Controlling the security of the airport airspace using the digital twin

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Abstract. The article aims to develop a neural model for digital air traffic control. The proposed approach uses the concept of socio-cyber-physical self-organization of distributed organizational and technical system, whose components are connected to 4G and 5G generation wireless networks. The advantage of the approach is complex integration of promising analytical management principles and their representation in hybrid intellect.

Introduction

Analysis of air traffic control (ATC) problems shows how vulnerable airport air environment can be in the absence of risk management mechanisms. The experience gained in solving this problem shows that there are many different methodological approaches. Human-machine systems have priority as an alternative to automation, limited flexibility, and adaptability in unpredictable conditions.

Various concepts of building dispatcher assistant systems are of considerable interest. They include the following:

- systematization of dispatching experience to highlight criteria, preferences, and schemes for the formation of new tools and technologies for dispatching in real-time [1],
- support base for dispatching decisions in hazardous weather conditions [2],
- self-organizing training neural network for forecasting the wind situation [3],
- systems for modeling and constructing a dispatch schedule [4].

The concept of a socio-cyber-physical system (SCPS) introduces a new trend in controlling the air situation safety [5]. It assumes self-organization of the air navigation process by introducing a distributed feedback system. An obstacle to implementing this approach is the too high complexity of airport services self-coordination. The solution to this problem makes it necessary to develop a unified environment for information interaction. An effective solution to this problem is voice exchange technology in the interaction between the dispatcher and the pilot in critical situations, including automatic synthesis of voice monitoring reports, urgent notifications, information about intentions and actions.

Basic voice service includes voice calls, voice recognition, voice communication system, digital emergency voice communication system, and others [6, 7]. Modern ATC safety systems evolved from ground-based to all-weather satellite architecture represented by digital addressable voice communications technologies of a new generation [8].
This article deals with the problems of ontological engineering of programming new-generation ATC systems. The proposed methodological principle for solving the problem posed is the organization of a bank of protocols of normative wireless communication of the "human-human," "human-CPS," "CPS-CPS" types. Here, a human is a dispatcher, an air traffic controller, and a pilot; CPS is an aircraft (unmanned or manned), an autopilot, and a digital dispatcher.

This approach is consistent with the concept of socio-cyber-physical self-organization, which lays emphasis on the multifaceted cooperation of people and automated systems [9]. The role of protocols is to formally present organizational models for situational analysis of emergencies and make proactive risk management decisions. The protocol rules are the hybrid intelligence for proactive remote control of air space security in the airport area. Of the most considerable interest is situational activation of the knowledge bank in the neural network self-organization of airport take-off and landing activities.

The 4G and 5G wireless technologies ensure fast messaging, their clear understanding, and high operational responsiveness.

1. Information and methodological basis for decision-making in the control of airspace loading in the airport environment

The approach proposed in this paper to ensure the security of the situation within an airport area focuses on ATC optimization. We propose introducing an intelligent unit into such a system to adapt the ATC loop signals to aircraft motion characteristics. Traditionally, embedded systems work as real-time operating systems. The SCPS technology ensures software and hardware stability, taking into account the human factor and system limitations determined by the adaptability of the control system under consideration to changing conditions.

The SCPS methodology offers advanced computer technology, combining estimates obtained by mathematical methods with subjective estimates based on the knowledge, experience, and experts’ intuition. In this paper, we propose to form an SCPS using digital twins (DT) at all levels of the ATC human-machine complex architecture. A block diagram of this architecture is shown in Figure 1.

We propose to decompose the SCPS application area into several segments: smart airspace management, smart information transmission networks, smart infrastructure, smart aircraft, and smart airspace load management system. A general requirement for them is to organize the transmission of messages using invariant means to random effects of destabilizing factors [2].

Today, we have a solution to the problems of building digital twins at various work levels with ATC systems. Now we can expand the provision of functional modules with intelligent tools and increase the efficiency of transmitting telemetry to control points.

Using 5G wireless technologies enhances the efficiency of air navigation services based on
operators, pilots, autopilot interaction, and coordination. The inclusion of digital twins in the control loop increases stability of technological systems.

The essential feature of the proposed approach to ensuring airspace traffic safety is hybrid intellect mechanisms. This requires further development of software and the technological potential of technical systems by allocating strategic and critical areas of their development. Such systems can have various architectural implementations in application systems, technologies, and physical elements. This “intelligence” system makes it possible to identify, interpret, and adequately respond to the dynamically developing impact of external factors, supporting the ATC system operation within the specified values of parameters. This paper considers 4G-5G wireless network technologies as the most promising means of controlling airspace security [10,11]. They also show considerable potential for formation of mobile cellular networks. Such networks aim to significantly increase the Internet speed, increase coverage, and reduce transmission time of a data packet. This generation of mobile communications has several fundamental advantages over 4G, such as higher data transfer speed, low signal latency, the ability to connect more devices, high-energy efficiency, significantly increased bandwidth, and high user mobility.

