Farid Saifutdinov

DEVELOPMENT AND TESTING OF THE DIGITAL TWIN CONCEPT AS A PROCESS DATA STORE IN GROUND TRAFFIC CONTROL SYSTEMS AT AIRPORTS

Summary of the promotion work

to obtain the scientific degree Doctor of Science in Engineering

Scientific area "Civil Engineering and Transport"
Scientific subarea "Telematics and Logistics"

Scientific supervisor:
Dr.habil.sc.ing., professor
Jurijs Tolujevs

RIGA – 2021

UDK 303.094.7:656.71

Transport and Telecommunication Institute

Saifutdinov F.

Development and testing of the Digital Twin concept as a process data store in ground traffic control systems at airports: Summary of the promotion work. Riga: Transport and Telecommunication Institute, 2021.

The submitted material retains the author's style and design.

ISBN

© Farid Saifutdinov, 2021

© Transporta un sakaru institūts, 2021

THE PROMOTION WORK PRESENTED TO THE TRANSPORT AND TELECOMMUNICATION INSTITUTE TO OBTAIN THE SCIENTIFIC DEGREE – DOCTOR OF SCIENCE IN ENGINEERING

OFFICIAL REVIEWERS:

***
***
***

***
***
***
***

***
***
***
***

***
***
***
***

CONFIRMATION

I hereby confirm that I developed the promotion work that is presented to the promotion council of Transport and Telecommunication Institute to obtain the scientific degree of Doctor of Science in Engineering. The promotion work has not ever been presented to any other promotional council to the scientific degree.

F. Saifutdinov

The promotion work is written in English. It consists of 5 chapters including the introduction and conclusions, as well as 2 appendices. It contains 135 pages, 52 figures, and 2 tables. The list of references contains 163 titles.

CONTENTS

ABSTRACT

The thesis “Development and testing of the Digital Twin concept as a process data store in ground traffic control systems at airports” is written by Farid Saifutdinov under the supervision of Dr.habil.sc.ing., professor Jurijs Tolujevs.

As an object of research in this work, the ground transport system of a modern airport is determined. The work is focused on solving the promising problem of developing automatic control systems for the movement of aircraft and ground vehicles in the airside zone of the airport. The organization IATA (The International Air Transport Association) formulated such a task in 2011 in a document called “Vision 2050”.

This work is based on the assertion that any control system for a complex technical object cannot be put into operation without testing it using one or several types of mathematical modelling. The ground transportation system at the airport belongs to a class of systems for the study of which it is necessary to apply computer simulation. A special way of using simulation models is the emulation mode when the model interacts with a real control system. This work does not concern the development of control programs themselves, but it proposes a tool for their training and testing, focused on the use of simulation models in emulation mode.

The control system must receive complete and accurate information about the state of the control object, for the collection and storage of which Digital Twin can be used. The work describes a universal computer program created by the author, which is designed to simulate critical situations in the airport transport system. The scenarios for the occurrence and elimination of such situations are set by an expert, and after their implementation using a simulation model, Digital Twin records the movement of all objects in a format that corresponds to the measurement data obtained using real equipment for determining the location of moving objects. The information accumulated in the Digital Twin is intended for training the created airport ground transport control system.

The novelty and purpose of this study is to develop and experimentally test the concepts of applying computer simulation and emulation methods to create a Digital Twin, which can be used as a source of information for a real-time control system both in its training mode and in normal operation.

Main results of this thesis are presented at 5 international scientific conferences and published in 7 scientific papers. The thesis consists of 5 chapters and includes 135 pages, 52 figures, 2 tables in the main body, 2 appendixes and 163 references in the bibliography.

1. RELEVANCE AND MOTIVATION OF THE RESEARCH

The main element of the air transport infrastructure is the airport, the capacity of which depends primarily on the organization of its transport process, which can be defined as the process of moving passengers, cargo, aircraft (AC) and ground vehicles (GV) in the air and ground spaces of the airport. The most difficult and important from the point of view of ensuring the safety of the airport operation are Airspace and Airside areas. Airspace processes are subject to strict international rules and are precisely defined for each specific airport. The greatest variety of options for organizing processes refers to the Airside area, where the ground movement of AC and GV is carried out. These days, centralized ground movement control is provided by either conventional airport controllers or dedicated ground movement controllers. Reducing the impact of the human factor on the safety of airport processes is an urgent task. In a document called “Vision 2050”, published by the IATA (The International Air Transport Association) in 2011, it is noted that in the future it is expected to introduce automated and automatic centralized control systems of the processes of GV and AC movement on the airport territory.

This work is based on the assertion that any control system for a complex technical object cannot be put into operation without testing it using one or several types of mathematical modelling. The ground transport system at the airport belongs to a class of systems for the study of which it is necessary to apply computer simulation. The ultimate goal of using computer simulation is to implement the interaction mode of a real control program with a model of AC and GV movement in the airport transport network. This mode of using simulation models is called emulation. This work does not concern the development of control programs themselves, but it proposes a tool for their training and testing, focused on the use of simulation models in emulation mode.

The control system must receive complete and accurate information about the state of the control object, for the collection and storage of which Digital Twin (DT) can be used. To train the control system to recognize critical situations in the airport transport system, it is necessary to have a “collection” of such situations and provide the ability to demonstrate them to the control system in real time. Thus, the primary purpose of using DT is to create a “collection of situations” by accumulating information about processes in the airport transport network. In this case, a simulation model can be used as a source of information, which was specially created to simulate given critical situations. At the stage of application of the control system, a DT similar in structure should collect information about real processes in the airport transport network and provide it to the control system.

Within the framework of this work, studies are carried out that are indispensable for the solution of the prospective problem of building an automatic control system for ground traffic at airports.

2. OBJECTIVES AND TASKS OF THE RESEARCH

In view of the fact that the above-formulated problem of building an automatic ground traffic control system at airports is in its initial stage of being solved, the following research objectives can be formulated:

1. To develop a methodology for using Digital Twin at the stages of creating and operating a ground movement control system at an airport, including the Digital Twin functions, as well as the content and form of information about traffic participants accumulated in it;
2. To identify the methods and tools of computer simulation that are most suitable for simulating given scenarios in the airport transport network and using simulation models in emulation mode in conjunction with the tested control programs.

In order to complete these objectives, the following tasks arise:

1. To review modern methods and systems that are used to control both transport systems at airports in general and ground movement processes in particular;
2. To consider new trends in the organization of transport processes at airports and prospects for improving the accuracy of systems for determining the location of mobile objects;
3. To evaluate the possibilities and practice of using various classes of software products for simulation modelling of transport processes at airports;
4. To study the practice of using simulation models in emulation mode and the prospects for using the Digital Twin concept for real-time process control;
5. To develop the Digital Twin structure and its application concept for the airfield traffic control system at an airport;
6. To substantiate the choice of the simulation modelling paradigm, which should be applied to simulate given situations in the airport transport network, and apply this paradigm when developing a universal computer program designed to simulate such situations;
7. To conduct computer experiments to simulate scenarios for the development of processes in the transport network of the airport, which lead to the need for the intervention of the centralized control system;
8. To save debugged scenarios by recording location and status data streams of moving objects in Digital Twin form, which can be used as a source of dynamic data when training and testing algorithms for centralized ground movement control at an airport.

3. OBJECT AND SUBJECT OF THE RESEARCH

As *the object* of this study, the processes in the ground transport network of the airport are postulated, where the movement of aircraft (AC) and ground vehicles (GV) takes place. On the other hand, *the subject* of research is computer simulation methods designed to simulate given scenarios and save streams of data on the location and state of moving objects in the form of Digital Twin (DT).

