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Multi-agentní simulace letového provozu a jeho řízení

Multi-agent model of air-traffic and its control

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Summary

The work presents scalable simulation of air-traffic and its control based on application of multi-agent approach. The multi-agent model of air-traffic domain is composed of agents representing human actors and system components acting in this domain. The first group of agents represents airplanes and their pilots who have influence to the studied characteristics of the whole air-traffic system. The second group of agents represents air-traffic controllers and their systems which they use. These agents precisely emulate behavior of human air-traffic controllers; integrate their workload model and key interactions with tools and systems used by them. Integrated workload model emulates a finite work human capacity with delayed execution of their actions and their influence to the whole air-traffic model. The proposed multi-agent model is actively used by U.S. Federal Aviation Administration (FAA) where the software system based on the proposed air-traffic model is used as an additional tool to precise but very expensive human-in-the-loop simulations. Moreover, this model enables to study influence of new concepts for air-traffic control propagating through the multiple sectors (butterfly effect) which is almost impossible to study within human-in-the-loop simulations restricted to limited number of involved sectors. The proposed model was verified and evaluated by third-party where parameters collected from multi-agent simulation were compared against ones measured during human-in-the-loop simulations with real air-traffic controllers working on those sectors.

Souhrn

Práce se zabývá problematikou škálovatelné simulace letového provozu a jeho řízení s použitím multi-agentního přístupu. Celý systém je složen z agentů reprezentujících přirozeně jednotlivé účastníky a systémy tohoto prostředí. Jedna část agentů reprezentuje letadla a chování pilotů, jež mají vliv na studium zkoumaných charakteristik celého systému. Druhá část agentů reprezentuje řídící letového provozu a jejich systémy. Tito agenti precizně emulují chování řídících, modelují také zátěžový model a klíčové interakce s podpůrnými systémy. Vnitřní zátěžový model emuluje omezenou kapacitu člověka se zpožďováním jednotlivých akcí a jejich dopadem na celý systém. Tento navržený multi-agentní model je aktivně využíván americkým úřadem pro civilní letectví (FAA) pro ověřování nových pokročilých konceptů řízení letového provozu a pomocných nástrojů, kde slouží jako doplněk k velmi precizním, ale také nákladným simulacím s lidmi. Navíc tento model přináší možnost studovat vlivy nových konceptů řízení propagujících se celým systémem (kaskádové efekty), jež nelze vůbec pozorovat v simulacích s lidmi omezených jen na několik málo sousedních sektorů. Vytvořený model byl verifikován třetí stranou, srovnáním parametrů získaných v multi-agentní simulaci a parametrů získaných během simulací se skutečnými řídícími pracujícími na stejných sektorech.

Klíčová slova

multi-agentní simulace; model řízení letového provozu; zátěžový model lidského operátora

Keywords

multi-agent simulation; air-traffic control model; human air-traffic controller workload model

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1. Introduction

Increasing air-traffic demand implies that new air-traffic management (ATM) concepts lowering controller loads, maintaining safety and increasing efficiency need to be designed and implemented. The capacity of ATM depends on many factors, such as availability of air-traffic controller (an air-traffic controller can handle only the limited number of airplanes), current or forecasted weather condition, availability of air-space and capacity of airport facilities. An issue occurs at peak hours when the current ATM system reaches its limits. To avoid the inefficiencies caused by the usage of holding patterns to keep airplanes from entering congested airspace, ground delay programs are applied nowadays so that airplanes have delayed the take-off beyond a flight's scheduled departure [1]. To handle increasing air-traffic, there is a need to modernize and automate ATM tools to help human controllers handle high amounts of traffic. Such new advanced functions would lower the cognitive load of controller, maintain safety (minimize near miss situations) and increase efficiency (optimize consumed energy and thus minimize pollution caused by growing traffic). The Next-Generation Air Transportation Systems (NextGEN) program [2] is designed to coordinate the evolution of ATM systems to satisfy future growth of air-traffic without losing efficiencies. Many interesting concepts are prepared in NextGEN, but before they can be implemented into daily usage they have to be rigorously tested.

The most precise tests and ATM studies are carried out within human-in-the-loop (HITL) simulations [3] where human interaction is integrated in the simulation model. HITL simulations in ATM are resource intensive requiring many people (human controllers, pilots and other ATM staff). Such simulations usually run in real-time and thus the test cases must be limited in duration and scope of studied airspace portion. It is not possible to simulate the whole airspace in HITL simulation as it requires integration of thousands of people providing ATM services into the simulation. New approaches have to be studied in large-scale area as minor local delays can potentially cascade into large regional congestion [4]. Thus, there is strong need for precise high-fidelity simulators where new concepts can be evaluated with comparison to current ATM procedures.

2. ATM Simulators

Beside the described agent-based model in this work, the Federal Aviation Administration uses several other ATM simulators. Usage of various different fast-time simulators helps to cross validate ATM study evaluations and allows the different simulation capabilities provided by those tools. The key distinction between presented agent-based model and these ATM simulators is the agent-based approach in designing high-fidelity models and interactions of human controllers and pilots. The proposed model can perform real-time and/or faster than real-time distributed large-scale airspace simulations.

The Airspace Concept Evaluation System (ACES) [5] is a non-real-time modeling and simulation environment developed by NASA Ames Research Center. The ACES prototype uses the distributed simulation approach called High Level Architecture (HLA). HLA is a set of processes, tools and middleware software developed to support plug-and-play assembly of independently developed models. Each component has internal rules and logic governing its behavior and interacting with others via messaging during decentralized runtime. Collected data are centrally post-processed after simulation.

