Design features of an information-measuring and control system for landing a swarm of small unmanned aerial vehicles

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Abstract. The problem of a small unmanned aerial vehicles (SUAV) swarm landing on a robotic platform is solved. The necessity of creating a controlled waiting area for a SUAV in the landing system is shown using simulation. The principle of SUAV air traffic organisation in the space-time waiting zone and the issues of a safe landing are revealed. The structure of the information-measuring and control system of the SUAV landing with the space-time waiting area and the buffer landing zone is proposed. Its main features are given and the possibility for landing a SUAV swarm of various structure is shown.

1. Introduction

The aircraft traffic safety and the reliability of the landing system in conditions of increased traffic intensity are the main requirements for any aerodrome. The work [1] shows a method of using multiple holding areas, which allows to streamline the movement of aircraft based on the use of the capabilities of modern automated air traffic control systems. In the context of the rapidly growing application rates of a small unmanned aerial vehicles (SUAV) in various fields of human activity the actual topics are: the use of robotic platforms (RP) [2], the use of SUAV swarms [3] and landing [4], the use of special SUAV groups [5]. Air traffic safety issues are also of particular importance in the duty area of the RP. The RP tasks include landing SUAV on the platform, charging or replacing their batteries, SUAV loading, etc. The main task in the design of RP is to automate the processes of RP service in the specified sense, their binding to public networks and to interacting RPs. Obviously, the SUAV arrival intervals to the RP for service should be regulated by air traffic control tasks. However, situations when the rate of SUAV admission is a random process with the high traffic intensity are possible. A variant of such service is to receive a swarm of SUAV or a large heterogeneous SUAV flow on any RP node. In this case, the RP acts as a server in the queuing system. The peculiarity of such a system is to ensure high requirements for air traffic safety in the landing zone and the reliability of its operation. The team of authors has proposed a method and system for landing a queued set of SUAV. The queue is represented by a set of SUAV in the space-time waiting area (STWA). SUAV performs circular movements along disjoint routes in a toroidal structure within STWA. To equalize the arrival
rate of SUAV on the landing line when leaving STWA, it is proposed to use the buffer landing zone (BLZ). In this regard, the task to justify the creation of the structure of the information-measuring and control system for landing (IMCLS) as part of RP is actual, which provides conflict-free service when landing a set of SUAV.

Objective: to prove the necessity of a controlled waiting area creation for landing a large number of SUAV on a RP, develop the structure and the main features of IMCLS for SUAV swarm landing.

2. Materials and methods

2.1. Rationale for the use of a specialized waiting area in the landing system

The time interval from the moment of the current SUAV reception for landing on the RP until the moment of its readiness to receive the next SUAV for landing will be called SUAV landing service time. A simulation model that allows to represent SUAV arrival to landing within the time-domain and its implementation as a service delay, is shown on figure 1, the simulation results are shown on figure 2. The model is simulated using GPSS/W [6] and represented as the M/G/1 system [7]. The input stream of SUAVs is characterized by a Poisson distribution of events with the following average values between service requests $\mu$: 60 s, 55 s, 50 s, 45 s and 40 s. The SUAV landing service time is a random variable and it’s determined by the three alternatives: $T_{\text{serv}} = 50 \pm 5$ (figure 2, curve 1), $T_{\text{serv}} = 60 \pm 5$ (figure 2, curve 2), $T_{\text{serv}} = 70 \pm 5$ (figure 2, curve 3). To take into account an interfering factors during landing, a model of a random wind gust of more than 10 m/s with a two-minute interval of exposure was introduced [8].

As can be seen (figure 2a), the time delay of the SUAV during landing can reach large values. The fluctuations intensity of the SUAV queue in the waiting area (figure 2b) is significant, which necessitates the creation of a specialized waiting area, allowing SUAV reception with a wide range of arrival rates. It follows from this that the waiting area should have the necessary margin for random SUAVs receiving and to be controllable for the purpose of an air traffic safety.

