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SELECTED ASPECTS OF APPLYING UAVs TO RECOGNIZE CHARACTERISTIC QUANTITIES OF FIRES

Wybrane aspekty zastosowania bezzałogowych statków powietrznych do rozpoznawania wielkości charakterystycznych pożarów

Abstract: *This paper presents the concept of using unmanned aerial vehicles (UAVs) for surveillance, reconnaissance and determining the extent of fire phenomena. The rapidly developing microelectronics means that UAVs are being used in many areas of life. One of these is firefighting. Their small size, ability to be remotely controlled and low cost have made drones a significant rival to conventional aircraft. The selection of appropriate sensors and control algorithms results in a device capable of efficiently assisting firefighters during operations, especially in difficult-to-access terrain such as forests. However, surveillance of large natural areas such as forests, airports and logistical bases is challenging. Using UAVs can greatly facilitate this process, making it more efficient. This article analyses the possibility of using drones to identify fire characteristic quantities (CFS) and presents a general algorithm for controlling a UAV formation.*
Keywords: fire alarm system, unmanned aerial vehicle, fire detection

Streszczenie: *W artykule przedstawiono koncepcję wykorzystania bezzałogowych statków powietrznych (BSP) w celu dozorowania, rozpoznania i określenia rozległości zjawisk pożarowych. Prężnie rozwijająca się mikroelektronika sprawia, że BSP znajdują zastosowanie w wielu dziedzinach życia. Jedną z nich jest pożarnictwo. Niewielkie rozmiary, możliwość zdalnego sterowania, niski koszt sprawiają, iż drony stały się znaczącą konkurencją dla konwencjonalnych statków powietrznych. Dobór odpowiednich czujników oraz algorytmów sterowania skutkuje powstaniem urządzenia zdolnego do sprawnego wspomagania straży pożarnej podczas akcji, szczególnie w trudno dostępnym terenie – np.*

lasach. Dozorowanie dużych obszarów naturalnych, takich jak np. lasy, lotniska, bazy logistyczne nie należy jednak do zadań prostych. Zastosowanie BSP może znacznie ułatwić ten proces, czyniąc go bardziej efektywnym. Artykuł koncentruje się na analizie możliwości wykorzystania dronów do rozpoznania wielkości charakterystycznych pożaru (WCHP) oraz przedstawieniu ogólnego algorytmu sterowania formacją BSP.
Słowa kluczowe: systemy sygnalizacji pożaru, bezzałogowy statek powietrzny, wykrywanie pożarów

1. Characteristic quantities of fires, possibility of detection and remote detection in rooms and open area

Fire is a spontaneous and unplanned combustion in a place not designed for it. The literature identifies two main causes of uncontrolled combustion. The first one is natural factors such as atmospheric discharges. The second ones includes human actions such as arson, fire starting or involuntary ignition due to negligence [1]. The direct combination of oxygen, combustible material and an ignition source initiates a fire. An excellent illustration and explanation of this phenomenon is the so-called fire triangle - Fig. 1. The characteristic sizes of a fire are the so-called fire parameters, which mainly include its size, type of substance being burned, and direction of spreading. In terms of size, the fire can be divided into four subgroups. The first one includes small fires, covering up to 70 m^2 of the area. The next subgroups are medium, large, and very large fires. The areas covered by the above categories are as follows: 71-300 m^2, 301-1000 m^2, above 1000 m^2.

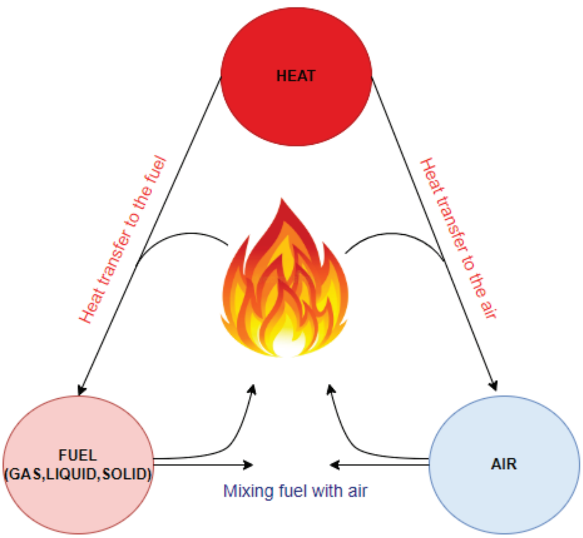

Fig. 1. Fire triangle, own elaboration based on [1]

