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TIME AND SPACE DISCRETIZATION IN THE DIGITAL TWIN OF THE AIRPORT TRANSPORT NETWORK

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The paper describes the concept of a Digital Twin (DT) creation, which could be used as part of a centralized ground traffic control system in the airport's apron area. The work is focused on the automatic control systems expected in the future, which will completely replace the ground traffic controllers that solve the centralized control's tasks in our days. It is assumed that the developed DT can be used both at the stage of training the control system and at the stage of its use. A special feature of the proposed DT concept is the clearly formulated principles of the observed process' time discretization and the space in which the movement of ground vehicles and aircraft occurs. The experimental verification of the developed concept was carried out using a special simulation model designed to generate data streams on the airport's transport network's traffic participants' location.

Keywords: airport, ground traffic, centralized control, digital twin, simulation

1. Introduction

The airport's transport network relates the aircraft (AC) routes that are preparing for take off or have already landed, as well as the ground vehicle's (GV) tracks, most of which perform operations for servicing aircraft located in an open stand or near the passenger bridge. Well-known types of AC maintenance operations include disembarkation and boarding of passengers, unloading and loading of luggage, AC refueling, delivery of on-board food, cabin cleaning, etc. For ground handling of one aircraft Boeing 737 type, at least eight GV units must drive up to it, not counting shuttle buses for passenger transportation. During the aircraft is on stand, which is not equipped with air bridge, four more buses also approach it: two for disembarking and two for boarding passengers. When servicing a larger capacity AC, the number of corresponding GV increases. Often, large airports serve up to 60 AC per hour, which leads to about 900 GV's trips in the directions there and back. If an average per minute starts a trip of 15 GV's and each trip lasts of 5 minutes average in one direction and 5 minutes in the opposite direction, then according to Little's law, there will be on route an average of 150 GV's at the same time. It is quite clear that sometimes there will be situations when the number of GV's in the transport network will significantly exceed the average value. We mustn't forget that the AC are also participants in ground traffic and AC and GV routes have many intersection points.

Currently, the processes in the airport's ground transport system are controlled by ground traffic controller. The main aid of the ground transport network object's control in the airport that the controller uses is the surface movement radar (SMR). If weather conditions allow, the controller also uses visual control, observing the transport network from the control tower. An information exchange with AC pilots or GV's drivers is carried out through the radio by voice communication.

The document "Vision 2050", published by IATA (International Air Transport Association), describes the prospect of implementing automated and automatic ground traffic control systems at the airport (IATA, 2011). The main objectives of such a concept implementation are to improve ground traffic safety and reduce the time loss during the AC servicing, appears as a result from waiting of the GV's arrival, involved in this service process. The prospects of reducing the time of AC ground maneuvering, which will lead to fuel consumption reduction and associated with it a harmful impact on the environment, are also important.

The first problem on creating an automatic control system is to obtain an accurate data about the current movement participants' location and their movement parameters. With a certain degree of accuracy, such tasks are solved by the well-known system A-SMGCS (URL1, 2021), which significantly expands the controller's functionality compared to the option when it has only SMR at its disposal. Work continues to improve the accuracy of moving objects' coordinates determination in the A-SMGCS system.

For example, in (Antonov *et al.*, 2015) and (Antonov *et al.*, 2016), it is proposed to install additional devices such as a satellite navigation receiver, a micromechanical inertial navigation system, an odometer and/or a relative velocity sensor on board mobile objects. The authors believe that the coordinated determination's achieved accuracy will allow to apply such an improved system even for driving unmanned vehicles. Additional useful information can be obtained also with the optical devices assistance. Intelligent Cameras can be installed on the airfield territory (Dimitropoulos *et al.*, 2005), and mobile objects can use on-board LiDAR type devices (Lee *et al.*, 2020).