2.2. Queueing system model with the buffer landing zone for the SUAV group

Simulation shows that the landing system on a RP for the SUAV group is represented by a queueing system of M/G/m of M/G/1 type. Since in the waiting area the distribution of SUAVs can be uneven and the speed of movement does not correspond to the speed of the RP service, it is recommended to use the BLZ to increase the effectiveness of the RP during landing service (figure 3). The main BLZ task is the SUAV traffic speed matching with the speed of the RP landing service. Thus, the queueing system model consists of a waiting area with the $N$ SUAVs, buffer landing zone with the $k$ SUAVS and the serving device - landing platform. For the case $N \leq k$, the BLZ can also act as a waiting area with an appropriate service protocol.

2.3. Features of the information-measuring and control system for the SUAV swarm landing

The joint operation of the SUAV group and the RP in the Queueing system during landing consists in solving two groups of tasks. The first one is related to the mobility and safety of SUAVs air traffic within the STWA, the second group is related to the task of a multi-station access to the service channel, i.e. to a common service resource. In general, there can be two such protocols: the first one implements an access from the STWA to the BLZ, the second one controls the access from the BLZ to the landing line on the RP directly. In this regard, the presence of an IMCLS is necessary.

The solution of these problems is significantly simplified if we use the analogy of telecommunication network functions based on the Open Systems Interconnection (OSI) model [9] and the tasks related to the air traffic and user service of the RP and SUAV network [10]. The SUAV swarm can be considered as a queueing network [11], and on a large scale it can be approximated by the Jackson model [12].
1) Features of the STWA construction and SUA V safe movement within it

**STWA structure.** An ordered toroidal structure of SUA Vs is proposed to ensure the conflict-free movement of the SUAV set. The structure is a two-dimensional ring formed by a fixed set of points. The set of points corresponds to the coordinates of the air traffic space. The STWA in a horizontal plane is a set of \(N\) equal radius circular structures, each of which fixed at a certain level of height and has an offset in the horizontal plane so that it forms \(N\) circular structures in the vertical plane with the same number of points. Many independent ring routes are organized (in one direction) in such a structure and the ring sectors are used by a SUAV to enter the STWA. In an ordered-structured space, the distance between points is determined by the conditions of a SUAV safe movement in a swarm.

The basic requirements for the structure of STWA:

1) strict ordered system development with the conflict-free and safe movement of a set of SUAVs;
2) the number of SUAVs in a swarm should not affect the fundamental way of drone interaction. At the same time, both structural stability (strict order of movement in the structure) and the corresponding requirements for air traffic safety must be ensured;
3) high performance of the SUAV swarm control system and the relative ease of its organization.

**SUAV traffic safety inside the STWA.** The traffic safety is determined by the correct route distribution for the drones waiting for landing. Figure 4 shows a variant when SUAVs enter one point of the sector (1st sector) for landing one after another.
Figure 2. a) The number of SUAV awaiting for RP service during landing; b) Queue fluctuation intensity.

Figure 3. Queueing system model for a SUAV group with a buffer landing zone.
Each route is characterized by a different phase shift, which gives an ordered distribution of SUAVs moving in the STWA. An access to the landing line is available through the certain points, for example that located in the upper horizontal circular structure. The SUAV that receives a route with a zero phase shift has the highest priority and can land from any sector, while moving strictly in the horizontal plane. In that case the route length is completely determined by the horizontal plane movement:

$$M_0 = R_{GR} = kL_{GP},$$

(1)

where $k$ is the number of sectors in a toroidal structure; $L_{GP}$ – the length of the path between the points of adjacent sectors in the horizontal plane. If the route has a non-zero phase shift, that is a multiple of the one phase discrete $\alpha = 360^\circ/m$, where $m = n$ – the number of points in a vertical plane sector (equal to the sectors number), then SUAV, when following from sector to a sector in a horizontal plane, should move(also counterclockwise) in a vertical plane in each subsequent sector additionally. In this case, its behavior when moving in the $i$-th segment in the vertical plane is determined by the expression:

$$R_{VP} = i\alpha L_{VP},$$

(2)

where $L_{VP}$ is the length of the path between adjacent points of the segment in the vertical plane. The closed cyclic paths are formed as the result of the simultaneous SUAV movement in two planes along the shortest paths between the points. It allows the SUAV to move with the different periods of transition through the points for landing and to loop over the necessary number of such transitions, if the RP is busy.