Fire detection is an essential task to minimize the effects of an unwanted phenomenon. The current state of knowledge and technological development allows for the design and implementation of Fire Alarm Systems (FAS). The principle of such systems is primarily based on monitoring, signalling and preventing fire spread. The central control unit (CFS) [2, 3] is the heart of fire alarm systems. The control panel is the system that monitors the operation of all sensors and system components and is also the supervisory component and the communication component. In fire alarm systems, the lowest layer, but still very important, is a group of detectors. The selection of the right type of detector for the FAS is of key importance in providing an optimum level of protection while avoiding false alarms generated by the system. There are many technological solutions to detect flames or smoke efficiently. The most common detectors include optical smoke detectors, ionization detectors, heat (temperature), flame, line, multidetector and aspiration detectors. Most of these components, however, are components that are predominantly used in buildings and indoor areas.

Approximately 9.14 million hectares of Poland is covered by forests, i.e., 29.2% of the country's total area. Recent years have shown that natural conditions, forests and human activity increase the fire risk. To this end, many institutions and companies try to implement innovative solutions to improve fire safety. However, the vastness of the area makes this task less straightforward and requires using the latest technology.

A wireless sensor network is one possibility for monitoring the physical and environmental conditions of large areas. Such a system is based on several hundred sensors distributed throughout the forest. The components communicate with each other and exchange information on current environmental conditions using a wireless network. The main element is the control panel, which fulfils an analogous role to that of a classic FAS [2]. The first company which brought such a concept to physical implementation was Bosch [4]. A small station equipped with a smoke detector, solar panel and intelligent software developed based on artificial intelligence, easily alarms the occurrence of a fire. Data collected from all installed sensors is used to teach the system continuously. This approach largely rules out the risk of a false alarm. The described architecture fulfils its purpose and provides a very effective system. Nevertheless, it has some significant drawbacks. Unfortunately, a large number of sensors is required to monitor very large areas, which has a major cost implication. Another aspect is the need for scrupulous maintenance of the installed equipment.

A different approach to surveillance of large areas is the application of thermal, infrared, and industrial cameras. The type of equipment used largely determines the autonomy of the overall surveillance system. CCTV cameras do not exclude human activity, which must primarily supervise the operation of a non-autonomous fire detection system anyway. In the opposite approach, integrated detectors can be used to enable fully autonomous fire detection. One example is a point flame detector using the infrared band (Fig. 2). Such a system consists of an infrared sensor and optical filters. Burning hydrocarbons emit light with a wavelength of 4.3 μm, which is the main stimulus for detecting flames.

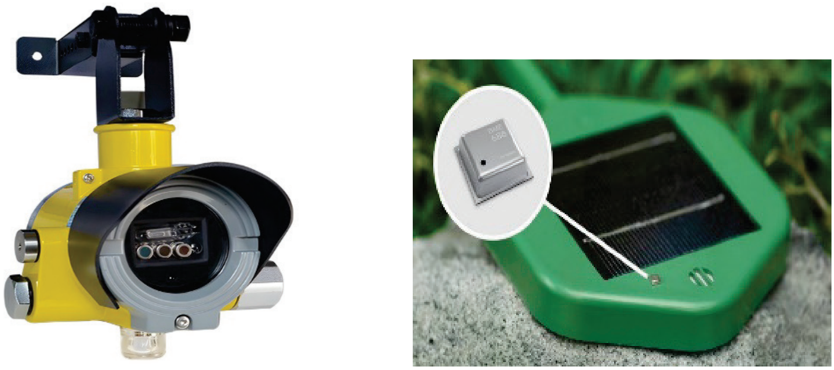

Fig. 2. Camera using the infrared band, designed for fire detection (left); BOSCH environment sensor (right) [4]

The two previously described methods of detection and signaling fire phenomena are stationary. The lack of sensors mobility limits the spatial recognition of a fire - Fig. 2. The use of increasingly popular drones can contribute to a more effective system. The big advantage of drones is the ability to scan large areas. Depending on the sensors and components used, new concepts and actual systems are being developed to facilitate the work of the fire brigade in the future. Very high fire detection reliability and an accompanying low false alarm rate can be achieved by combining a thermal imaging camera, a microwave radiometer and additional smoke particle sensors [5]. Depending on the type of sensors used, engineers create systems dedicated to predetermined tasks - Fig. 3.