The A-SMGCS system in its current state is capable to perform some functions of AC movement automatic control on the runways, taxiways and on the apron. The system can warn the controller about the occurrence of a conflict between two AC, as well as between AC and GV. The controller makes the control decisions when conflict situations appear in the ground transport system and thus performs centralized control of this system. An automatic control system implementation means the complete replacement of controller with appropriate computer programs. In the airport's transport system of the future, the functions of the GV's will be performed by unmanned vehicles. The centralized control of processes will be transferred to computer programs based on the principles of artificial intelligence.

While there is no information that such programs are already being tested at airports, but there is no doubt that specialists have already begun to develop them. Any control system should solve two tasks: a) to identify already observed or expected deviations of the controlled object current state from the required or acceptable one, and b) to develop control actions aimed at the control object. To solve the first problem, the control system must rely on a complete and accurate control object's information model, commonly called a Digital Twin (DT). For learning control system of conflict situations recognition in the airport's transport system, such situations are necessary to demonstrate to her. Thus, the same in structure DT should be applied both at the control system's training stage and at the stage of its use.

This paper describes the experimentally proven concept of a Digital Twin creation for centralized control system of the airport ground transport. The concept's feature is clearly formulated time discretization principles of the observed process and the space, in which movement occurs GV and AC. The experimental verification of the developed concept was conducted using a special simulation model, designed to generate data streams of the traffic's participants' location in the airport's transport network.

2. State and prospects of Digital Twin application in aviation

It is accepted that the concept of DT was first formulated in (Grieves, 2005). The DT's essence should be a dynamic virtual copy of a real system or process, which leads a kind of "parallel life" in relation to the original. To refer the original the terms "physical asset" and "physical twin" are often used. The DT itself is also sometimes called "device shadow" or "digital avatar". Cause the concept of DT is relatively new, the authors of the articles and the developers of the corresponding applications by a virtual copy understand a variety of information models. For example, NASA experts (Glaessgen and Stargel, 2012) believe that the term DT can be almost any complex simulation model of a real object that serves to display its life cycle. In (Madni *et al.*, 2019) four types of models are defined, which the authors associate with the concept of DT:

- Pre-Digital Twin is an ordinary simulation model of a non-existent object;
- Digital Twin is a simulation model, in which regularly, but not in real time, data receives from a real object;
- Adaptive Digital Twin is a simulation model in which data receives from a real object in real time;
- Intelligent Digital Twin is an extension of the previous type, in which machine learning features added.

The first ideas for implementing DT were related to the virtual modeling of purely technical objects, such as starting with a separate ship engine and up to the scale of the ship's entire technical support. The main feature of the DT was its direct connection to the physical system, which was carried out by one-way data transmission from numerous sensors are installed in the system. The main function of DT was to store data about the system's current state, which could be used, for example, to predict failures of specific system nodes. Further It's began a discussion on the possibilities of the DT concept application for technological processes' virtual modeling and even complex business processes of enterprises.

In the aviation field, the focus at first was also on purely technical systems. For example, the DT form displayed an airframe's status (Tuegel, 2012) or an AC engine (Zaccaria *et al.*, 2018). At present, numerous statements of experts concerning the prospects of the DT concept application for processes monitoring and controlling at airports are beginning to appear. It should be emphasized that such statements refer specifically to the prospects, cause there are not existed ready-made integrated solutions yet.

For example, in (URL2, 2021), it is reported that SITA Lab is developing a project that aims to create a DT for one of the airports in the United States. Such a DT should monitor the processes on the airfield, in the traffic areas in front of the airport building, as well as in the security check areas. Experts note that the main problem is to create a data collecting system, and in case if it is successfully solved, it will take from 5 to 10 years to complete the project. In (URL3, 2021), it is reported about a wide program of DT concept implementation at Copenhagen Airport. As the first, the tasks of monitoring the airport premises condition will be solved, for example, the degree of their congestion and air quality. In the future, a creation of other DT is planned and to connect them to A-CDM (Airport Collaborative Decision Making) systems type.