4. DEGREE OF THE THEME RESEARCH

In a broad sense, the theme research is related to the problem of building an automatic ground traffic control system at airports, which is defined in the document "Vision 2050" (IATA, 2011) as a promising task, for the solution of which no specific deadlines can be assigned. The Advanced-Surface Movement Guidance and Control System (A-SMGCS), which is used at various levels of development in dozens of airports around the world, can be considered as a starting point on the way to solving this problem (EUROCONTROL, 2020). However, the replacement of the human dispatcher with control programs remains only a theoretical concept (Augustyn and Znojek, 2015), for the implementation of which the first concrete steps described in this work are proposed.

In a narrow sense, the theme research is determined by the two goals formulated above, which are related to the concepts of *computer simulation*, *emulation* and *Digital Twin*. Currently, there are no works that are directly devoted to the use of these technologies to solve the problem of automating ground traffic control at airports, therefore, the degree of the theme research is considered in terms of the availability of these technologies to solve the tasks set out in the work.

In the field of *computer simulation* of dynamic processes, the paradigm concept is important, on the basis of which both the conceptual model of the research object and the executable computer program are built. In (Borshchev, 2013) three paradigms "continuous", "discrete event" and "agent based" are defined, which are considered to be classical today. However, the work shows that none of these paradigms can unambiguously describe the principle of modeling processes in the airport transport network, and an extended definition of the applied paradigm is given. Among the papers that consider the use of Airport Simulation Software, it should be noted (Bertino et al., 2011), (Kageyama and Nakamura, 2018), and (Sekine et al., 2021). An overview of packages from the Traffic Simulation Software group is offered in (Ejercito et al., 2017), and the experience of using these packages for modeling processes at airports is described in (Zhang, 2020), (Bandaru, 2017), (Tonguz, 2018), and (Pashkevich et al., 2021). Interesting from the point of view of this work, examples of applications of packages from the General-Purpose Simulation Software group are reported in (Scala et al., 2015), (Lopez et al., 2019), and (Tomasella et al., 2019).

Emulation as a way of applying simulation models is relatively rare in modelling practice. The essence of emulation is that the control object is replaced by a simulation model that interacts with real control programs. The work describes examples of emulation applications, which relate to the field of Automated Guided Vehicles (AGVs). These examples can be found in (Helleboogh et al., 2006), and (Rintanen and Thomas, 2021). An example of another application for the emulation mode is the Floating Car Data (FCD) concept for traffic management (Astarita et al., 2020).

It is generally accepted that the concept of *Digital Twin* (DT) was first formulated in (Grieves, 2005). The essence of DT should be a virtual copy of a real system or process, which leads a kind of “parallel life” in relation to the original. NASA experts (Glaessgen and Stargel, 2012) believe that the term DT can be used to refer to almost any complex simulation model of a real object that serves to represent its life cycle. In (Madni et al., 2019), provides a definition of four types of models that the authors associate with the concept of DT. The actual practice of applying the DT concept in aviation is reported in (Rolls-Royce_1 URL; Rolls-Royce_2 URL), and (TEST-FUCHS URL).

5. STATEMENT OF THE PROBLEM

Based on an extensive literature review and examination of airport practices, the problem can be stated as follows: the solution to the problem of automating ground traffic control at airports has not yet reached the project phase, but there is a need and a sufficient number of prerequisites for the implementation of research work in this area, the aim of which is to develop a Digital Twin application concept for the various phases of the life cycle of the control system to be built.

6. METHODOLOGY AND THE METHODS OF THE RESEARCH

In this study, the methodology of computer simulation and dynamic databases in the form of Digital Twin is used as the main one. Many of the concepts proposed in this work are based on broad engineering knowledge in the field of Positioning and Navigation, as well as the principles of managing all types of transport processes at airports. In the field of computer simulation, a special paradigm is used, which is most similar to the “continuous” paradigm. The prototype of a universal program for simulating scenarios in the airport transport network was created using the VBA programming language and is intended for use in the MS Excel environment. The source code of the program contains about 2300 lines.

7. SCIENTIFIC NOVELTY OF THE RESEARCH

The following results can be considered as a scientific novelty of the research:

1. A method for computer simulation of processes in a transport network has been developed, which implements two features that are absent in commercial simulation packages:
   - the behaviour of each movable object in the model can be specified in the form of an exact scenario;
   - a dual approach is used to represent the 2D space of the transport network, in which the position of objects is simultaneously determined by both continuous coordinates (x, y) and discrete coordinates of the cells of the grid-based space.

2. The Digital Twin structure was developed and tested experimentally, based on the simultaneous use and mutual conversion of two types of protocols: Event Protocol and State Protocol.
3. A methodology for the creation and use of Digital Twin at the stages of training, testing and operation of a centralized system for controlling the movement of objects in the transport network has been developed.

The concepts proposed and investigated in this work can be applied in the development of a process control system not only in the airport transport network, but also in any other in-house transport network, where the required performance and safety are provided by centralized control functions.

8. PRACTICAL VALUE AND IMPLEMENTATION OF THE RESEARCH

The following statements highlight the practical importance of the research:

1. The GTSS program developed by the author is universal, since it can be used to simulate processes in the transport network of any airport. The demo model described in the work was applied to simulate processes in a specific medium-sized airport.
2. The GTSS program allows describing and simulating scenarios for the development and elimination of critical situations in the airport transport network by capturing information coming from expert controller with practical experience in ground traffic control at the airport.
3. The scenarios implemented using the simulation model and accumulated in the Digital Twin can serve as an information base in the training procedures that will be carried out for the centralized ground traffic management system at the airport.
4. The formats of data accumulated in the developed Digital Twin can exactly correspond to the formats used in processing streams of data on the location of mobile objects, which come from real equipment located both on board the objects and as part of the aerodrome equipment.

9. APPROBATION OF THE RESEARCH

The preliminary results, inferences and findings of the research were presented at 5 scientific and research conferences in Latvia and Germany. The developments and findings made within this research were used in pedagogical practice at the Transport and Telecommunication Institute in form of case studies incorporated into subject “System modelling”.

10. STRUCTURE OF THE THESIS

The thesis consists of 5 chapters including the introduction and conclusions, as well as 2 appendices. It contains 135 pages, 52 figures, and 2 tables. The list of references contains 163 titles.

Chapter 1 begins with a brief description of the problem that this paper addresses and introduces a potential reader to the motivation behind the research.

In addition, the scope is specified, and relevance is highlighted along with novelty. The main research questions are stated, and tasks are formulated. At the end of the chapter, a definition of the subject and object of research is given, and these are formulated that are submitted for defense.

Chapter 2 provides an overview of the current state and prospects for improving the management of transport processes at airports. The chapter begins with a brief description of the types of transport processes, which include Aircraft Traffic, Airside Traffic, Passenger Flow, and Baggage Handling. Special attention is paid to the processes of ground movement of the vehicles and aircraft, which takes place in the Airside Area of the airport. Airport Collaborative Decision Making (A-CDM) is considered as a frequently used management system, which is a complex multi-level and multifunctional system that controls all the above-mentioned transport processes at the airport. The use of artificial intelligence technologies, unmanned vehicles, as well as Remote and Virtual Tower are considered as modern trends in the organization of transport processes. Since the very first problem of automation of traffic control in the airside area is to increase the accuracy of determining the coordinates of moving objects, part of the review is devoted to modern methods for solving this particular problem. The chapter concludes by looking at the principles of the Advanced-Surface Movement Guidance and Control System (A-SMGCS), which can be seen as a starting point towards solving the problem of fully automating ground movement control at airports.