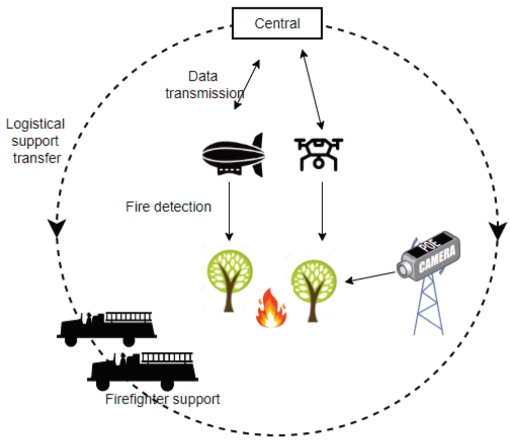

Fig. 3. Integrated Forest Fire Detection and Suppression System (own elaboration based on [5])

Combining stationary fire detection systems with UAVs generates significant technological issues. The possibility of detecting fire from the air is mainly determined by the parameters of the cameras or sensors used. The current market presents solutions that can be used to supervise vast areas. The AVIOTEC IP starlight 8000 camera from BOSCH is a device that can detect fire at up to 300 m. The basic parameters of the camera include, above all, lens focus, resolution, power supply method, working conditions, data transfer method and weight. The last parameter plays a key role which will have a significant impact on the flight range of the unmanned aerial vehicle. The currently available fire detection systems weigh between 200 g and 2 kg. Depending on whether the designer decides on a simple solution based on Raspberry Pi or professional surveillance systems, he must consider the selection of an unmanned aerial vehicle with sufficient payload. It should be noted, however, that the current range of manufactured drones offers machines with a lifting capacity of up to several kilograms.

The ever-evolving automation industry presents us with ever-newer solutions, algorithms and models in the field of UAVs. Engineers are creating adaptive systems based on sensors and artificial intelligence, resulting in a high degree of autonomy. The use of unmanned aircraft formations has also become a current trend. Many of the integrated machines are proving to be lethal weapons on the battlefield, an interesting light animation, but does such a technique make sense in firefighting applications?

2. Review of control methods and algorithms for unmanned vehicles in terms of their application to CFS detection

Formation control of multi-role UAVs has become one of the most challenging issues of current UAV research areas. The increased interest in drone formation control is due to the many opportunities that such technology provides us with.

Drone swarms can be divided in various ways. The first division distinguishes between fully and partially automatic formation structures. From another point of view, the classification can be presented as single-level swarms in which each drone is its own leader and multi-level swarms with dedicated UAV handlers.

An architecture based on a wireless network or other form of communication with a ground base station is currently one of the most popular ways to control drone formation. The described control technique has quickly found its way in numerous light shows. The Winter Olympics opening ceremony in Pyongchang in 2018 featured a light formation of 1218 Intel drones. The spectacular performance was memorable for many spectators, and the technology used almost four years ago is still being improved.

The centralization-based architecture consists of a ground control station. GCS (Ground Control System) receives telemetry information from all the drones in the swarm and then sends commands back to each drone in the swarm Fig. 4. In some solutions, the GCS communicates with individual drones in real time, sending commands to the flight controllers on board each UAV [6].

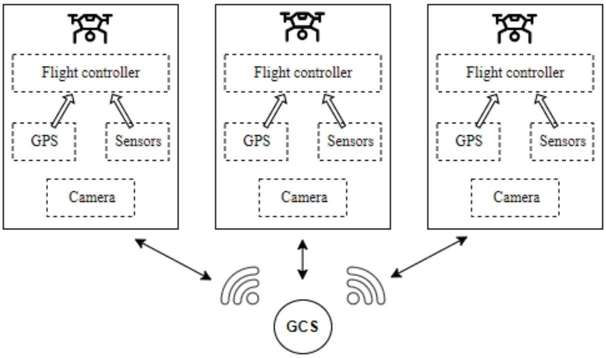

Fig. 4. GCS-based network control structure, a centralised drone group management system [6]

Leader-Follower formation control refers to the presence of a following autonomous robot and a so-called leader in this structure. The Leader-Follower approach applies to different types of robots or vehicles [7]. The current state of the art presents many types of control, communication, and structural solutions for this method. There are two main UAV swarm configurations in the leader-follower model, namely the secondary and diamond formations. Each configuration has both advantages and disadvantages – Fig. 5. The diamond method provides greater coverage of the supervised area. This phenomenon is a great advantage when the purpose of the formation is to monitor a specific area.

