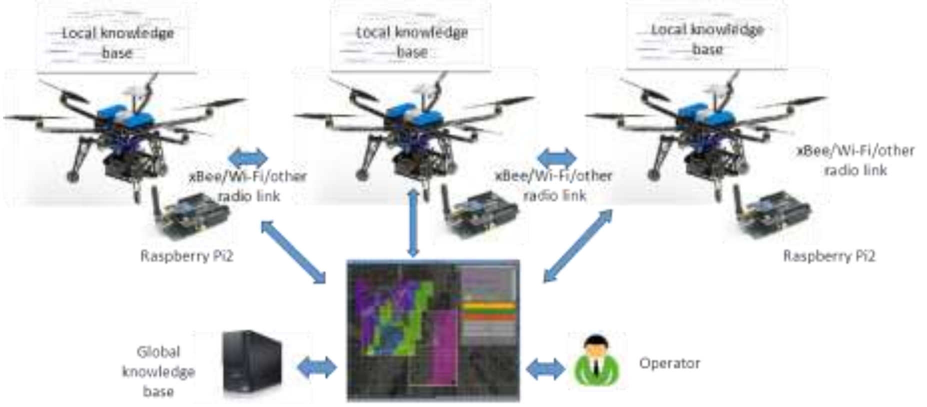

Fig. 4. Prototype high-level architecture

As part of the multi-agent approach, each active entity type within a solved problem is represented by a software agent, which formalizes the logic and needs of that entity.

In addition, each UAV has a separate single-board computer with multi-agent software for distributed mission planning via wireless communications. Scheduling in this case is a process of negotiation between agents in order to determine the compromise resulting plan.

During initial scheduling, the survey area is divided into a finite amount of observation squares with dimensions that correspond to characteristics of the UAVs and their equipment. For example, for the UAV with camera sensor width 4.55 mm, the focal length 3.61 mm, the flight height 119 m, the image width and height 4000 and 3000 pixel respectively, we expect ground sampling distance (GSD) of 3.75 cm/pixel and image footprint on the ground 150 m. Therefore, for the area of 32x32 observation squares we expect the total area of 23.04 square kilometers. Thus, there is a survey mission with 1024 sub-tasks for the available UAVs (see Fig.5).

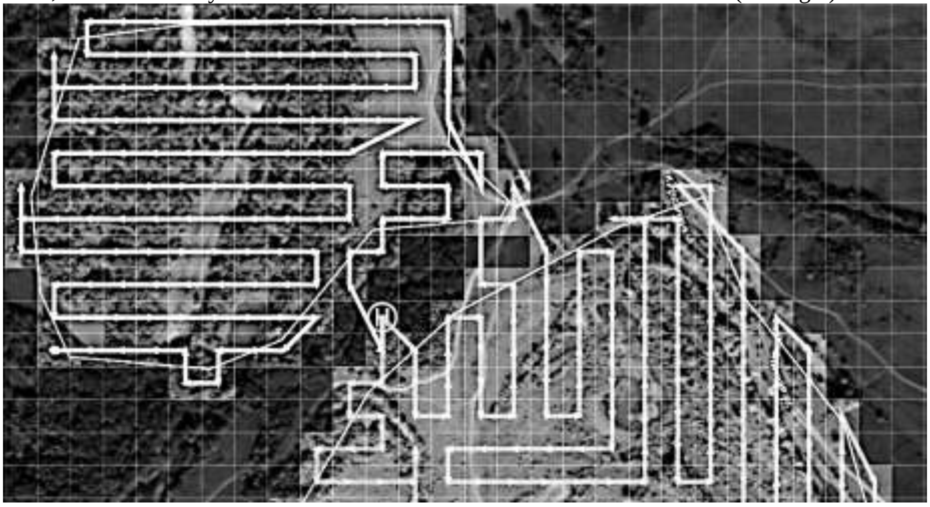

Fig. 5. Observation squares grid with UAV routes

After that, each observation square is associated with its sub-task to perform. Each sub-task has a timestamp of UAV flight in hh:mm:ss. The timestamp renews at the next UAV flight over the observation square. Considering these facts, UAV agents can track how long the square was without supervision. It is important for the patrol mission planning.

When the operator sets mission parameters (boundary points of observation area, mission type, UAVs), all sub-tasks become available for scheduling and are transmitted to UAVs matching mechanism. This mechanism is responsible for the initial distribution of individual sub-tasks (observation squares) between individual UAVs of the group. In fact, the mechanism performs clustering to aggregate observations squares.