A significant feature of 4G-5G technologies is that they increase the signal transmission speed and its quality due to multiple antennas. Note that the restrictions in the requirements for the minimum power of transmitters and the maximum size of the controlled space in this problem are not significant.

Network slicing allows mobile operators to deploy logically isolated networks, each of which will allocate for specific needs, such as broadband access, video broadcasts, and others. In this way, the next-generation mobile network will be able to adapt more flexibly to various applications. Each task receives the appropriate resources and technologies that will allow avoiding overloads and delays in the signal transmission. Besides, devices located close to each other will be able to exchange data directly, device-to-device (D2D).

Like any technology, 4G and 5G carry risks. For example, a neural network has a risk of cyberattacks. Users should take care to ensure their safety and protection. Despite the planned redistribution of frequencies provided for special services, and institutions, including scientific laboratories, space, and military departments, many frequency spectra still operate. The allocation of bands for use in ATC requires comprehensive agreement.

Often next-generation networking uses the existing infrastructure inherited from earlier generations. With more flexible encoding and expanded data channels, 5 GNR speeds will be 25-50% faster than LTE. Simultaneously, large-scale implementation of physical infrastructure and software solutions will allow maximizing the 5G capabilities.

To deploy standalone networks, we need to install new types of stations and transmitting devices. Since we are talking about shorter waves, which are less resistant to interference and obstacles generated by the environment, the coverage radius of each base station will decrease. That will require a denser infrastructure that will consist of so-called Small cells.

As for mobile communication stations with a capacity of 20-40 W, it is advisable to replace them with more economical stations with low power consumption, whose power ranges from 2 to 10 W — they should provide mass coverage in the high-frequency range and gigabit speeds.

Small cells fit better into the airport environment on lighting masts or building walls. Thus, we can conclude that the 4G standard is relevant. It meets many user requirements and is not yet widespread. Therefore, today there is an active construction of 4G networks. 5G is promising since it promises a new quality of communications and entire digitalization of aviation services. Owing to high speeds, bandwidth, and low response, many interesting technical innovations will be available, including the Internet of things, aerial unmanned vehicle control, and the dispatcher virtual reality helmets.

2. Mechanisms of air traffic safety controlling based on a digital twin
Evaluation of hybrid intelligence effectiveness shows the prospects for introducing SCPS into ATC facilities. SCPS expands the possibilities of contact algorithmization. For example, algorithmization
of interaction between the element base of monitoring, control, and regulation of software and hardware.

The evaluation of the hybrid intellect possibilities shows the prospects for introducing SCPS into ATC. The Internet and 4G-5G wireless communications technologies expand and simplify the cyber-physical self-organization. This paper proposes to build the SCPS on four traditional elements: channel, sender, recipient, and message. The channel type determines the sender, recipient, and message types:

- agent survey service (web service of the site integrator);
- service of the electronic message system (to exchange packages of monitoring results and setting up the rules/Protocol of technological processes);
- service of the subject-oriented informatization system (to automate the distributed collection of information in a consolidated analytical report);
- service for multi-agent control systems (builder of controlling processes for managing individual technological processes);
- service for planning and implementing monitoring results (reporting data on the current state of operation of local information and control functional modules).

This implementation of the interaction of elements makes it possible to connect human intelligence with the "intelligence" of the cyber-physical techno-sphere, forming interactions in the contour of organizational and technical systems with semantic decision-making technology. In general, hybrid intelligence proposes a trained neural system in coordinated teamwork of dispatchers, pilots, autopilot, and their interaction with the smart airport infrastructure.

We assume that ATC’s target function is to maximize the reliability of the airspace loading management system while maximizing psychological comfort of its participants. Accordingly, the digital twin’s target function of risk-controlling of the air situation dynamics can be written:

$$K_R = \min_{KQ, KS, KD} \max_{(1-\alpha), (1-\beta), P_i} f(KQ, KS, KD, (1-\alpha), (1-\beta), P_i)$$