In (URL4, 2021), it is reported that Hong Kong International Airport plans to get smart airport status. At the first stage, DT will be mainly used for processes 3D visualization at the airport, but then it is planned to develop analytical applications that can solve forecasting problems. In (URL5, 2021), it is reported that 51WORLD, a company known for its developments in the field of information technologies, and the China Academy of Civil Aviation Science and Technology have started work on the smart airport project, of which the DT concept is a part. In 2020, 23 demonstration projects in Beijing, Guangzhou, and Shenzhen cities have already been implemented. It is noted that major problems arise due to necessity of integration previously developed and independently running process control's systems at the airport.

3. The concept of DT application in the airport's transportation system control

The airport's transportation system includes two overlapping transport networks (routes for GV and AC), as well as the mobile objects themselves in the form of GV and AC. The focus on the task faces objects movement centralized control, the essence of which is to recognize and process the so-called critical situations. It is assumed that on-board (local) mobile objects control systems cannot recognize such situations in a timely manner to make such decisions on how to get out of them that would be acceptable to all traffic participants. It is also assumed that the centralized control system wouldn't take over on-board control systems' functions. On-board control systems will still perform such functions as the distance keeping between vehicles or avoiding collisions with obstacles.

Figure 1 explains the basic concept of DT application in system of the centralized control of airport's transportation system. The main function of DT is the data collection and accumulation about mobile objects' (GV and AC) location and condition, also this data provision to operators or software applications in a form that allows to solve the tasks of monitoring and analyzing processes in the airport's transportation system. Each message received from an object is fixed in DT as a data record. At the beginning of such a message is a time stamp, and then follow the data about the object's location and status. While messages from objects can come at any moment of time, DT generates for applications the data, that are attached to a discrete time with a set step of Δt . The minimum Δt step size is determined by performance of collection and data processing system. The actual Δt step size may be larger than the minimum, but it should provide sufficient accuracy in mobile objects coordinates' determination, whose speed almost never exceed 40 km/h. In the experiments with DT model are described below, the step $\Delta t = 0.2s$ was used.

Figure 1. The concept of DT application for object's control in transport network

In Figure 1, DT is shown in dynamic database form, where data is stored that relates to three time periods:

- to the past periods of Δt time (history);
- to the current observed period of Δt time, the end of which will be marked as current time t ;
- to the future periods of time (future) in cases when in part of real-time applications there are tools for short-term forecasting of individual objects behavior.

Figure 1 shows an example, in which messages are received from one object of the AC type and two objects of the GV type. For each object its own “track” allocated for recording data records. The current Δt step shows how messages are received asynchronously, but then they are brought to the moment of time t by DT tools. For the AC, two data records are shown, which are results of its location prediction in the nearest seconds of the process is observed. When a critical situation is detected, the program-controller sends commands to the mobile objects which are affected by this situation. If an average of 30 objects are in motion at a small airport at the same time and each data record has 100 bytes size, so as a step of $\Delta t=0.2s$ in DT, 54 MB of data will be accumulated per hour. If in a large airport there will be not 30, but 300 of such objects, then and 540 MB per hour on the scale of modern information systems is a negligible number.

