Improvement of the architecture of a universal robotic platform designed for swarm structures basis of small unmanned aerial vehicles

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Abstract. The model of the landing system for swarms of small unmanned aerial vehicles in fact consists of a queuing system with a space-time holding zone serving as a gathering device for small unmanned aerial vehicles, where the holding elements are represented by the sequentially connected buffer zone for aerial vehicle landing and the landing line itself with a robotic landing platform. The passage of aerial vehicles from the holding area to the landing zone is controlled by the landing line access protocol. Safe movement of small unmanned aerial vehicles in the holding and landing zones is ensured by the information-measurement and management landing system of a universal robotic platform. The article suggests using the “landing system capacity” as one of the indicators of system performance efficiency.

1. Introduction

Research tests are currently conducted on the transit-terminal nodes of the automatic network for unmanned monitoring of objects and territories serving as robotic platforms for deployment, protecting, taking off, landing and maintaining several small unmanned aerial vehicles (SUAVs) in various aerodynamic schemes. The hardware and software management and communication system provides local or remote (via the Internet) control over the types of work and modes of operation of the platform and its components. The platform is represented by a single-channel queuing model of an “airfield type” with one take-off and landing platform and a limited-length application queue for servicing, which limits the further improvement potential for the designed unmanned networks for a number of reasons:

- absence of “mutual assistance” between transport platforms servicing the same type of SUAVs of other departmental networks;
- introduction of requirements like “must provide mutual assistance” into the technical specifications leads to safety performance deterioration due to an increase in the intensity of air traffic of various SUAV flows in the surrounding space. This results in the necessity for adjustment of the architecture that determines the most important aspects of the robotic platform design.

The architecture of a system is usually understood as a framework determining the most essential aspects of its design: selection and justification of its structural scheme, model, functions performed, operation principles, interaction with other objects, etc. [1]. The universal robotic platform (URP) is a
queuing system that provides safe service for SUAV “take-off/landing” requests [2]. Increased intensity of landing requests or a change in the internal structure of the flow (for example, a swarm) leads to the formation of SUAV queues seeking service and deterioration of the platform performance safety in take-off and landing modes. In [3], the authors specify the problem of “next generation air transportation system (NextGen)”, where the vehicle air traffic is basically represented by adaptive routes dependent on various factors (weather, traffic characteristics, user preferences, etc.). Consequently, the authors assumed the process of vehicle arrival at the landing point to be stochastic. When modeling the queuing system specifically, the normal distribution law was applied to deviations from the planned aerial arrival.

Thus, taking into account the prospects of NextGen, the URP is an SUAV queuing system particularly ensuring safety of air traffic for SUAV structures in the landing zone in conditions of increased intensity of SUAV flows. The authors in [4] provide a solution to the issue of air traffic safety of a swarm of SUAVs over airfields and populated areas. Variants of designing a servicing robotic system for numerous SUAVs are given in [5], which also suggests a possibility of simultaneous landing of several SUAVs on different platforms of the system.

Objective: to increase the efficiency of the universal robotic platform service for swarm structures of small unmanned aerial vehicles.

Tasks to be solved:
1) to specify the model and efficiency of SUAV swarm structures service in the URP landing system;
2) to specify functional parts of the landing system structural scheme, their purpose, and interrelations;
3) to determine the design principles of newly introduced functional parts of the landing system.

2. Methods and materials
In conditions of high intensity of SUAV arrivals for landing, when the landing time of one vehicle exceeds the average interval of their arrivals for service, the URP model becomes a queuing system (figure 1) [6].

SUAV gathering device is a space-time SUAV holding area
Service device is a URP with predetermined landing time

Figure 1. URP model in conditions of high intensity of SUAV arrivals for landing.

Figure 2 shows histograms of modeling results (based on GPSS/W [7]) of URP service for numerous SUAVs with predetermined initial data: SUAV Poisson distribution with an average interval of 35 sec between arrivals; landing time of one SUAV on the URP is 50±5 sec; modeling time is 1 hour.

It can be seen that the landing system is characterized by a stable queue of SUAVs waiting for landing.

The following indicators and parameters are suggested to assess the efficiency of the URP landing system as the one with a holding area when servicing swarm structures.

1. Maximum time of SUAV swarm service by the landing system:

\[ T_{servLS} = T_{HA} + T_{land} \]  \hspace{1cm} (1)

where \( T_{HA} \) is the time in the holding area and in the buffer landing zone (see below); \( T_{land} \) is the SUAV landing time (from the moment the SUAV starts moving from the initial landing line point until its positioning on the platform after landing). This indicator is a preset value meant to limit the time of landing system-provided service.
2. Landing platform performance:

\[ G = \frac{1}{T_{\text{land}}} \quad (2) \]

3. The number of SUAVs of a swarm structure served by the landing system with \( m \) landing platforms:

\[ N = N_{\text{hold}} + m \quad (3) \]

where \( N_{\text{hold}} \) is a number of SUAVs in the holding area and in the buffer landing zone.