Chapter 3 analyzes the practice of applying various methods and tools for simulation modelling of transport processes at airports. The ultimate goal of such an analysis is the choice of a method and tool with which it will be possible to solve the problem of modelling scenarios in the airport transport network in the most rational way. Particular attention is paid to the rather rare practice of using simulation models in emulation mode, but it is this mode that can be used to debug traffic control programs at a particular airport. The chapter offers a critical analysis of the interpretation options for the concept of Digital Twin (DT) and discusses the relationship of this concept with the techniques “real-time simulation” and “online simulation” that appeared more than 20 years ago. After analyzing the problems of modelling the spatial arrangement of objects, the decision on the choice of a paradigm and a software method for modelling scenarios in the airport transport network is substantiated.

Chapter 4 describes the experience of developing and using a software tool for modelling scenarios in the airport transport network. The first part of the chapter contains a description of the conceptual solutions, on the basis of which the universal simulation program GTSS was developed. The presentation of concepts begins with an explanation of how models created with this or a similar programme can be applied to the various stages of the development of an automatic control system. The following describes the general concept of using DT both at the development stage and during normal operation of the airport transport network control system. The advantages of discrete time and discrete space solutions that were implemented during the development of the GTSS program are described in detail. When creating a digital twin associated with the GTSS program, the concept of two types of protocols, Event Protocol and State Protocol, was implemented, the latter of which is a carrier of measurement information about objects such as AC and GV, which travelled in the network in accordance with specified scenarios. The second part of the chapter describes the process of developing and verifying a demonstration model of the transport network for a specific airport. The chapter ends with a detailed description of a simulation experiment, which shows the development and correction of a critical situation in the airport transport network.

The *conclusions* list the main results of the study and highlight the most important findings. It is shown that the statements put forward for defence have been confirmed. Finally, recommendations for further research are given.

11. STATEMENTS PUT FORWARD FOR DEFENSE

The following statements are put forward for defense:

1. The developed concept of the Digital Twin application, together with the simulation model, applies to all stages of the life cycle of an airport ground traffic control system. At the training stage, the control system can use the data on the decisions made by the controller, accumulated in the Digital Twin. During the testing phase, Digital Twin can offer the control system scenarios of typical critical situations in which it is necessary to make control decisions. During normal operation of the control system, Digital Twin performs the functions of converting and storing data on the location and status of objects that are traffic participants in the airport transport network.
2. When applying the concept of Digital Twin in the management of the airport transport system, the original meaning of this concept as a dynamic storage of data on processes in the airport transport network should be preserved. The interpretation functions of the data stored in the Digital Twin should be conceptually and programmatically separated from the Digital Twin itself, which creates conditions for the development of an unlimited number of applications using this data both for controlling processes in real time and for retrospective analysis or forecasting their development in the near future.

12. SUMMARY OF THESIS CHAPTERS

12.1. Transport processes at airports

Current state and problems

The main transport processes at the airport, which can be studied both separately and in interaction with each other, include the following: Aircraft Traffic, Airside Traffic, Passenger Flow, and Baggage Handling. Aircraft Traffic represents the movement of AC both within the Airspace of an airport and beyond. Airside Traffic represents all ground traffic within the Airside area of an airport intended for take-off, landing, taxiing, parking, and servicing of AC (aircraft, helicopters, and gliders). Passenger Flow is the movement and service of departing and arriving passengers in airport buildings. Baggage Handling refers to the handling of passenger baggage flows.

The main attention in this work is paid to transport processes that relate to Airside Traffic. Although the main facilities in the airside area are AC, the number of GV in the airside area at the same time is multiplied by the number of AC. GV carry out the ground handling of AC, airport infrastructure and security services. The main participants of Airside Traffic in addition to AC are Pushback tugs, Catering trucks, De-icing vehicles, Snowplowing, Sweeping and -blowing vehicles, Airstairs, “Follow me” cars, Apron or Shuttle buses, Belt loaders, Container loader and transporters, Water trucks, Lavatory-service vehicles, Refueling, Ground power units, Air start unit, Fire trucks etc.

Ground movement in the Airside area of the airport is performed by two types of vehicles: AC and GV. The main movement is carried out along the paths marked on the ground surface. Altogether, these paths form two transport networks that have intersection points. Some AC and GV movements over relatively short distances are carried out in free space without being bound to marked paths.

Nowadays, the direct control of vehicles in the airside area is carried out by AC pilots and GV drivers. Also, the general management of the transport process is carried out by controllers. All this means that the human factor has a strong influence on the processes in the airport transport system. The problem of ensuring safety, both in the air and on the ground, is one of the most important in aviation. Analysis of the causes of aviation accidents shows that in 5-15% of cases they are not identified, in 15-20% of cases they are associated with equipment failure, including as a result of external factors, and in 70-75% of cases – with a human factor. Reducing the influence of the human factor on processes at airports is the goal of many programs of international organizations working in the field of aviation.

Airport Collaborative Decision Making (A-CDM) is one of the airport optimization programs adopted and implemented by IATA, ICAO and Eurocontrol. A-CDM is a fundamentally new approach to the interaction of participants in the process of operating flights at an airport: the airport operator, airlines, ATC unit (Air Traffic Control), service companies, planning and coordination of the use of airspace and air traffic flow management bodies. The implementation of A-CDM allows each partner to optimize their solutions in cooperation with other partners participating in the program, taking into account their preferences and constraints, as well as the actual and projected situation.

It should be noted that the A-CDM is an information system that does not solve real-time AC or GV traffic control tasks. Although there are 347 airports in 46 European countries that are used by civil aviation, only 30 airports have implemented the A-CDM system.

New trends in the organization of transport processes at airports

Artificial intelligence technologies are designed to radically change the approach to organizing transport processes at the airport as a whole. For example, Assaia's ApronAI product that uses AI has already been deployed at 30 airports and 5 airlines. Assaia's ApronAI optimizes daily operations and helps employees to be more efficient by providing them with highly accurate and relevant data. Assaia's ApronAI consists of three products Turnaround Control, Safety Manager and Stand Manager, which generate and collect data, create alerts, facilitate decision support and provide process automation.

Assaia's ApronAI uses a video surveillance system as a source of information, and the system itself is built on the basis of several well-known technologies adapted for solving applied problems. Machine vision can recognise events occurring on the apron, and machine learning helps to answer "if-then" questions. Having accumulated a huge array of information about flight service processes, the system will be able to reliably predict the end time of a particular operation, instantly evaluating a large amount of incoming variable data. In turn, multidimensional optimization is faster and more efficient than a human to cope with solving certain problems.

The implementation of *unmanned vehicles* can be attributed to the current and promising trends in the development of transport processes at the airport. Such vehicles are equipped with an on-board computer with a system for influencing controls using data from various sensors. For AC, such sensors are heading (GPS), roll, pitch, altitude, speed sensors, other aircraft systems, and much more. For cars, such sensors are video cameras, LIDAR sensors, radars, and GPS. It is envisioned that unmanned vehicles at the airport will first be used to scare off birds or cargo transportation. In the future, they can also be used to transport passengers in the landside area of the airport.

