Increase of flight operations effectiveness using automated control over a fleet of various UAS

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ABSTRACT

Following paper presents a research aiming to increase the efficiency of an Unmanned Aerial System (UAS) fleet during mission execution. The developed system allows to reduce the mission time by considering the fleet diversity. System is based on a multilevel optimization, applying an innovative trajectory generation method. The Mixed Integer Linear Programming (MILP) algorithm was adopted, so the trajectories for individual platform were optimal (shortest). The developed solution considers not only the area but also the UASs performance and sensors capabilities. The mission operator with the dedicated GUI could control and designate the platforms for various tasks. The method was tested on various platforms with different performance. The method proved its efficiency reducing the mission time up to 15%. Finally, the system was successfully tested in real environment with the use of three various platforms.

Introduction

Nowadays, Unmanned Aerial Systems (UASs) are used in various tasks and missions. Typical applications include gathering of data using various sensor systems such as photo and video cameras, laser scanners, chemical sensors and radars. Effectiveness of the operation is very important for the system user. For mission, like object tracking or area scanning, increased system’s efficiency transfers into lower costs (Baek, Kwon, Yoder, & Pack, 2013; Peng, Zhao, Lin, & Chen, 2013; Rafi, Khan, Shafiq, & Shah, 2006; Rafi et al., 2006; Ruangwiset, 2009), but for some specific types of missions (e.g. Search and Rescue operations), higher efficiency equals to reduced operational time which results in higher chances to find the survivors and save their lives. In the simplest approach, the effectiveness of the flight operation may be treated as time spent by the aerial vehicles to fulfil the mission (Forsmo, Grotli, Fossen, & Johansen, 2013; Ruangwiset, 2009). The overall components of mission time are not only the time spent in the air but also time on the ground required for systems’ preparation, recharging batteries or refill of the tanks, or maintenance of the vehicle between flights. For the presented research, missions covering larger areas were selected. Such missions may include gathering photos for photogrammetry, laser scanning of the ground, crops condition assessment or search and rescue missions. In such missions, it is required that on-board sensors cover the whole area of interest. The mission time is a crucial parameter to be optimized by the system. Such a mission may be performed by a fleet of various UAS (Forsmo et al., 2013; Kopyt, Narkiewicz, & Malecki, 2015). To cover the area in shortest time, the proper trajectories need to be provided considering not only the UAS performance but also the sensors’ parameters (Ahmadzadeh, 2005; Lichota, Sibilski, & Ohme, 2017; Patel, 2011; Santamaria, Segor, Tchouchenkov, & Schoenbein, 2013). Results presented in the paper were obtained during a 3-year research project called OpUSS “Optimization of Unmanned System of Systems” performed by a research team from Warsaw University of Technology in cooperation with Lockheed Martin Company.

UAS – various types of platforms

Each of the presented types of vehicles have its unique characteristics and performance parameters. Fixed-wing vehicles are very efficient in forward flight, but cannot fly at very low speeds, e.g. below the stall speed. Helicopters, on the other hand, may fly at very low speeds, may even hover or fly backwards or to the sides. However, the penalty for such a flexibility is the power consumption which is larger than for a fixed-wing aircraft with the same take-off mass. Also, the maximum speed of the helicopters is significantly lower than that of the airplane. To fill the gap between helicopters and airplanes, several different ideas were presented in the past. Today, the most important...
configurations which combine low-speed performance of the helicopter with the high-speed performance of the fixed-wing vehicles are tiltrotors, tiltwings and VTOL planes (Figure 1).

**Methods for mission effectiveness increase**

An obvious solution to increase the effectiveness of the UAS missions may be multiplication of the systems (Ollero, Lacroix, Merino, & Gancet, 2005). However, in the typical approach, when each of the UAS is controlled by a single operator, this also leads to multiplication of the operation’s cost and the need to separate the aircraft (safety reasons). The solution may be operating a fleet of selected UAVs being under control of an automated system supervised by a single operator. The mission effectiveness may be additionally increased by using a system that consists of various platforms (Shanmugavel, Tsorudos, White, & Żbikowski, 2010; Yang, Polycarpou, & Minai, 2013).

**UAV platform selection**

Enhancing mission effectiveness, a decision should be done to use UAS which suits the mission requirements best. In the field of unmanned aerial vehicles, there is a wide spectrum of configurations including classical fixed-wing designs, through various configurations of rotorcraft: helicopters, multirotor, autogyros, tiltrotors, to VTOL. Each of the named types of vehicles have different performance metrics, different limitations and optimum flight parameters. Also, in the same class of vehicles, the aerodynamic and dynamic properties of the designs may be completely different. From the mission performance point of view, very important may be such parameters as take of weight, cruise speed, stall speed, optimum and economic speeds, turn radius, climb speed, take-off distance or landing distance. For many applications requiring high quality of the gathered data, very important factors will be the level of vibrations and steadiness of the vehicle flight. Here, the fixed-wing platform usually beats the rotary-wing ones, however it should be mentioned that rotary-wing platforms (especially classical helicopter) usually can withstand higher winds than similar weight planes. Considering various types of platforms, it is usually possible to select optimum platforms for specific missions, which of course may also lead to increase of the operation effectiveness.