4. The capacity of the SUAV swarm landing system with a preset time limit for the landing system-provided service (1):

- for a system with one landing platform:

\[ P_{LS} = (N + 1)G|_{T_{\lim}=T_{\text{serv}},LS} \quad (4) \]

where \( T_{\lim} \) is a limited time of SUAV remaining in the system;

- for a system with \( m \) parallel functioning landing platforms:

\[ P_{LS} = (N + m) \sum_{i=1}^{m} G|_{T_{\lim}=T_{\text{serv}},LS} \quad (5) \]

The “swarm landing system capacity” parameter (4) and (5) is a product of co-and counter-variant system values with memory similarly to a loaded data communication network [8]. It characterizes both the speed properties of the system (landing system performance) and gathering properties with a preset time limit of SUAV remaining in the system.

Figure 2. Distribution of SUAVs in the URP holding area (a). Distribution of SUAV time delay when landing on the URP with account of waiting time in the holding area (b).

Landing system modeling results: Mathematical expectation (ME) of the number of SUAVs in the queue – 6, Mean square deviation (MSD) of SUAVs in the queue – 2 (a); ME of SUAV time delay when landing – 8 min, Time delay MSD – 3 min (b).

When detecting and solving URP functional tasks, it is suggested to use similarities with an open system interconnection reference model (OSIRM) or a model of TCP/IP protocol stack [9]. An example of using network tasks in the interconnection of multiple SUAVs is given in [10]. Hardware and software implementation of SUAV and URP with respective software creates a basis to develop a network transport system (NTS) meant to control SUAV air traffic and a network information system (NIS) providing information exchange between the system objects and implementing information-measurement processes, control and data processing tasks. Similarly, solution procedures for functional NIS tasks (based on OSIRM) are to be transformed into solution procedures for NTS tasks. Thus, the problem of SUAV access from the holding area to the landing line in the NTS can be solved based on the protocol of multiple access to the NIS channel common resource. The examples can be protocols of local computing systems, routing tasks in networks, etc.

The principle of improving the URP structure for SUAV swarm landing is shown in figures 3-4.
Figure 3. Suggested SUAV swarm landing system.

Figure 3 shows that a space-time holding area (STHA) is made for SUAV swarm landing, where SUAVs follow non-crossing routes waiting to enter the landing line. The SUAV movement in the STHA and its exit from the STHA are organized and controlled by the information-measurement and management landing system (IMMLS). The IMMLS also interacts with SUAVs and enables additional STHA control elements in order to ensure air traffic safety for numerous SUAVs in the landing zone. Buffer landing zone is used to coordinate (level) SUAV speeds in the holding area and on the landing line.

3. Results and discussion

The universal robotic platform solves the problem of automatic landing of single SUAVs. It includes the subsystems of control over airspace and SUAV take-off/landing trajectory; SUAV capture and hold, and others (figure 5), which ensures the required accuracy and safety of SUAV landing with due account of external factors. Furthermore, solution of functional tasks of the abovementioned subsystems offers a possibility to characterize the efficiency of the SUAV landing system in terms of the speed of SUAV service when landing on the landing platform. The tasks of SUAV landing itself are shown in the left column of figure 6.
When serving a group of SUAVs, including the conditions of high intensity of a random inflow of SUAVs, the landing system must solve two problems: first, to ensure air traffic safety for numerous SUAVs in the landing zone; second, to implement the function of gathering and managing numerous SUAVs in the landing zone. In this regard, a special space-time SUAV holding area is required, that must have a dynamic structure for efficient landing of a swarm or a group of SUAVs randomly arriving at the landing platform. Such structure is meant to create the required number of independent cyclic routes, while taking into account the number, trajectory and speed of SUAV movement. The toroidal structure, the sizes of which are determined by the landing system capacity $P_{LS}$ (4) and (5), allows satisfaction of these requirements. The related tasks are shown in the central column of figure 6. The presence of a holding area for SUAVs arriving with high intensity presupposes the creation of a system for their gathering. Since there is also a limited number of landing platforms (at least one), the landing system serves as a queueing system for SUAVs. An important goal in it is implementation of the SUAV landing line multiple access protocol. This protocol must prevent conflict situations. The corresponding group of tasks affects the performance efficiency of the SUAV swarm landing system; it is shown in the right column of figure 6.

Since the process of landing of various SUAV groups includes both implementation of the speed characteristic of the system (landing platform performance) and its gathering properties (SUAVs in holding mode), the efficiency of such system is suggested to be assessed by the capacity of the SUAV swarm group landing system (formulas 4 and 5). It is determined by the preset number of landing platforms, time limit on SUAV remaining in the air and specified landing time from the point of the landing line beginning to the landing platform. The characteristics of the gathering property determine the size and structure of the STHA, and, therefore, the number of SUAVs safely present in the STHA.
4. Conclusion

To improve URP service efficiency in SUAV swarm landing, it is suggested to: introduce a space-time structured holding area and a SUAV buffer landing zone into the URP landing system; create an information-measurement and management landing system ensuring air traffic safety in the landing zone of SUAV swarm structures and their management; develop a stack of protocols for SUAV swarm landing line access.

It is suggested to introduce the concept of “swarm landing system capacity” for assessment of URP efficiency with a preset time limit of SUAV remaining in the system. It allows determination of the number of SUAVs on hold in the STHA in conditions of the limit.

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