However, the most effective solution would be to create a formation management algorithm independent of the GCS and the selected leader. In the presented concept, each drone has information about the on-board data of its partners. Such a solution results in high autonomy and reliability. Each drone is a vital link that directly influences the behaviour of the whole system and, consequently, the GCS. A single UAV equipped with a fire detection module notifies the rest of the formation of the occurrence of danger.

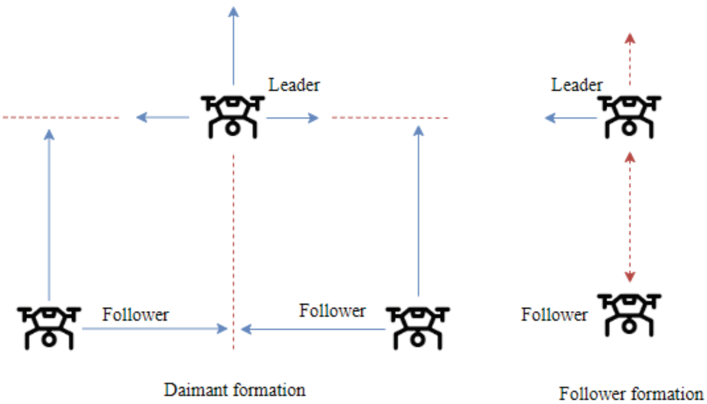

Fig. 5. Typical configurations of UAV formations (own elaboration based on [7])

3. Analysis of selected UAV control option for characteristic fire size detection - modelling using Matlab/Simulink environment

Despite the implementation of a strictly software-based concept of formation flight control, great importance was attached to the eventual physical system feasibility. The main assumption is to base the procedures and algorithms on commonly available data, the acquisition of which during flight does not involve complex measurement systems - Fig. 6. To this end, the drones use only information on distance from each other and mutual angular bearing for formation control.

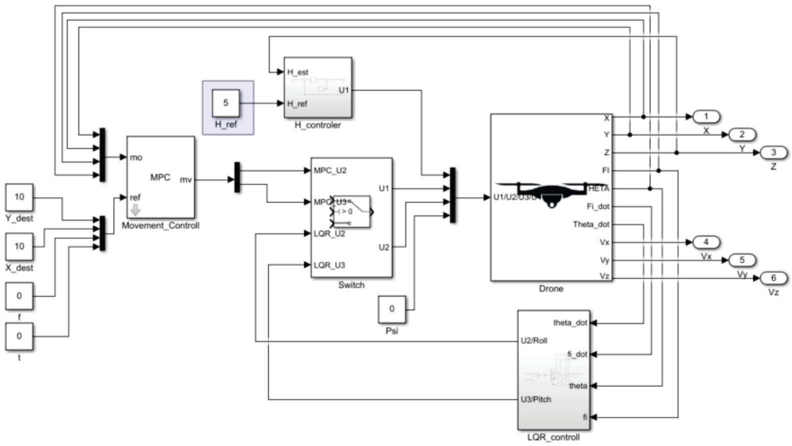

Fig. 6. Structure of the UAV model with flight controller where: Movement_Control - MPC controller responsible for the flight phase, H_controller - altitude controller, LQR_controller - stabilisation steer (source: own development)

The algorithm described focuses on two tasks of a four-element UAV formation, the first being an approach manoeuvre in a close group focused on a fire phenomenon. The second movement phase is a circular fire surveillance manoeuvre. When forming a close group, any spaced UAVs autonomously determine a meeting point and concentrate around it. In the second phase of the programme, the UAVs perform a manoeuvre to rotate the entire formation over the area at risk. The circling of the UAV over the threat in a physical solution can contribute to the observation and detection of fire characteristic quantities. For example, the degree and direction of fire spread can be used to inform the firefighting team on the ground as a basis for their strategy.