**Sensors selection**

Mission optimizing will strongly depend on the onboard sensors applied as well. Selection of the sensors should
consider not only the type of mission and type of gathered information (pictures, videos, laser scans, etc.) but also the type of selected aerial platform. Dynamics of the platform, turn radius, vibrations level, cruise speed or stability performance should be studied to pick the best solution. Quite important factors are SWAP (size, weight, and power) and the payload. The sensors used in the research are cameras fixed on a gimbal mounted to platforms.

**Trajectory planning**

Current UAS control systems usually provide a basic solution which application provides safe and intuitive trajectory – mostly lawnmower-like trajectories (Figure 2) (Baek et al., 2013; Chitsaz, 2007; Huang, 2001). In most cases, this solution is not optimal, and providing more advanced systems of UAS control and dedicated algorithms, this element could be improved. There are also other, similar methods like: Zamboni pattern (Figure 3) (Burlington, 2001; Jackson, 2007).

**Warsaw University of Technology (WUT) -developed system**

In the project called OpUSS “Optimization of Unmanned System of Systems”, a research, system development and simulations were conducted, and finally, a real-life test was done to show the potential improvement of the UAS mission performance when several elements of the system are selected in the optimum way. The study covered selection of various aerial platforms, application of the optimum trajectory planning for each aerial vehicle and application of the automatic fleet control system. The developed system main element was an alternative method for trajectory generation using the UAS individual performance (Culligan, 2006; Maza & Ollero, 2007).

**UAVs fleet**

In the following research, the fleet of various UASs (Figures 4–6) is of three types: fixed-wing electric plane (called Rekin), fixed-wing piston engine plane (called Citabria) and electric, classical configuration helicopter (called T-Rex) (Quigley, 2005).

The dynamic parameters of all the three vehicles were different (see Table 1).

It was assumed that for any mission and task, whole fleet is available and the best platform is selected based on the task parameters.

**Trajectory planning – an MILP algorithm**

One of the key elements of the developed system is the Mixed Integer Linear Programming (MILP) method that was applied (Forsmo et al., 2013; Richards & How, 2002). The main idea of using this new method
The objective of the mission is to provide a minimum time solution to cover the search area (i.e., visit all cells of the grid in an optimal sequence). The corresponding cost function is then as follows:

\[ J = \min \sum_{c=1}^{W} \sum_{k=1}^{T} (kT_d b_{kc}) \]  \hspace{1cm} (2)

where
- \( J \) - cost function,
- \( W \) - number of grid cells,
- \( T \) - number of steps in mission time horizon,
- \( T_d \) - time step,
- \( b_{kc} \) - binary variable with information if the cell was visited
- \( k \) - time step index.

The decision variables are components of a binary vector \( b_{kc} = [b_k = 1, c = 1 \ldots b_k = T, c = W] \), which represent the sequence of visited cells. The cost function is not equivalent to a total mission time, but it is the sum of subsequent time instants at which cell centres are visited.

### Mission control system

In the presented research, a system for controlling a fleet of UASs was developed. A general structure of the system is presented in scheme (Figure 7). The developed Mission Computer Application (MCA) was a tool allowing a single user to control the course of the mission by gathering data from all the UASs and setting tasks for all the UASs. The process was automated, but to assure high level of safety, safety pilots for all UASs were provided together with the Ground Control Station’s (GCS) operators. The MCA software was developed in the LabVIEW environment. A main screen of the Graphical User Interface (GUI) is shown in Figure 8.

The MCA allows user to upload flight plans for all the used UASs – in Figure 8, the plans for all platforms are shown together with waiting zones (black circles). The fleet status is shown on the LED-screen allowing the user to quickly assess mission realization. The mission was controlled with a set of four dedicated buttons each one starting a different task: Locate, Target, Track and Abort. After selecting the desired task, an automatic command was sent to each of the platform and the portion of the flight plan was activated by the autopilots systems. During the mission, position of the UASs is presented on the map together with actual UASs’ status and telemetry data (position, speed, altitude and heading). The software allows also logging all the data exchanged during the mission for the postprocessing purposes.

### Optimum mission planning

To obtain an optimum trajectory for each UAS, the operator indicates in the MCA the mission area available for all fleet using a map or a photo from, i.e., google earth. An operator also introduces to the system available platforms and their
performance. The systems consider the individual UAS parameters selected for the mission i.e. maximum speed, minimum speed, sensors’ Field of View (FOV), turn radius, etc. The wind and weather conditions are not considered in the research at this stage. Considering it together with the area to be covered, the mission area is automatically divided into the subsections for each UAS, respectively, to their capabilities. The final and most important step of the optimization is to provide a single trajectory for the platform, so that the full area is covered in shortest time.