One of the areas of airport modernization is the implementation of the *Remote and Virtual Tower* (RVT). RVTs enable safe and cost-effective ATS (Air Traffic Service) to be implemented from a remote location close to one or more aerodromes in rural areas where dedicated local ATS systems are exhausted or not cost effective, but where aviation provides local economic and social benefits. These features can also be used to provide contingency services at medium to large airports. Thus, RVT technology is applicable for aerodromes with low flight intensity or as an emergency control system in case of emergencies (fire, destruction of a control tower, etc.). An airport camera takes a 360-degree image of the airport, which contains more detail than the human eye can detect. Each airport is connected to the Remote Tower Center via redundant networks. These networks are high speed networks that use both fiber cables and radio links.

Determining the spatial location of objects

Positioning is the process of determining the location of a particular object in relation to objects whose location is already known. Both *global* (GNSS) and *regional positioning* (RNSS) systems are based on the use of satellite technology.

In global positioning systems, coordinates, direction of movement and speed are determined using GPS and GLONASS systems, or satellites of other navigation systems (Galileo, BeiDou). The accuracy of determining the location of objects varies from 2 to 6 meters. If the positioning system uses signals from several orbital constellations, then the error does not exceed 2-3 meters. In the future, as technology develops, the accuracy is planned to be increased to several tens of centimeters. To ensure high accuracy of navigation, more advanced navigation systems are required than GNSS. For example, to improve the accuracy and possibilities of using GNSS as a means of landing AC, differential correction systems are used, which belong to the GNSS Augmentation group. Such a system is based on the integration of external and satellite data in the calculation process.

The main purpose of LPS (*Local Positioning Systems*) is to quickly position and monitor situations within strictly defined boundaries. Despite the widespread use of GNSS systems, the use of local positioning systems within an airport may be advisable in at least two cases. Firstly, it is the segmentation of the received signals from local and other systems, which allows more efficient control of the ongoing processes. Secondly, local positioning can be organized in places where other types of positioning cannot be available for a number of reasons (inaccessibility of GNSS signals, a large amount of interference, high density of objects, etc.). The set of technologies used for this type of positioning is quite wide: they can be used as wireless and radio-frequency technologies (Wi-Fi, Bluetooth, RFID, ZigBee, nanoLOC, UWB) and infrared, ultrasonic, optical, inertial, etc.

Ground traffic control based on A-SMGCS

ICAO and EUROCONTROL have defined the Advanced-Surface Movement Guidance and Control System (A-SMGCS) to ensure the safety and efficiency of ground movement in airport traffic areas (runways, taxiways, and apron areas). ICAO published the first A-SMGCS Regulation in 2004. The A-SMGCS provides observation and issuance of warnings about the movement of both AC and GV on the territory of the aerodrome. The A-SMGCS is applicable to any airport, to all types of AC and GV, and its implementation should be based on requirements arising from estimates of operational needs and costs, as well as individual benefits of a particular airport.

The A-SMGCS is a system that supports ground movement operations at an aerodrome in any weather conditions based on defined operating procedures. It consists of a surveillance service that provides location, identification and tracking of mobile objects, and may include a combination of other services as well. A-SMGCS improves access to those parts of the GV and AC manoeuvring zone that are hidden from the airfield control tower's view, creating the same opportunities for managing traffic objects regardless of their location on the aerodrome.

The *Surveillance Service* is a key and paramount element of the system, as it is the source of information for the rest of the A-SMGCS components and objects. The *Airport Safety Support Service* facilitates controlled area operations to improve safety by enabling controllers to prevent hazards or incidents resulting from operational errors or errors by the controller, crew or vehicle driver. The *Routing Service* generates a route for each facility based on known aerodrome parameters and restrictions or after interacting with the controller, and is the activator of the Guidance Service and some elements of the Airport Safety Support Service. The *Guidance Service* is a service that improves the movement of objects in the movement area by the means of visual aids in conjunction with the Routing Services and Surveillance Service, and clearances issued by the controller.

Although the role of the controller remains the leading one in the A-SMGCS, this system can be considered as a starting point on the way to solving the problem of fully automating ground movement control at airports. The essence of such a solution is to transfer all the functions of the A-SMGCS controller to the appropriate computer programs.

12.2. Methods and tools for modeling and emulation of transport processes at airports

The main practical goal of this work is to build a simulation model that can be used as a tool for training and testing software for centralized ground movement control systems at airports. The result of this chapter is a decision on how to build such a model, but this decision is based on studying a large number of examples of using various methods and tools for building models that have at least some common properties with the model being designed in this work.

Application of various classes of software products for simulation of transport processes at airports

In order to justify the choice of tool for solving the airport transport simulation problem, the work considers the experience of model building using software products belonging to four classes:

- Airport Simulation Software (e.g., TAAM, SIMMOD, AirTOp and CAST);
- Road Traffic Simulation Software (e.g., VISSIM, SUMO and Aimsun);
- General-Purpose Simulation Software (e.g., AnyLogic and Simio);
- General-Purpose Programming Languages (e.g., C#, C++, Java, JavaScript, Python, and Visual Basic).

The best known products in the *Airport Simulation Software* group include TAAM, SIMMOD, AirTOp and CAST packages. The TAAM, SIMMOD and AirTOp packages are focused on the AC motion processes, while the GV motion processes are modelled almost automatically. There is a special CAST Vehicle Ground Handling module only in the CAST package, which makes it possible to set the GV movement control strategies. The choice of specific strategies is made by specifying special input parameters of the model.

It should be noted that all these packages are expensive commercial products, and they are relatively rarely used for solving research problems. Additional difficulties for researchers arise due to the fact that the source code of such packages is closed and there is no possibility for flexible changes in the rules of behaviour of individual participants in ground movement. Most often, such packages are used in large projects developed for specific airports. Due to the factors noted above, publications related to the use of products from the airport simulation software group are quite rare.

Packages from the *Road Traffic Simulation Software* group allow a high degree of adequacy to simulate the processes in traffic systems. It is generally accepted that each model can be attributed to the class of micro-, meso-, or macromodels. In the context of this work, only micromodels are of interest, in which the movement of each individual vehicle or pedestrian is displayed. There are many commercial packages and programs in the public domain that belong to the Traffic Simulation Software group, but in one of the latest reviews of this group, the Vissim, SUMO and Aimsun packages are noted as the most advanced.

Authors of some publications criticize the package manufacturers from the Traffic Simulation group, which, with a focus on airports, created support tools only for simulating passenger flows at terminals.

The following packages from the *General-Purpose Simulation Software* group are most often used for modeling transport, manufacturing and logistics systems: AnyLogic, Arena, AutoMod, Delmia Quest, Enterprise Dynamics, ExtendSim, Flexsim, GPSS, Plant Simulation, ProModel, Simio, Simul8 and Witness. Most of these packages support the "discrete event" paradigm, but some of them allow the simulation of continuous processes based on the Δt principle.

The paper considers 25 scientific publications in which packages from this group are used to simulate transport processes at airports. Most of the models are simple queuing systems that handle the flow of passengers in the terminal building or the flow of AC ready to take off. There are no examples in which moving objects (passengers or AC) act on the basis of individual scenarios.

General-Purpose Programming Languages are used to designate simulation models for airport processes when none of the commercial packages from the three groups described above are used. Authors often do not indicate the specific programming language used, since this aspect of the model development process is clearly secondary. An important fact is that for solving many research problems, specialists develop models based on their own program code. The main advantage of such models is the absence of restrictions both with respect to the logic of the development of the modeled processes and with respect to the input and output data of the model.

Application of simulation models in emulation mode for debugging control software

The essence of emulation is that the control object is replaced by a simulation model that interacts with real control programs. The model includes a sensor part, from where signals are sent from various "sensors and counters" corresponding to the devices of the real system. Control programs process these signals and generate control commands that are perceived by the executive part of the model. The model responds adequately to control commands, that is, the same changes and events occur in it as should occur in a real system.