The drone is tasked with finding the aircraft opposite itself in formation. The same function is performed by D2. The transformed cosine law (1) was used to determine the mutual position of the aircraft, using only the distance parameter. Knowing all the distances between the UAVs allows quadcopter D1 to calculate the angles α, β, γ – Fig. 7.

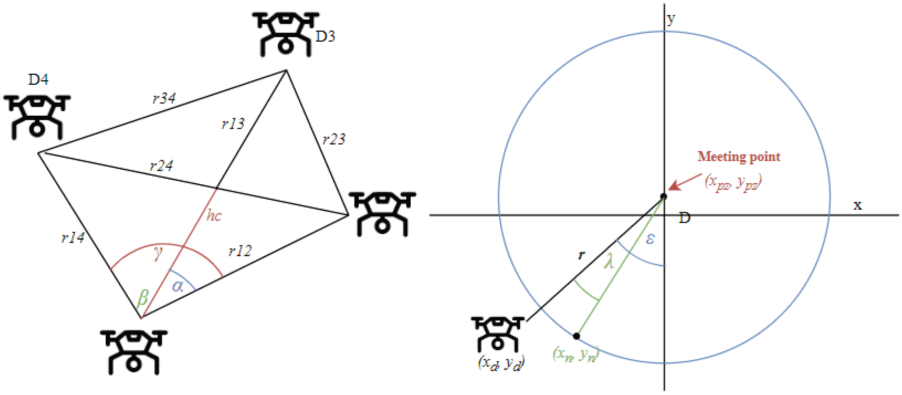

Fig. 7. Principle of rally procedure and UAV group turnover (source: own elaboration)

The next step of the algorithm is to determine a virtual rally point that will allow the UAVs to approach each other relative to each other. To this end, the distance h_c (4) was determined from the observed mathematical relationships in the individual triangles.

$$\alpha = \arccos\left(\frac{{r_{12}}^2 + {r_{13}}^2 - {r_{23}}^2}{2 \cdot {r_{12}}^2 \cdot {r_{13}}^2}\right) \tag{1}$$

$$P_{\Delta ABC} = P_{\Delta ABD} + P_{\Delta ACD} \tag{2}$$

$$\frac{1}{2} r_{12} r_{14} sin\gamma = \frac{1}{2} r_{12} h_c sin\alpha + \frac{1}{2} r_{14} h_c sin\beta \tag{3}$$

$$h_c = \frac{r_{12} r_{14} sin\gamma}{r_{12} sin\alpha + r_{14} sin\beta} \tag{4}$$

The execution of formation rotation becomes possible by planning future flight points by each unmanned aircraft. The following reasoning is presented for a single drone, but it should be emphasized that each co-participant in the formation performs the same computational steps. The assumed flight point with coordinates x_n, y_n is the new target location for each UAV - formula 5 [6].

$$\begin{cases} x\_n = \pm(r \cdot \cos(\varepsilon + \lambda)) + x_{pz} \\ y\_n = \pm(r \cdot \sin(\varepsilon + \lambda)) + y_{pz} \end{cases} \tag{5}$$

The numerous simulations indicate the correctness of the adopted formation control techniques and the correctness of the implemented UAV formation algorithm.