4. The advantages of discrete time

The analysis of the objects relative position in the airport's apron zone can only be performed for certain time moments. It means that the coordinates (x, y) of each object have to correspond to the time moment t for which the corresponding calculations are performed. Already at DT's concept developing stage, it is should proceed from the assumption that messages about the objects coordinates would come in asynchronous mode, i.e. at random times. Synchronous mode can be imagined, for example, in the case when data comes from surface movement radar (SMR). But even in the presence of such radars, other technical aids located both on board the objects and in the airport's apron area will also be used to determine the mobile objects' location. The moving objects' location's data flow should be redundant, as possible information losses due to radio interference or technical aids' failures. In any case, the total data flow will be asynchronous, with what to information receiving frequency from different sources will differ. In such conditions, the data binding with the objects coordinates to the moments of discrete time is mandatory condition for using this data for situation analysis in the airport's transportation system. Figure 2 shows an example of the coordinates (x, y) correction of mobile objects Obj1 and Obj2 during the transition from real time to discrete time. The calculated coordinate value is obtained by linear extrapolation of the last two measurement results. Between the moments $(t-2\Delta t)$ and $(t-\Delta t)$, the object Obj1 did not change its location. At the time interval between the moments $(t-3\Delta t)$ and $(t-2\Delta t)$, no measurement data was received for the object Obj2. Therefore its coordinates for the moment of time $(t-2\Delta t)$ were calculated under the assumption that the object retains the speed and direction of movement.

Figure 2. Correction of coordinates (x, y) during the transition from real time to discrete

The primary data obtained from the objects' location measuring tools in this study frames has name Event Protocol, and the data connected with discrete time has name State Protocol (Saifutdinov *et al.*, 2021). Implemented within the frame of the DT transition from real time to discrete time means conversion of Event Protocol to State Protocol. Figure 3 shows an example of such a transformation for the case of three mobile objects and three discrete-time moments with an interval of $\Delta t = 0.2s$.

Event protocol			
real-time stamp	object name	X-coordinate (m)	Y-coordinate (m)
10:45:11.82	GV2_2	573,60	315,12
10:45:11.83	AC2_1	525,60	376,68
10:45:11.85	GV2_3	679,95	377,55
10:45:12.00	GV2_2	573,60	318,54
10:45:12.03	AC2_1	525,60	375,46
10:45:12.04	GV2_3	679,46	376,30
10:45:12.23	GV2_3	679,20	372,85
10:45:12.24	AC2_1	525,60	372,24
10:45:12.25	GV2_2	573,60	320,49

State protocol								
discrete time	object name	X-coordinate (m)	Y-coordinate (m)	location	speed (m/s)	direction ID	target	priority
10:45:12.00	GV2_2	573,6	318,5	GV108	5	S	GV51	1
10:45:12.00	GV2_3	679,5	377,1	GV28	4	NW	GV51	1
10:45:12.00	AC2_1	525,6	376,0	AC197	4	N	AC218	1
10:45:12.20	GV2_2	573,6	319,5	GV108	5	S	GV51	1
10:45:12.20	GV2_3	679,2	373,0	GV29	5	N	GV51	1
10:45:12.20	AC2_1	525,6	372,4	AC197	4	N	AC218	1
10:45:12.40	GV2_2	573,6	323,3	GV108	5	S	GV51	1
10:45:12.40	GV2_3	679,2	372,0	GV29	5	N	GV51	1
10:45:12.40	AC2_1	525,6	371,6	AC197	4	N	AC218	1

Figure 3. The transformation Event Protocol to the State Protocol

The Event Protocol is shown in the most compact form when it contains only the object identifications and their coordinates (x, y). When creating the State Protocol, there are not only the coordinates (x, y) correction, but also other additional parameters identification, for example:

- by comparing the coordinates (x, y) with the airport map, the name of the transport network section is determined or other apron zone's territory where the mobile object is located;
- by processing the results of several measurements of coordinates (x, y), the mobile object' speed and it's moving direction are determined;
- as an option, any mobile object attributes, stored in the Scheduling/Routing system, can be recorded, for example, the trip destination and the priority.

As mentioned above, the data from the State Protocol is used to analyze the current situation in the airport's transportation system and obtain statistics or short-term forecasting of the processes development.