Fig. 1 shows two ways to use emulation, one for debugging programs in the Programmable Logic Controller (PLC) and the other in the Materialfow Controller. Virtual Conveyors module is a simulation model running in emulation mode.

Most often, the simulation model is processed on a separate computer, which must be hardwired to the computer on which the control programs are installed. The main effect of the use of emulation is that the time for debugging and commissioning complex control programs is significantly reduced. A large economic effect is achieved, for example, in the case of using emulation when commissioning a management system for a large, automated warehouse (Fig. 1).

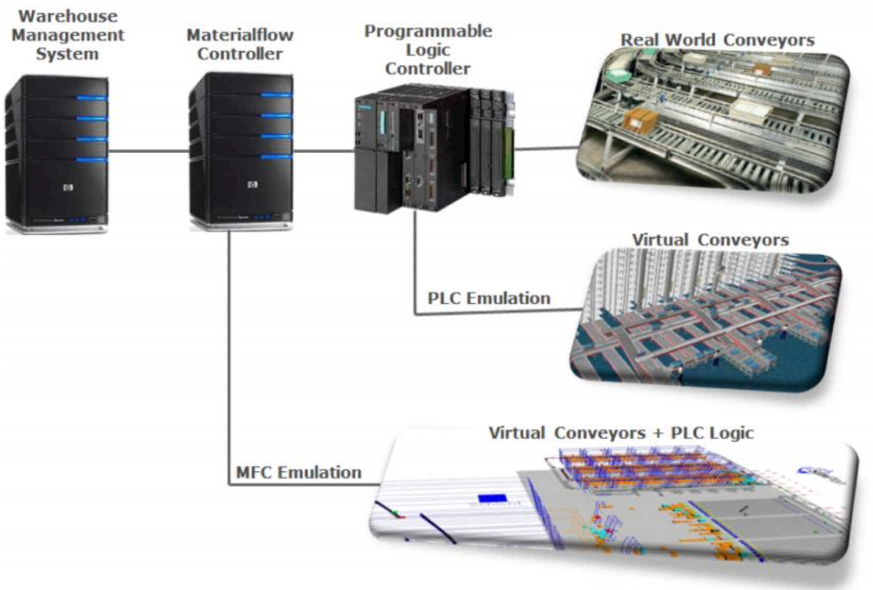


Fig. 1. Schema of different emulation approaches (Spieckermann et al., 2012)

Since there is practically no information on the application of this method in the field of aviation, the paper looks at examples of testing programs for centralized control of transport processes in areas where there is already a useful experience in solving such problems. The first group of examples relates to the field of Automated Guided Vehicles (AGVs), and the second to the use of the Floating Car Data (FCD) concept for road traffic control.

Digital Twin as a result of the development of the Online Simulation concept

The first ideas for the implementation of Digital Twin (DT) were associated with virtual modeling of purely technical objects, for example, from a single ship engine to the scale of the entire technical support of the ship. The main feature of the DT was its direct connection with the physical system, which was carried out through one-way data transmission from numerous sensors installed in the system. The main function of DT was to store data about the current state of the system, which could be used, for example, to predict failures of specific system nodes.

The DT concept begins with the acquisition of real-time data from a physical object. Any digital models that do not work in this mode are not related to the DT, but if they are connected to an object, they become part of the DT.

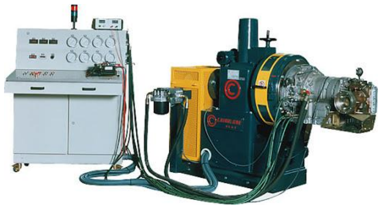
Typical applications for DT are as follows (Fig. 2a):

– the operation of the facility in normal operation mode;
– the operation of the facility on the test bench.

The term DT is often misapplied to models of the following type (Fig. 2b):

– conventional mathematical models and Finite Element Method;
– conventional discrete event or continuous simulation models;
– CAD models including dynamic 3D models and models for virtual tests.

a)



b)

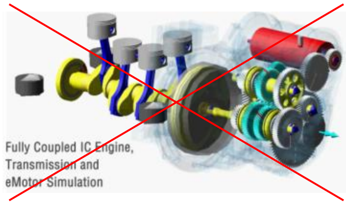


Fig. 2. True and fake Digital Twins

Rolls-Royce is developing virtual replicas of aircraft engines under a concept called IntelligentEngine. This concept assumes that the engine collects complete information about its condition and has continuous two-way communication with the service system. Rolls-Royce has built the Testbed 80, which assembles the world's largest aircraft engine, the UltraFan. Each fan blade of this engine has a digital twin that stores data about all tests performed. The TEST-FUCHS company has developed a broad application program for the DT concept in all areas of aircraft design, manufacture, testing and operation.

Numerous statements by specialists concerning the prospects of applying the DT concept for monitoring and controlling processes at airports are beginning to appear. It should be emphasized that such statements refer exactly to the prospects, as there are no ready-made comprehensive solutions yet.

It should be noted that long before the appearance of the term “digital twin”, “real-time simulation” and “online simulation” techniques were used in the field of simulation modelling, in which the simulation model exchanges data with a real physical object.

The fully developed idea of using online simulation to predict and eliminate dangerous situations is illustrated in Fig. 3. The term “Cycle” refers to the step Δt, which in this system was equal to 5 minutes. During this time, information is updated in the four drives shown in Fig. 3. The concept shown here emerged during the development of a project to build an early warning system to control passenger flows at a major airport in Germany, so communication with existing airport information systems was used to update the information in the accumulators.

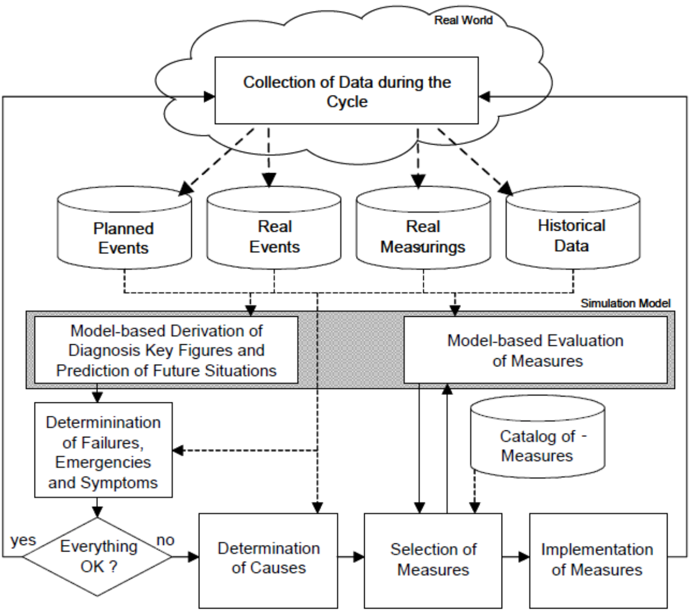


Fig. 3. Online simulation based Decision Support System (Hanisch et al., 2003)

The online simulation-based system considered above deserves special attention, since in fact it is an example of a DT, which not only collects information from a real object, but also implements the use of this information to regularly run a simulation model. Moreover, the simulation results are applied to control the object using DSS. This example once again shows the feasibility of separating the functions of the "real" DT from the functions associated with the use of the data it provides. In fact, the "real" DT in the considered system is what is shown in the upper part of Fig. 3, that is, the "Collection of Data" block and four types of accumulators, which together form a dynamic database.