(1)

where

- $K_R$ – the coefficient of readiness to use the ATC system, determined by a comprehensive assessment of its reliability;
- $K_Q$ – coefficient of reliability ratings for ATC participants;
- $K_S$ – coefficient of ATC participants, work organization characteristics;
- $K_D$ – coefficient of factors affecting air traffic safety characteristics;
- $\alpha, \beta$ – the probability of a risk situation when using protection resources in the ATC process or when the available protection resources fail, respectively;
- $P_i$ – the probability of failures and failures of the protection system against destabilizing factors, which characterizes the $i$-th ATC selected strategy, when $i=1, 2, 3, \ldots, I$

In (1), $K_Q, K_S, K_D$ are considered as constraints on the ATC process stability data blocks:

Set $Q$ defining $K_Q$:
- a summary of estimates of aircraft operators;

Set $S$ defining $K_S$:
- aircraft registry;
- parameters of dynamics of critical airspace loading of the controlled airport according to route maps and time intervals of aircraft flights;
- plans for periodic flights in the airspace with a visit to a controlled airport, presented in the digital air navigation map;
- evaluation of the routes accessibility;
- parameters for planning the air navigation map for an arbitrary time interval (for example, season, month, decade, week, date);

Set $D$ defining $K_D$:
• parameters of climate phenomena and weather conditions according to incoming reports;
• characteristics of the emergency layout system;
• norms for dynamic switching of control powers for collision risk control.

Along with signaling, the occurrence of a risk event, the function of such a system is to maximize the probability of failure-free operation under restrictions on the resources available to air traffic controllers and minimize the probability of failure. We assume that the set of conditions (organizational, economic, legal, technological) that affect the ATC system's readiness to determine the airport control strategy [12]. In this case, we will define the set of acceptable strategies by displaying the $O_1$ operator:

$$O_1: Z, D, Q, S \Rightarrow K_D$$

(2)

Where $Z$ is a set of possible ATC strategies. As a characteristic of each strategy $z_i \in Z$, we will consider estimates of ensuring the ATC process reliability according to the requirements for the values of the probability of failure-free operation of the ATC system ($p_i$). The algorithm for choosing such a strategy is formed as the display by the $O_2$ operator:

$$O_2: Q, D, S, p_i, Z \Rightarrow Y$$

(3)

Where $Y$ is a set of rules that define the strategy for using protection resources in the ATC process. This paper will consider expression (3) as a simulation model of the ATC algorithm, which determines the reliability of its participants with the strategy $z_i \in Z$ for probability $p_i$. Moreover, the characteristics of each participant in the ATC system limits the value of $p_i$. The evaluation of the effectiveness of the ATC algorithm implementation represents the display of the $O_3$ operator:

$$O_3: Q, D, S, p_i, Y \Rightarrow U$$

(4)

$U$ is a set of strategies ordered by the degree of preference accepted at this airport.

SCPS assumes that each strategy implementation considers the specifics of each of the ATC participants' social aspect according to the estimates of $Q$ characteristics.

Now, we can formulate the task of optimizing the ATC process:

$$\forall p_i, F(q, d, s, p_i, y(q, r, s, p_i)) \Rightarrow K_B \rightarrow extr$$

(5)

under constraints:

$$H(q, d, s, p_i, y(.)) = 0$$

$$I(q, d, s, p_i, y(.)) > 0$$

Where $y(.)$ is the description of the mapping by the operator $O_2 \forall p_i$. In our review, the problem of optimizing the ATC process (5) using a digital twin of the system reduces to building a neuro-network based on the criterion of maximizing the availability coefficient with known reliability estimates of its elements. So the set $D$ defining $KD$ includes rules for dynamic switching of control powers for preemptive control of collision risks.

The task of developing standards that determine the probability of failure-free operation of each of the ATC participants is very relevant. The twin model can become a useful tool for algorithmization of air traffic safety control to ensure compliance with these requirements with a known probability of natural and human-made phenomena in the airspace. As a result, the required level of aircraft traffic safety depends on an acceptable probability of dispatcher's failure-free operation and the allowable probability of failure in the aircraft's test and operation. The preferred format is a distributed multi-level neural network reformatted to the spread control dynamics in functional failure risks [13].

Conclusion

The paper proposes a neural network dispatcher that determines the proactive risk controlling of airspace loading in the airport area. It proposes to build such a dispatcher based on the ontological model of the socio-cyber-physical system of geospatial proactive network risk controlling of mobile
unmanned and manned vehicles. The prospects of the proposed approach to the digitalization of air traffic safety control in the airport area relate to the organization of the dispatcher's work accompanied by a stand-in traffic controller, which allows for flexible distribution and redistribution of their functions in extreme conditions. Among the advantages of 4G-5G technologies, we highlighted the achievement of high data transfer speeds, reduced latency when transmitting a data packet, reduced power consumption, broader system bandwidth, and, what is no less important, increased device connectivity.

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