Each UAV agent determines its individual area of interest as the corresponding cluster, that is, a set of observations squares, in which the agent has to build a flight path to perform UAV area supervision. Flight plan is also produced by UAV agent onboard a drone’s single-board computer. UAV agent analyzes the list of available sub-tasks and evaluates alternatives sets of paths based on the set of planning criteria.

As one of the criteria, the number of possible turns of UAV is considered. As a starting point the algorithm of rapid aerial mapping was considered [11]. Later on this criterion was evaluated into the criterion of total UAVs path distance, which is described further.

During distributed route planning process each UAV agent tries to find possible unvisited and unplanned observation squares (sub-tasks) of specified length (algorithm parameter) from the initial (Home) point. Each alternative set of sub-tasks estimated by a drone agent according to two criteria, described below. The set with the best value is sent for coordination to agents of other drones and to the operators' consoles.

When all the squares in the zone of responsibility of the drones (cluster) are planned, the behavior of the agent of the drone is switched to the optimization of the route. In the process of optimization, the agents of the drones transmit to each other the forecasts of the completion time of the routes. In the event of significant differences in the completion times (the set parameter of the system), agents try to redistribute the observation squares (sub-tasks) among themselves to reduce the delta of the time difference.

This approach allows controlling sub-tasks distribution and balancing in real time, and unlike similar methods of path forming [11-13], it is originally designed to increase the total system performance, resource utilization and reduce mission execution time. Agent key performance indicators (KPI) are applied to evaluate and compare different flight plan trajectories (sub-tasks chains) based on criteria of UAV agent satisfaction.

For prototype, two criteria have been chosen to calculate the agent satisfaction for the considered chain of observation squares. First, the criterion of area observability depends on sub-tasks squares observability. The meaning of this criterion is to enforce agents selecting those observation squares, which were most unexplored in the previous time intervals. UAV agent satisfaction depends on the time during which the square remained without supervision, that is, from the time during which no UAVs of a group were flying over a square for observing (see Fig.6).

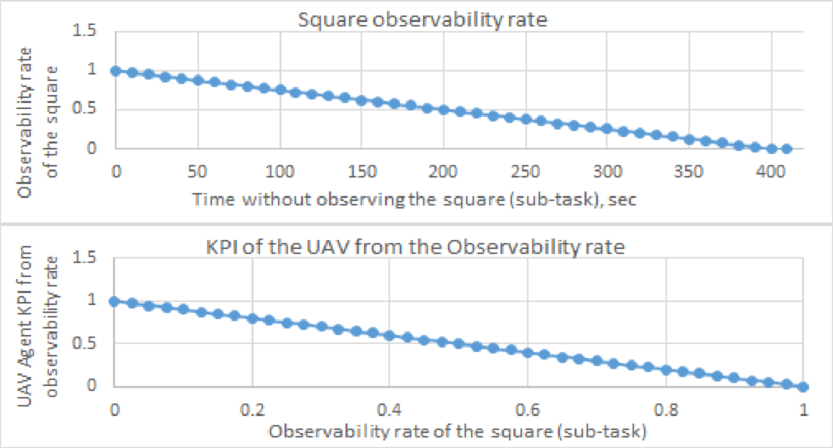

Fig. 6 – UAV agent KPI from observability rate of observation square

The second criterion is the total UAVs path distance. The meaning of this criterion is to enforce agents to select a set of squares, which lie along the same line. This provides efficient use of UAVs resources - minimum number of turns on the path and minimum distance without observing a square. UAVs agent KPI are higher when its path contains a set of observations squares lying on a straight line. The attractiveness of the selected squares for the UAV agent is higher, the higher the ratio of path length on observed squares to the total path length (see Fig.7).

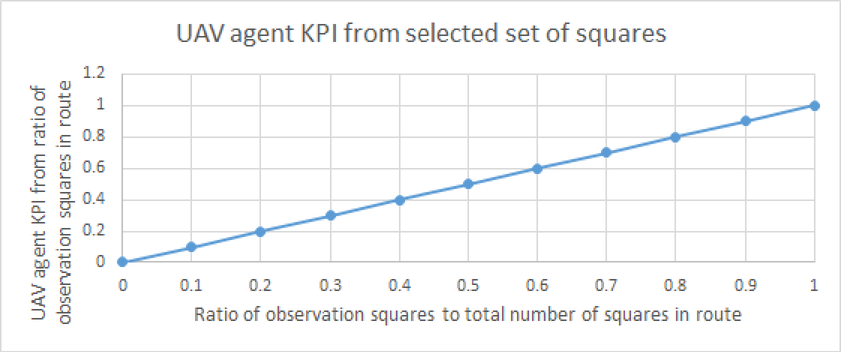

Fig. 7 – UAV agent KPI from path distance with observation squares

The overall system satisfaction at a certain step of work is defined as the sum of all UAV agents satisfaction on the criterion of area observability and on the criterion of total UAVs path distance considering criteria weights (the sum of the weights is always equal to 1).