When the SUAV leaves the STWA for landing or moves to the BLA it is proposed to use the access protocols that are used in the LAN or modern wireless access systems. And apply the analogy of the multiple SUAVs systems with the telecommunication systems [10,11].
SUAV can make an emergency landing while moving in the STWA. For this purpose, under the toroidal structure (on the ground, for example), a marker (light or another type) is placed under each sector, the marker acts as a beacon for an emergency landing in one sector or another. At the same time, the landing process should correspond to the passage of the route through the lower point of the vertical structure, and from there go to the direction of the beacon.

2) The structure of the information-measuring and control system for landing a SUAV swarm

The algorithm of interaction between the SUAV and RP starts from the moment when SUAV is detected and operates until the landing on the RP (figure 5) using the IMCLS. The IMCLS structure is shown on the figure 6. It includes a subsystem that allows SUAV to obtain the additional information for a better orientation in the direction of the RP and access to the RP. The control and STWA and BLZ air traffic management subsystems also included. The system uses hardware and protocols to implement the multiple access of SUAVs to the BZP and the landing line. IMCLS has a special blocks that enable statistical analysis and selection of the STWA dimension.

3. Results and discussion

The IMCLS solves the following tasks: air traffic safety in the landing zone; conflict-free multiple access of SUAV to the BLZ and RP landing line. The lighting and radio technical support subsystem includes a complex of lighting equipment, infrared equipment for the SUAV orientation, as well as a group of beacons, for an independent SUAV landing in emergency landing mode. The subsystem for detecting, measuring coordinates and correcting the trajectory of SUAV is based on a set of paired optical cameras located in a certain way on the RP. The cameras detect the SUAV and allow the subsystem controller to calculate its three-dimensional coordinates.

SUAV data are transmitted to the landing system controller for organizing a “friend or foe” request signal in the RP general access channel (the channel is assigned to the RP). In case of a positive decision, the landing system controller starts a communication session: determines the main characteristics and requirements of the SUAV for landing (battery charge level and other parameters that determine the priority of landing), sends the SUAV specified coordinates, the coordinates of the point vector and the point of entry in STWA, route SUAV in STWA or a marker, with the response signal.

When the marker access to the BLZ or to the landing line is used to control the SUAV flow in STWA, the receivers are placed on the ground (or another surface – the roof of the building, etc.) opposite the sectors and receive the marker (temporary identifier) from each of passing SUAVs. The received data is sent to a specialized landing system access controller. SUAV routes have a fixed different length with a corresponding waiting time for landing and guaranteed access to the landing line (or BLZ) in STWA when the marker access is used. The use of the access control protocol with a request channel requires the presence of SUAV landing request signals when approaching the exit point of the STWA (in the group request channel).

In this case, response signals from the landing system controller (landing clearance) are transmitted by SUAV in its individual subchannels of the functional landing channel. In addition, the landing system controller periodically sends signals, using the subchannels, for the SUAV movement correction in the STWA. Such signals must be used with any access protocol. An access protocol, similar to the Ethernet LAN protocol, should provide not only the control over the occupancy of the RP by the SUAV before passing the boarding gate, the procedure for randomizing the SUAV exit process to the BLZ and mutual “visual” control of the SUAV, but also a channel for the landing prohibition when a collision of an IMCLS requests is detected.
The recording and data storage unit and the unit for a loading analysis and STWA structure selection are intended to collect and store a set of statistical data to determine the dimension of the toroidal structure of STWA and the structure formation.
4. Conclusion
A toroidal STWA with an ordered structure is proposed for the safety of air traffic in the landing zone. In order to match the SUAV speeds and the RP service speed, it is recommended to use the BLZ, which increases the RP utilization factor. Information-measuring interaction between SUAV and the RP, landing area air traffic control and the solution of the problem of a SUAV multiple access to the resource of the RPs landing system is carried out by the IMCLS. The structure of the IMCLS and the algorithm of interaction between the SUAV and the RP during landing are shown. The tasks of an air traffic control system in the landing zone and the methods of the SUAV control are identified. It is proposed to use well-known protocols of LAN and wireless access networks as a basis to implement the tasks of a SUAV multiple access from STWA to the landing line.

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