5. The advantages of the discrete space

The advantages, that appear in the situations analysis' procedures in the transport network as a result of space discretization are most conveniently to explain by the example of solutions used in the GTSS (Ground Traffic Scenario Simulation) model described below (Saifutdinov and Tolujevs, 2020). The analyzed 2D-space of transport network is presented in the form of grid-based space and is divided into cell with 2m side. Figure 4 explains the method of graphical imaging and coding of network sections, intended for AC or GV movement. It is assumed that objects can move in by eight directions, i.e. i.e. horizontally, vertically, and at an angle of 45°. Section S2 starts in cell A and ends in cell B. When encoding sections, the condition is fulfilled that the previous section ends in the starting cell of the next associated with it section. It means, that cell A is the end point for section S1, and cell B is the end point for sections S2, S3, and S7. Simultaneously cell B is the starting point for sections S4, S5, and S6. The sequence numbers of the section's cells correspond to the objects moving direction by this section.

Figure 4. Method of graphic imaging and coding of transport network sections

Figure 5 shows the result of applying this method of describing the transport network in MS Excel for a specific airport. A total of 223 sections were set for this network. The borders of the sections are marked with short strokes in the drawing. Sections can intersect, i.e. any cell can belong to several sections. When encoding a section, it is assigned an arbitrary name. Figure 3 shows that in the position “location” the letters “GV” are used in the sections names, by which GV's move, and the letters “AC” are used in the sections names, by which AC move. Network sections can be encoded in any sequence independently of each other. To encode a single section in MS Excel, it is enough to assign color and sequence numbers to its cells. The corresponding program will move the following data to the table about each cell: its coordinates (i, j) in the Excel table, graphical coordinates (x, y) in meters for the lower left corner of the cell, the length of the transition between the centers of neighboring cells, and the code of this transition direction, i.e. the value of N, S, W, E, NW, NE, SW or SE.

Figure 5. Fragment of the transport network in a grid-based space on a MS Excel worksheet

Although it may seem that this way of the transport network description will not provide sufficient accuracy in analyzing the relative positions of moving objects, the limited accuracy is compensated by the simplicity of the corresponding analysis algorithms. In addition, it keeps in mind that the centralized control system does not analyze the movement kinematics of objects with an accuracy of centimeters, cause it is the task of local navigation and control systems. Its main task is to get a picture of all mobile objects location in the apron zone at least with an accuracy of 3-5 meters and predict the occurrence of dangerous situations. Figure 6 shows 2D “shadows” that accompany mobile objects in the same grid-based space in which the transport network model is located. Such “shadows” play roles of control areas, which greatly simplifies the task of analyzing the objects relative position, for example, compared to the method of controlling the polygons intersection. It should be noted that the idea of “shadows” for modeling the collision of mobile objects has long been proposed in the field of marine navigation (Davis *et al.*, 1980). In this area, it has become generally accepted the term “ship domain”. In most modern papers on this topic, for example (Kang *et al.*, 2018), use complex geometric models that will be quite effective in analyzing two or three slow-moving objects. In the case when such problems will have to be solved several times per second for hundreds of objects, the use of such models will require very large computational resources.

Figure 6. Control areas of mobile objects

The control areas shown in Figure 6 must be created manually for all types of mobile objects that may appear in the airport transport network. It is assumed that in the protocols shown in Figure 3, the coordinates (x, y) refer to the so-called mobile objects' referent points, which are marked as black dots in

the objects nose part. Cause in the State Protocol there is position “direction ID”, so ability appears to quite correctly display the object's control check area's cells when it is located on a transport network's section or on a free site. The fact of objects' dangerous approach can be relatively easily established by the analysis of the boundary cells' location of their control areas.

6. Simulation program GTSS

The GTSS simulation program was developed as a tool that allows to generate data streams from mobile objects in the system of ground transport at the airport. The main result of using the GTSS program is DT, in which the data is presented in the form of State Protocol (see Figure 3). The GTSS program is universal, cause with its help can be used to display the processes in the ground transport network of any airport. The GTSS program fully implemented the principles of time and space discretization, described above. The left part of Figure 7 shows a fragment of the model, created by using the GTSS program, and the right part explains possible ways of information's exchange between the model and its external environment.