**Sample simulation results**

Before the system could be tested in real environment, simulation tests were performed. Various tests cases and obtained results proved that the trajectories provided by the system were shorter – which directly decreased the mission time. The sample tests were compared to the lawnmower method. In addition, the system was tested for various systems’ performance settings. This set of tests proved that the system considers the flight performance of individual UAS with proper altitude separation which was crucial for the optimization process. Finally, the system was tested in a real environment with the use of three different platforms.

**MILP vs. lawnmower trajectories**

In this section, a comparison of MILP simulation results vs. intuitive lawnmower trajectories is presented. The airplane lawnmower trajectory is

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**Figure 7.** Structure of the developed fleet control system.

**Figure 8.** Mission Computer Application GUI main screen.
composed of several segments, each of them contains a straight line and a curvilinear section. At every curvilinear part, an aircraft-coordinated turn is performed. At a straight-line section, an aircraft accelerates and then flies at the constant, maximal velocity, and at the end decelerates to required turning velocity. The MILP algorithm was used to generate more sophisticated trajectories. Several tests were done, and the sample of results is presented in Table 2 as well as in the figures 9 - 13. The tests were done for various types of grids (regular and irregular). The time increase is presented in Table 2 and the trajectories are presented in Figure 9.

The parameters constant for all simulation cases are given in Table 2. The comparison was done for various numbers of grid cells and grid patterns. A grid pattern reflects constant cell number with their various surface distributions. The results of two numbers of cells: $W = 12$ and $W = 9$ are presented here. Summary of these simulations results is presented in Figure 10.

The results presented proved efficiency of MILP algorithm above the lawnmower one. For various number of cells and grid structures, a mission time reduction from 6% to 15% was obtained.

**Table 2 Various areas time comparison for various grids**

| case no. | Area shape | Mission time for MILP [sec] | Mission time for lawnmower [sec] | Difference [%] |
|----------|------------|-----------------------------|-----------------------------------|----------------|
| 1        | regular 4x4 | 99                          | 97.6                              | -1%            |
| 2        | regular 3x3 | 54                          | 57.49                             | 6%             |
| 3        | irregular 48 | 48                          | 56.38                             | 15%            |
| 4        | irregular 60 | 60                          | 65.75                             | 9%             |
| 5        | irregular 60 | 60                          | 65.75                             | 9%             |
| 4        | irregular 72 | 72                          | 76.9                              | 7%             |
| 5        | irregular 72 | 72                          | 76.9                              | 7%             |

*MILP for various platforms*

In Figure 11 (left – airplane, right – helicopter), the optimal trajectories obtained using MILP are presented, for an airplane and a helicopter. For the research, the wind influence was not considered. The differences between computed trajectories result from different flying qualities of both aircraft. An airplane (fixed wing) has a relatively large turn radius which forces gentle turns, and an airplane higher flight velocity decreases the number of steps required to complete the task. A helicopter allows for more “tight” manoeuvres, but it requires more steps to visit all cells due to its lower forward flight velocity.

Additional study of aircraft flying qualities (minimum velocity, maximum velocity and maximum acceleration) was performed for three various aircraft – two airplanes and a helicopter – used in the project for demonstration. The aircraft performance data are given in Table 1. In Figure 12, three trajectories are shown for UASs available in the project. The aircraft have various flying qualities in terms of velocities and turn radius, they require different time to complete the mission and trajectories are different.

It can be noticed that trajectories are different for various flight parameters. That confirmed the MILP algorithm application for various types of UAS. The other conclusion is that for more regular areas, the MILP advantages are not so significant.

**System application in real environment**

Finally, the system was tested in real environment at the Przasnysz airfield with the use of two UASs. The simulation result and the realized trajectory by the UAS were almost identical that can be seen in Figure 13.

Both aircraft managed to perform the generated trajectory keeping the minimalized flying time. Thus, the MILP algorithm and the control system proved its applicability in real environment. The two trajectories...
are presented in Figure 8, where the irregular shape was to be covered by two various platforms.

**Conclusion**

Presented research briefly shows an alternative method to increase the effectiveness of UAS during the various types of scanning missions by the time needed. The developed Mission Computer Application (MCA) integrated with the MILP algorithm allows to optimize a fleet of different platforms using their individual performance. The research and simulation that were developed proved that using the abovementioned method resulted in significantly reduced mission time in the air. The MCA not only uses the MILP algorithm but also allows to control the selected UAS in real environment. From the MCA console not only the shorter paths may be generated but being connected to the autopilot systems allows to apply and control the UAS fleet easily. The various test cases and the tests in real environment proved that the system provides a new approach for common missions used in UAS society. One of the
advantages of the system is its scalability and modular architecture that allow to implement various types of platforms with different performances.

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