Stating of requirements for the model of transport processes at the airport and the choice of a modelling method

The task of choice and correctly denoting the *modelling paradigm* is far from trivial. After the work of G. W. F. Hegel "Science of Logic" (German: "Wissenschaft der Logik"), which was published between 1812 and 1816, almost no one wrote serious papers about the very concept of "discrete quantity" or about the inextricable connection between the concepts of "discrete quantity" and "continuous value". Many authors and practitioners believe that "discrete event" modelling has this name because the events in the model occur at "discrete time moments". In models of the "discrete event" type, events most often can occur at any moment in time, and therefore such a time should be called continuous, since no precisely defined values are predetermined for it. Of course, discrete event models can also use discrete time, when its values are calculated using a given step "delta T". In this case, it would be correct to say that the events in the model occur at "moments of discrete time".

The behaviour of the variables t (model time) and S (state variable) should be clearly defined for each model. Both variables can be either continuous or discrete. As a result, four basic combinations are formed (Fig. 4). In the case of continuous time, the t axis shows only random times t1, t2, etc., when events occur in the model. In the case of discrete time, all time stamps are shown in "delta T" steps. An indication that the variable S is discrete is the marks on the coordinate axis S(t). In their absence, the variable S is continuous, that is, it can take any unlimited values.

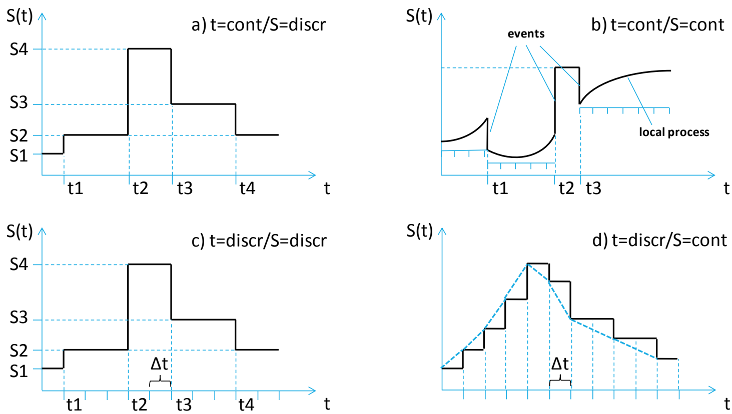


Fig. 4. Four types of processes based on a combination of "time/state" features

In the *created model*, it will be necessary to frequently repeat the calculation of the instantaneous velocity and coordinates (x, y) of moving objects to demonstrate their continuous movement in the form of 2D animation, that is, to use discrete time with a small value of "delta T". The need for such a solution is also associated with the fact that in the future a real automatic controller will have to receive information about the current state of all traffic participants also several times per second. Thus, in relation to the time of the model, the decision is made: *t is discrete*. Since the coordinates (x, y) of moving objects will most often be displayed as state variables, the decision is made with respect to the state variable S: *S is continuous*.

The space with continuous coordinates (x, y) can additionally be divided into cells with coordinates [i, j], where i and j are row and column numbers, respectively. For example, in MS Excel worksheets, the x direction is the j direction, and the y direction is the i direction. If the dimensions are assigned to a cell, e.g. 2x2 meters, then the following transformation of coordinates is trivial: (10.7; 15.3) → [8; 6]. Since for each point with coordinates (x, y) the coordinates of the cell [i, j], in which it is located, are known, many tasks of controlling the movement of objects can be reduced to checking the belonging of the points of the object to the corresponding cells. For example, two polygons are not in a state of intersection if they have no common cell.

The considered examples of modelling, which have at least some properties that are like the properties of the formulated problem of modelling transport processes on the airfield, indicate that such problems can be solved only with the help of *General-Purpose Programming Languages*. All types of commercial simulation software considered in this chapter, for various reasons, do not provide the conditions for the implementation of all the formulated requirements for the model. The following describes fundamental solutions for modelling the movement of objects with a focus on the use of General-Purpose Programming Languages.

1. Moving objects and obstacles are in 2D space, which uses both continuous coordinates (x, y) and cell coordinates [i, j].
2. Each moving or stationary object is described using a convex polygon, the points of which can be located in several cells of discrete space.
3. One of the points of the moving object is declared as a reference. The current position of the object is determined by the coordinates of the reference point (x_{ref}, y_{ref}) and the rotation angle α relative to the north direction.
4. It is agreed that there are eight discrete directions of orientation of moving objects, i. e. $\alpha \in \{N, NE, E, SE, S, SW, W, NW\}$.
5. For each class of movable objects, eight graphic models are created that display the location of the occupied cells at the specified coordinates (x_{ref}, y_{ref}) and rotation angle α (Fig. 5).

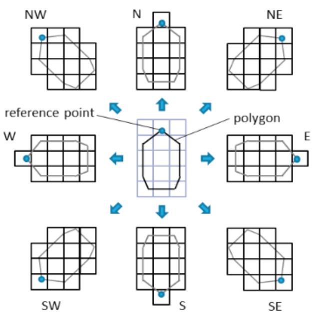


Fig. 5. Eight graphic models of a moving object

6. The real trajectory of the R_{real} object is replaced with a sequence of cells according to Bresenham's line algorithm. The simulated path R_{sim} passes through

the center points of the cells that this path is composed of (Fig. 6). At any time, the reference point p_{ref} can be at any point on the path R_{sim}, depending on the distance traveled, and its position is determined by continuous coordinates (x, y).

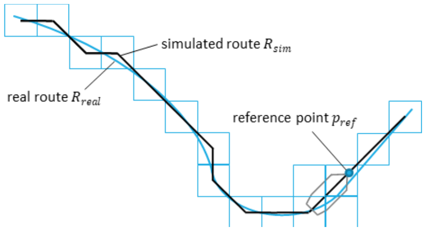


Fig. 6. The replacement of real route with a sequence of cells

All the above-described features of the simulation model of processes in the airport transport network can be implemented using the VBA programming language in the MS Excel environment.

12.3. Digital Twin application concept development and scenario simulation in the airport transport network

Ways to use simulation model and DT together

Fig. 7 shows the four stages of the software development process for a centralized ground traffic control system at an airport.

At the *data collection* stage, the user creates typical scenarios for the emergence of critical situations in the airport transport network, enters scenario descriptions into the model and, using animation, and observes their implementation. Debugged scenarios are recorded in the DT in the form of state protocols of the traffic participants. At the stage of *data validation*, the ability of the model to reproduce a given process in the transport network of the airport is used not only based on a scenario, but also on the basis of a protocol of states of traffic participants. Each protocol is processed by a model, and the user has the ability to check the correctness of the reproduced process using animation. At the stage of *system training*, the user acts as a teacher and interacts with the control program by transferring expert information to it. If the CS→SM→DT→CS system becomes closed, then the model and the control system interact in emulation mode. At the *system application* stage, the control program is connected to the real transport network of the airport. Data comes from the measuring equipment in the form of an unsynchronized event protocol, which is called measurements data in Fig. 7d. This event protocol is converted into a state protocol by means of DT and is fed to the input of the control system.