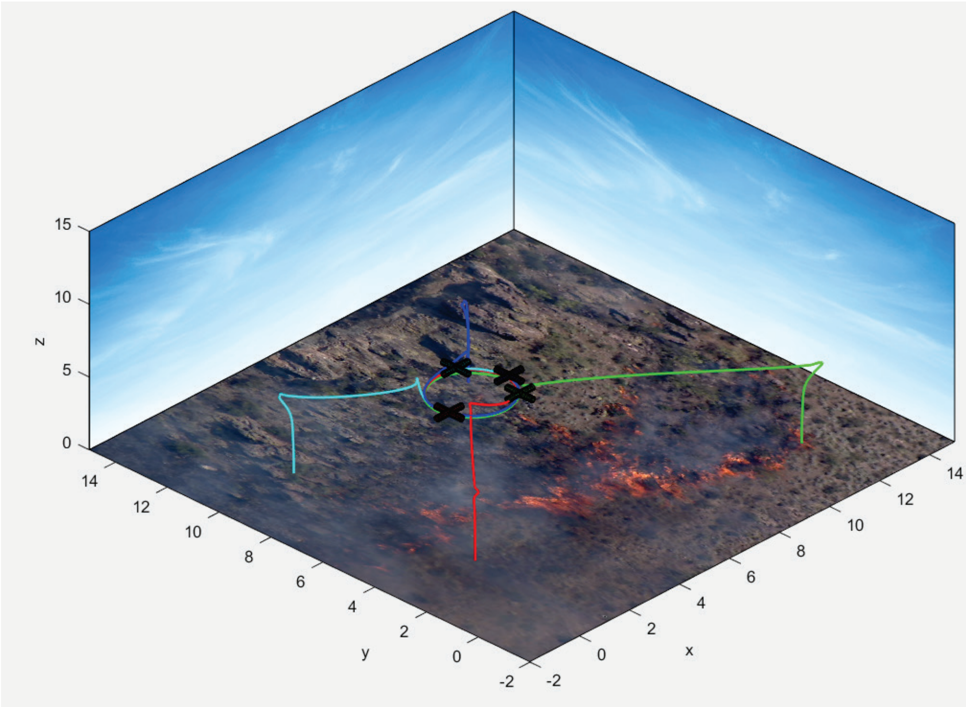

Fig. 8. Visualisation of the area surveillance algorithm (source: own elaboration)

4. Conclusions

The developed program achieves the predetermined objectives. The presented technique of controlling unmanned aerial vehicles can find application in the surveillance system of large open areas. An exemplary scenario for the operation of a team of UAVs could be the individual operation of each of them in the most remote forest parts. When the algorithm is triggered, and the single UAV control is switched to an autonomous swarming algorithm, each UAV will find itself in a group and then automatically start moving towards the rally point. The return of the drones to the point determined by the algorithm will result in the majority of the supervised area being scanned. The main function of the algorithm is to detect a fire phenomenon. However, combining an unmanned aerial vehicle with a fire detection system will enable much more. The information necessary to undertake firefighting actions by fire departments is, for example, data on the size of the fire or its direction of spread. A swarm of unmanned aerial vehicles monitoring a fire event with the use of appropriate computational techniques will be able to provide relevant information directly to groups undertaking firefighting operations.

The selection of detectors has a huge impact on the potential physical implementation of the system. The use of UAV formation and swarm algorithms can find its application in reducing false alarms. Each of the four UAVs equipped with a sensor and smoke analyzer can form a segment of the signaling system. The type and number of sensors used significantly affects the reliability of the system. Combining a thermal imaging camera with an infrared band camera can provide a very effective data fusion system [10, 11].

The reliability aspect [3, 9] is important from the point of view of any engineer. The answer to the question of how flexible a given system is and how resistant it is to various types of errors has a huge impact on the final performance of the algorithm. Due to the choice of a control strategy based on a decentralized command system, the number of operational aircraft does not affect the operation of the swarm. This means that the loss of one of five UAVs does not result in an absolute disintegration of the system.

The mathematical basis of the presented algorithm rests on the distance parameter. The table below shows the effect of distance measurement inaccuracy on formation shape behaviour (Table 1). An increase in the measurement inaccuracy of the mutual distances between UAVs results in UAV positioning errors. These errors directly result in the formation shape being deformed. In the case of a distance measurement inaccuracy of 25 cm, the shape of the formation starts to resemble a parallelogram. Both distances D1-D2 and D2-D3 are increased by 28 [cm] with respect to the reference system. In the case of circular motion, due to the determination of the common center point and the radius of rotation for all UAVs, the trajectories of the individual UAVs coincide over time. However, the introduced measurement inaccuracies do not result in a complete disorganization of the drone swarm and thus, in the unfitness of the system to perform the task [6, 8].

Table 1

Values of formation parameters depending on distance measurement error

Parameter	Reference value	Distance error	
		10 cm	25 cm
Distance D1-D3	2.820 m	2.951 m	3.101 m
Distance D1-D2	2.007 m	2.131 m	2.28 m
Angle γ	90.02°	87.75°	83.91°
Angle α	45°	42.85°	41.23°

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