$$KPI_{\text{system}} = k_{\text{area observ.}} * \sum_{i=1}^{N} KPI_{i\ \text{area observ.}} + k_{\text{path dist.}} \sum_{i=1}^{N} KPI_{i\ \text{path dist.}} \qquad (1)$$

During coordination of the flight plan in the group, each UAV provides a set of possible options for changing position. Each of these options is characterized by satisfaction indicators for the UAV (observability and path distance). The overall system satisfaction at a particular planning step is defined as the sum of KPIs of all agents, considering criteria weights. The higher the total KPI of the system, the better the quality of solution in the context of the selected criteria.

Dynamic scheduling mechanism implementation provides adaptive relocating of sub-tasks between UAVs to minimize differences in completion times. During flights UAVs exchange data about execution time forecasts. The UAV detects significant difference between its completion time forecast and the time of another UAV. After that, the UAV agent calculates how many sub-tasks should be transferred from or to the other UAV to reduce the difference between completion times. The UAV agent sends a request to reallocate the calculated number of sub-tasks to other UAVs. Then sub-tasks are reallocated to other UAV(s) or rejection is received (for example, if the UAV has already got some extra sub-tasks and is overloaded in terms of execution time). Thus, adaptive balancing mechanism ensures that the mission is performed in the shortest time even in cases of UAVs various performance and unplanned events.

During the prototype development phase, the General Designer's Stand is implemented to test the proposed multi-agent planning solution. This is the simulation tool for modeling different scenarios of survey and patrol missions with joint UAV group.

General Designer's Stand is represented by 9 separate screens for viewing main indicators and statuses of drones in the group, as well as 4 panels for managing external events, joint group and individual UAVs, knowledge base (see Fig.8).

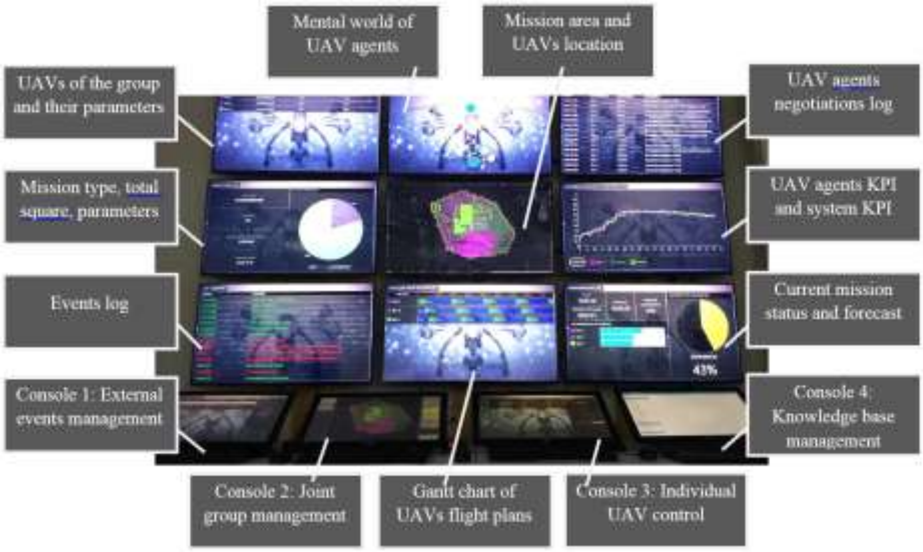

Fig. 8 – General Designer’s Stand is a simulation tool for UAV group missions modeling

In addition to the stand, there are several computers with single-board computers and installed multi-agent software for distributed planning (Smart UAV Agents onboard UAV). The onboard UAV units are created on the basis of Raspberry Pi 2 and integrated with Pixhawk PX4 flight controller.

5 Experimental results

A series of experiments was completed during the experimental phase to research the system performance . The input data for every experiment contained the same survey area with 1024 observation squares but a different collection of available UAVs. The main purpose of the experiments was to evaluate effectiveness of distributed scheduling mechanism and assess the formed UAV flight plan with estimation of the time required for preparing flight plans. Other purposes include assessing reaction of the swarm and Smart UAV agents to tasks changing during the scheduling process and even during mission execution in real time.