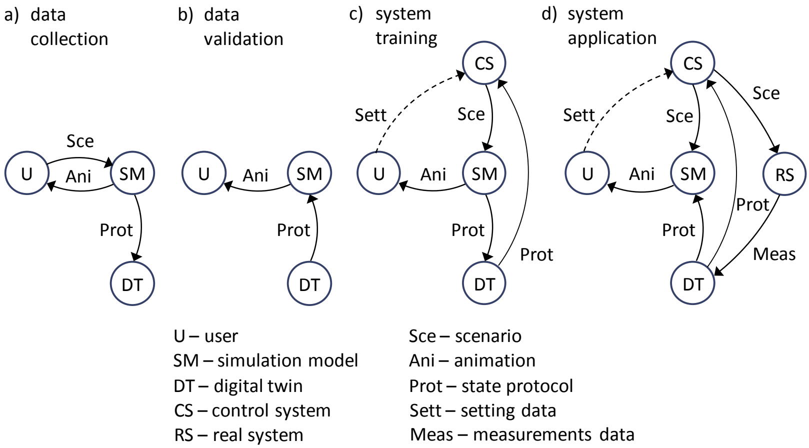


Fig. 7. Applying of the simulation model and the Digital Twin at various stages of development of the automatic control system

The concept of applying DT in the management of the airport transport system

Fig. 8 explains the basic concept of using DT in a centralized airport ground traffic control system. The main function of DT is to collect and accumulate data on the location and state of mobile objects (GV and AC), as well as provide this data to operators or software applications in a form that allows solving the problems of monitoring and analyzing processes in the airport transport system. Each message received from an object is recorded in the DT as a data record. At the beginning of such a message, there is a time stamp, followed by data on the location and status of the object. While messages from objects can arrive at any time, DT generates data for applications tied to discrete time with a given Δt step. The minimum step size Δt is determined by the speed of the data collection and processing system.

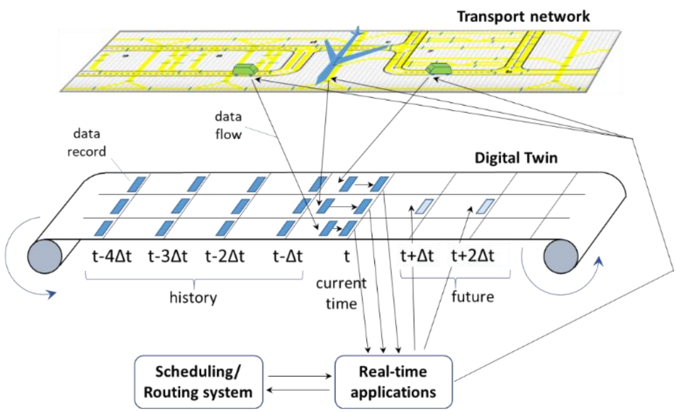


Fig. 8. The concept of applying DT for control of objects in the transport network

In Fig. 8, the DT is shown in the form of a dynamic database, which stores data that is related to three time periods: history, current time, and future. Data records in the future area can appear in cases where real-time applications include means of short-term forecasting of the behaviour of individual objects. Fig. 8 shows an example in which messages are received from one AC type object and two GV type objects. Each object has its own "track" for data records. For the current step Δt, it is shown how messages are received in asynchronous mode, but then by means of DT they are brought to time t.

The concept of construction and properties of the GTSS program

The GTSS (Ground Traffic Scenario Simulation) program was created in the form of a special laboratory, in which the researcher gets the maximum amount of freedom to experiment with the model of the transport network of a particular airport that he created. The GTSS program is written in the VBA programming language and is intended for use in the MS Excel environment. The main advantage of this solution is the perfect availability of all kinds of data: model input data, current state parameters of all model elements and simulation results. GTSS implements a continuous animation of the object movement processes in 2D space. The left part of Fig. 9 shows a fragment of the model created using the GTSS program, and the right part explains the possible ways of exchanging information between the model and its external environment.

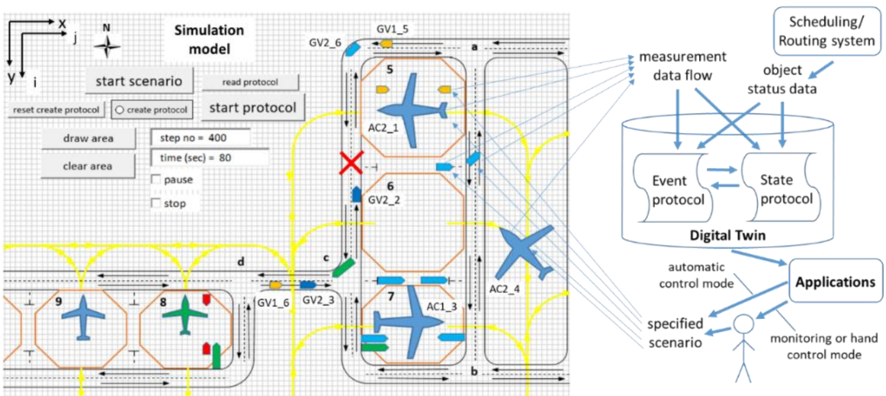


Fig. 9. Ways of applying a model created with the GTSS program

Fig. 9 illustrates the two main modes of applying the simulation model. In "hand control" mode, the model user manually describes the movement scenario of a specific AC or GV. As this scenario implementation result, a planned critical situation arises in the model, which requires the intervention of centralized management. In the absence of a tested automatic traffic control program in the Applications block, the user of the model takes the role of the ground movement controller. He develops and introduces into the model a new scenario that describes the behaviour of traffic participants after the moment of making control decisions.

In the “automatic control” mode, the required initial scenario is also specified by the model user, but the scenario of behaviour of traffic participants after a critical situation occurs is determined by the tested control program. It is this mode of application of the simulation model that is the emulation.

The primary data obtained from means of measuring the location of objects within the framework of this study is called the Event Protocol, and the data tied to discrete time is called the State Protocol. The analysis of the relative position of objects in the apron zone can be performed only for certain points in time. This means that the coordinates (x, y) of each object must correspond to the time moment t, for which the corresponding calculations are performed. Thus, the State Protocol is the main component of the DT applied in the real control system. For the same reason, the State Protocol is the main output of the model made with the GTSS program. Fig. 10 shows an example of a State Protocol that the GTSS program saves as a text file.

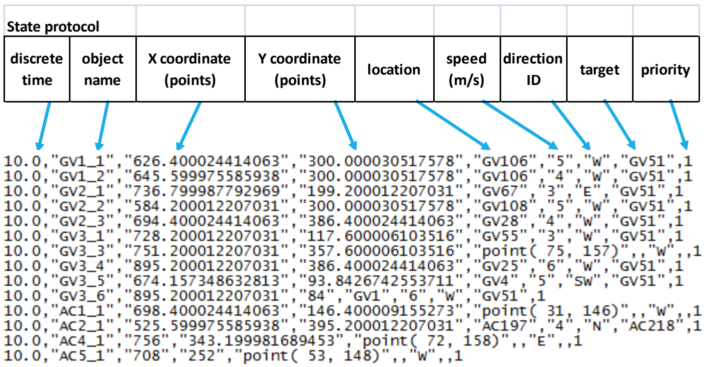


Fig. 10. Fragment of a real State Protocol file

Modelling critical situations

GTSS has tools that allow the user to describe in detail the behaviour of each vehicle, both before the critical situation occurs (primary process) and during the commands received from the controller (secondary process).

Fig. 11a illustrates a simple example of a decision-making situation when the object GV2_2 is moving at a very low speed due to engine failure. As a result of this, an accumulation of GVs was formed, which follow it. Objects GV2_1, GV2_4, GV1_3 and GV3_2 cannot overtake object GV2_2, because it is forbidden to drive in the oncoming lane.

The controller prohibits entering the network section between intersections *a* and *c* from the east direction (see the red line “stop” in Fig. 11b). Objects GV2_1, GV2_4, GV1_3 and GV3_2 are allowed to enter the oncoming lane, overtake object GV2_2 and return to the right lane before the intersection *a*.