Figure 7. The ways of the model usage, created with the GTSS program

The main feature of the GTSS program is her orientation on modeling accurately described scenarios of processes flows in the airport's transport network. Every such scenario describes the traffic participants group's behavior, which structure includes both the GV and the AC (Saifutdinov *et al.*, 2021). The scenario is made up in such a way that in the process of its implementation there is a critical situation in which it is necessary a decision making at the centralized control's level. The model user observes the process in the transport network using computer animation and stops the model at the moment, when it is necessary to make decisions and send appropriate commands to the traffic participants. The entire simulated process of the occurrence of a critical situation is recorded in the GTSS program in the form of DT. Based on the data contained in the DT, the analytical or training application in the future will have to automatically recognize a critical situation, as the user-controller does now. Thus, by the GTSS program assistance, it makes no sense to model the routine operation of the airport's transport network for several hours as a random process, since the model user wants to see only known to him examples of critical situations types' appearance, among which the following can be noted:

- on one of the transport network's sections, there is an obstacle appears to vehicles passage, for example, due to the fall of a load on the roadway;
- a priority vehicle appears in the network, which should arrive at the destination as soon as possible;
- a vehicle appears in the network that has failed and must be evacuated from the place of it stopped;
- there is an unacceptably large congestion of vehicles or even congestion on one or more sections of the transport network observed;
- there are vehicle's brakes or steering have failed, as a result it moves in a dangerous path.

For the first three types of situations, the recognition task is not relevant, since all transport process participants, including the controller, can find out about it based on the received information messages. Many other situations should be determined by automatic recognition.

The GTSS program gives possibilities to simulate the processes that will be observed in the system after making decisions at the level of the central control system. To do this, the user of the model changes or creates again the scenarios of the behavior of traffic participants after the decision-making moment and continues processing the model using these scenarios. It is quite clear, that the continuation of the simulated process is also written in the form of DT. If DT is intended to be used not only for recognizing critical situations, but also for developing control actions, the corresponding decisions of the controller should be recorded in a separate protocol, since only the physical results of these decisions making will be visible in the DT itself.

7. Summary and conclusions

Unlike the authors of the other papers discussed above, the authors of this paper abandoned another attempt of blurring the DT concept and retained the original sense of this conception as a dynamic data store about the functioning process of the original object. The main purpose of DT – to provide actual data to any number of applications on the state of the original, the role of which in this work is performed by the airport's ground vehicle system. This example of using DT shows the usefulness of the concept of separating applications from the DT space itself, rather than treating them as part of that space. The variety of possible applications is almost unlimited, and in any system, their number and functions will change over time. There are already known examples of using DT to solve problems of monitoring, diagnostics and short-term forecasting of the original-object's work. There is no doubt that the world of such applications will develop intensively, first of all, in the direction of increasing the intelligence of the corresponding computer programs.

The DT created and tested by the authors is actually a DT model, since the real DT must be connected to a real data collection system in the airport's transport network. But in relation to the model created with the GTSS program, this DT is real, cause it accumulates the entire data stream, created by the simulation model. Suppose the composition and structure of the data in the developed DT will not differ from those that expected in the real system. In that case, present DT can be used for the development and testing a real software of the centralized control's system of airport ground transport. Since the GTS program is created with open source, it is not difficult to change the event and state protocols' formats to bring them into line with the technical characteristics of any real data collection system.

The development of applications that use DT for centralized management of ground traffic at the airport is not the subject of this work, but is considered as a direct continuation of it. It is already clear that the automatic system must solve at least three tasks: to recognize the prerequisites or the fact of a critical situation occurrence, determine the range of affected by this situation traffic participants, and develop commands to resolve the critical situation. Since today such tasks are solved by the airport ground traffic controller, the prospect of using machine learning methods in the development of an automatic control's system becomes obvious. The DT presented in this paper can be used as a data source that meets all the machine learning system requirements.

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