It should be noted that the logic of drone agents can be performed on a single-board computer (used Raspberry Pi2 connected to Pixhawk PX4 on 3DR IRIS+) directly on the drones or on any compatible computer connected to the system. In the presence of stable communication channels between drones and operator consoles, there was no difference in time between the two variants. However, all the results of the experiments presented below were obtained using directly the single-board computers of the Raspberry P2 and are related to the simulation of the survey mission. Results of experiments are shown in Table 1.

Table 1. Results of experiments for different numbers of UAVs

Indicator	**1 UAV**	**3 UAVs**	**4 UAVs**	**10 UAVs**
Time of planning process, sec.	165	62	50	21
Execution time forecast, min.	1205	404	304	145
New area addition time (rescheduling), sec.	6	9	15	13
Overall system KPI (agents satisfaction), %	95	78	79	68

Considering the results, one can make some assumptions and conclusions:

1. The planning process time depends on the number of observation squares in the mission and the number of UAVs involved in scheduling. With the same number of squares, the more devices are involved in distribution process, the faster scheduling works. Alleged explanation is the distributed nature of the planning mechanism, which allows for use of all resources of computing devices in the planning process, which uses all available resources of distributed single-board computers. This reduces the planning time even though there is a need to coordinate routes and search for possible conflicts. However, the need for good communication channels between UAVs should be noted.

2. The bigger the number of UAVs involved in the mission, the less time is required for the survey mission. This is because the entire mission area is divided into separate areas and distributed among several UAVs performing flights in parallel.

3. Thirdly, the system reaction time in cases of disruptive events reduces when a smaller number of UAVs is affected by this change, because coordinating all changes

requires negotiation between all agents affected by these changes. For example, when adding a new sub-area of 256 squares for a group of 10 UAVs, only some of the most closely-located UAVs are "diverted" to new tasks. This reduces reallocation time, because not all Smart UAV Agents are distracted by negotiations and approvals.

4. The overall efficiency is characterized by the indicator of system KPI, which is determined by satisfaction of each Smart UAV Agent. Generally, the KPI value for a single-working UAV is higher than the overall KPI for a group of UAVs. This is because UAVs in a group are forced to compete and negotiate to coordinate the final mission plan. They search for a compromise solution, which reduces the individual satisfaction of each Smart UAV agent. Thus, the overall KPI index can be considered only as a signal of plan optimization necessity. And this indicator only can be compared with similar indicators of similar UAVs groups, for example, similar UAV types and number of devices.

5. Multi-agent planning methods provide real-time ability to manage a group of UAVs and monitor and adjust performance of the group through agent key performance indicators and criteria.

In addition to the stand experiments, several test flights of 3DR IRIS+ with onboard multi-agent software were performed. These flights also confirmed the results of simulations.

6 Conclusion

Software systems for management and control of robotic devices and UAV groups are actively developed at the present time. For successful use of such systems, their functionality should allow for adjustment of plans in the changing environment. This includes reaction on unforeseen situations with relocation of tasks between UAVs in a group.

During the project, distributed multi-agent planning prototype was implemented and examined. The planning process is organized through wireless communication between individual Smart UAV Agents on each UAV. Hardware modules for 3DR IRIS UAVs and Pixhawk PX4 flight controller are implemented on the base of single-board Raspberry PI 2.

The developed prototype is developed to plan and coordinate actions of the UAV group, even in real time when some disruptive events occur during mission execution. Therefore, it is possible to fulfill the mission even if several UAVs are excluded from the group. Two criteria have been initially proposed, but this list can be extended and adapted to different domains.

To finalize the prototype and introduce the technology to the market, an industrial partner has been involved. Rassvet JSC in Rostov region has wheat fields with more than 30 000 ha of surface fragmented in smaller areas. The company uses top-level technology and John Deere equipment for wheat production and export sales. Specialists need to monitor all these fields covering large distances on a daily basis (more than 700 km a day).

As the next battle-proven stage in the development, there will be in-field experimental research of a swarm of drones for the industrial client’s fields. One of the tasks is to offer not only flight task scheduling algorithms, but a convenient completed end-user toolkit for crop monitoring. The tool should allow to connect to a group different models of drones and automatically manage their work in large areas. It is necessary to consider the applicability for the system of various models of drones available on the market, and not only models with open source flight controller (e.g. PX4 with Mavlink protocol). It is also necessary to investigate the use of heterogeneous groups of drones (rotary and aircraft type, autonomy, payload), as well as the number of necessary operators for different groups of drones and depending on the number of drones in groups.

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