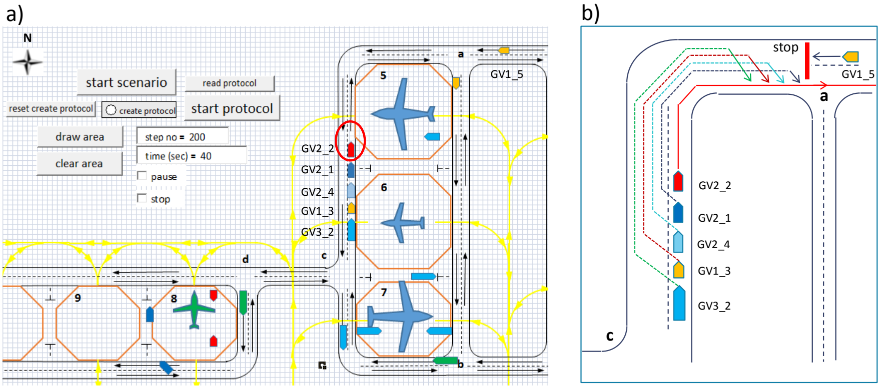


Fig. 11. Making decisions about changing the routes of objects in the event of a critical situation

The procedure for using the GTSS program for modelling and analyzing a specific decision-making situation, as well as it's further processing in order to train the control system, includes the following points:

1. Drawing up a verbal description of the chosen decision-making situation.
2. Getting an animated picture of the primary process of forming the required situation.
3. Development of control commands and observation of the animation picture of the secondary process.
4. Analysis of the characteristics of the secondary process. In case of negative or insufficiently positive development of the secondary process, changes are made to it by repeating paragraph 3.
5. Fixing (recording) of the finished scenario in the DT in the form of a State Protocol.

The model user observes the process in the transport network using computer animation and stops the model at the moment when decisions need to be made and commands need to be sent to the traffic participants. The entire simulated process of the emergence and elimination of a critical situation is recorded in the form of an external file, which is a DT component.

13. CONCLUSIONS

Summarizing the most significant results of the research, the following conclusions can be drawn:

1. The prerequisites for solving the problem of automatic control of ground traffic are progress in the field of Artificial Intelligence and Unmanned Vehicles. A precondition for the use of such technologies is to improve the accuracy of determining the coordinates of moving objects in Positioning and Navigation Systems. The work provides examples of ideas and developments that should provide a solution to this problem in the near future.
2. To date, the most advanced automated control of ground traffic functions are part of the Advanced-Surface Movement Guidance and Control System (A-SMGCS), but the controller's role is still the leading one in such a system. A-SMGCS can be seen as a starting point towards solving the problem of fully automated ground traffic control at airports.
3. After considering about 60 examples of the development of simulation models of transport processes at airports, it follows that the most effective tools for the study of control algorithms for such processes are created by using general-purpose programming languages. It is these tools that provide enough degrees of freedom for the modeller and allow him to plan and conduct any experiments aimed at developing and testing control algorithms of ground traffic at airports.
4. The main function of the Digital Twin in the management of the transport system in an airport should be to collect and store data on the location and condition of traffic participants. Digital Twin must perform preliminary processing of data arriving in asynchronous mode, and in the form of a synchronized protocol provide this data to the automatic control system. The presentation of data in the form of State Protocol creates conditions for the development of a large number of applications that can use this data both for controlling processes in real time and for retrospective analysis or forecasting their development in the near future.
5. The developed methodology of simulation modelling of processes in the airport transport network, based on a discrete representation of both time and space, was experimentally tested during the development and application of the GTSS program. The methodology is effective since it makes it possible to simplify the solution of the problems of analyzing the relative position of moving objects while maintaining sufficient accuracy in displaying their location in the airfield space.
6. The developed methods for describing and modelling scenarios for the emergence and elimination of critical situations in the airport transport network make it possible to fully take into account the experience of expert controllers and save the scenarios modelling protocols in a form

focused on their application at the training stages of the automatic control system.

As the best option for the application and development of the results of this study, the emergence of a project is seen, within the framework of which the idea of training and testing the ground movement control system at a specific airport would be brought to the practical implementation. The first stage of such a project should be the solution of the problem of automatic identification of prerequisites or ready-made facts of the emergence of various kinds of critical situations. At the second stage, it is necessary to make the control system to determine traffic movement participants who can be affected by a critical situation and to whom personal control commands should be sent. Finally, at the third stage, the control system must learn to automatically generate such control commands. It is quite clear that in solving these problems, the main role will belong to the methods of artificial intelligence and machine learning.

Although the GTSS program demonstrates how to solve many fundamental problems of data generation intended for training a control system, it is only a laboratory prototype, as it works in the MS Excel environment. The main weak point of the program is the speed of its processing on a computer, which may turn out to be insufficient when simulating a large number of critical scenarios typical for a particular airport. It is recommended to create a new version of the GTSS program using the "fastest" programming language, C++. At the same time, of course, the methodology for modelling processes in the transport network implemented in the first version of the program and the tabular method of entering a large amount of data required to describe user-defined scenarios will remain.

PUBLICATIONS WITH AUTHOR'S PARTICIPATION

1. Saifutdinov, F., Tolujew, J. (2019) Transport Processes in Airports – Current Status and Problems. In: Proceedings of 12th International Doctoral Student Workshop on Logistics, June 6, 2019, Magdeburg, Germany, pp. 131-135. ISBN 978-3-944722-83-2
2. Saifutdinov, F., Tolujevs, J. (2020) Analysis of Navigation Systems for Landside Transport Processes Control. In: Reliability and Statistics in Transportation and Communication. Lecture Notes in Network and Systems 117, Springer, pp. 552-561. doi.org/10.1007/978-3-030-44610-9 (Scopus)
3. Saifutdinov, F., Tolujevs, J. (2020) A Model for Ground Transportation Systems Simulation at Airports under Centralized Control. In: ECMS 2020 Proceedings. European Council for Modeling and Simulation, pp. 5-10. doi.org/10.7148/2020-0005 (Scopus)
4. Saifutdinov, F., Jackson, I., Tolujevs, J., Zmanovska, T. (2020) Digital Twin as a Decision Support Tool for Airport Traffic Control. In: 61st International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS 2020), Piscataway: IEEE, pp. 1-5. doi: 10.1109/ITMS51158.2020.9259294 (Scopus)
5. Saifutdinov, F., Jackson, I., Tolujevs, J. (2020) Modelling Data Streams of Object Positioning in Airport Ground Transportation Systems. In: International Scientific and Practical Conference "Rīgas Aviācijas Forums", Riga: Dienasbizness, pp. 40-43. ISSN 2661-5738
6. Saifutdinov, F., Jackson, I., Tolujevs, J. (2021) Scenario Modeling in a Centralized Airport Ground Traffic Control System. In: Reliability and Statistics in Transportation and Communication. RelStat 2020. Lecture Notes in Networks and Systems, vol 195. Springer, Cham, pp. 184-193. https://doi.org/10.1007/978-3-030-68476-1_17 (Scopus)
7. Saifutdinov, F., Tolujevs, J. (2021) Time and Space Discretization in the Digital Twin of the Airport Transport Network. Transport and Telecommunication Journal, vol.22, no.3, 2021, pp. 257-265. https://doi.org/10.2478/ttj-2021-0019 (Scopus)
8. Saifutdinov, F., Jackson, I., Tolujevs, J. (2022) An Emulation Oriented Method and Tool for Test of Ground Traffic Control Systems at Airports. Aviation, Vol. 3, 2022. (paper accepted for publication) (Scopus)