The National Airspace System Performance Analysis Capability (NASPAC) [6] is an integrated set of computer modules designed to model the entire airspace system, the en-route structure and traffic flows, as a network of inter-related components, reflecting the effects of weather conditions, air-traffic control procedures, and air-carrier operating practices. NASPAC uses a mixture of intelligent error-checking, high processing speed, and fine-tuned control of simulation runs to accelerate assessments of airspace performance. The NASPAC simulation flies individual aircraft through daily itineraries and provides statistical reports on delays and observed flow rates.

The Reorganized ATC Mathematical Simulator Plus (RAMS Plus) [7] is a fast-time discrete-event simulation software package providing functionality for the study and analysis in ATM. The RAMS Plus package contains integrated editor and display tool, rapid data development, stochastic traffic generation, 4D flight profile calculation, sectorisation, conflict detection and rule-based resolution, airspace routing, free-flight and RVSM zones and reporting package.

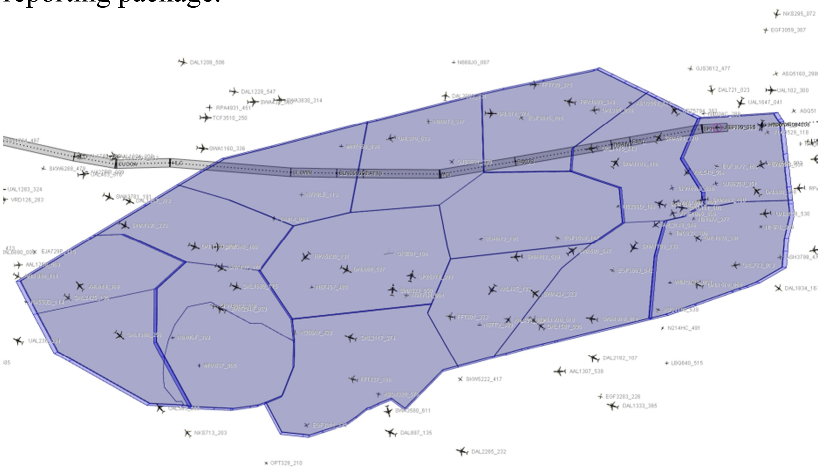

Figure 1: Agent-based ATM model of Kansas City air-traffic control center (ARTCC) showing one altitude.

3. Agent-Based ATM Model with Combined Time-Stepped and Event-Driven Simulation

In the proposed agent-based ATM model, pilots and air-traffic controllers are simulated as autonomous intelligent agents implemented as software agents in the multi-agent platform Aglobe [5]. The simulation state of the model is visualized using advanced visualization, see Figure 1. The model is composed from four different types of agents: (i) pilot agents, (ii) ATC agents, (iii) environmental simulation agents and (iv) scenario control and visualization agents. Each flight in the simulation is represented by one pilot agent. This agent represents a pilot flying a simulated airplane in simulated airspace based on performance models from Base of Aircraft Data (BADA) [9] maintained by Eurocontrol. The agent integrates all intelligent algorithms necessary for flying airplane like flight management system carrying out flight. The pilot agent operates its radio and interacts with ATM service through the sector radio communication channel. The pilot agent is responsible for confirmation and implementation of provided control clearances.

The ATC agent represents a human controller providing ATM service in the sector for which it is fully responsible. The ATC agents emulate interactions with available ATM tools and provide control to pilot agents via simulated sector radio links.

Environment simulation agents are responsible for the simulation of the virtual world in which airplanes are operated. They provide simulation of physical behaviors of airplanes (movement, fuel burns), define airspace constraints and integrate atmospheric model (weather condition) influencing airplane movement. The simulation environment provides precise modeling of sector radio communication. The sector radio is a half-duplex medium where only one participant can transmit at a time and interferences could happen.

The multi-agent simulation combines two simulation approaches: (i) time-stepped and (ii) event-driven. The *time-stepped* simulation advances simulation time by predefined equally-sized time steps. The new states of the simulation are computed after each time step and each round of simulation begins with sensor computation and ends with gathered agents actions. A time-stepped approach is used for the simulation of the environment (movement of airplanes, weather, etc.). For example, U.S. en-route controllers use ATM displays which provide update of airplane positions every twelve seconds. In such case, the agent-based simulation is configured with the same time step. This doesn't mean that anything happening between two simulated time moments is lost; everything is computed analytically even if the time is advanced by 12 seconds. The time-stepped simulation can be executed in real-time, which is suitable for HITL simulations, or in faster than real-time execution.

All other activities in the model are operated as an *event-driven* simulation. Each event is scheduled with a timestamp and the simulation framework processes events in time order. Events scheduled for the same time-stamps are processed based on their mutual priorities. An agent processing an event can advance non-processed events scheduled within a given interval to later time. This can simulate the duration of processed action. By using events the simulation is deterministic and can integrate controlled randomness into the simulation through proper random seeds. It is possible to make simulation only time-stepped or purely event-driven.

For simulations consisting of many actor agents an effective distribution scheme maintains high simulation fidelity and maximum simulation speed (providing results as fast as possible). Each processor in a network of host computers manages the events from pilot agents and controller agents in geographically partitioned area. The partitioned area is dynamically changed based on the number of pilot agents in that area. Using such load-balanced approach, the model is able to simulate complete one day airspace operation consisting of over 50,000 flights within less than 1 hour [10].

4. Model of Human ATC Controller

The current version of the multi-agent model of air-traffic contains precise modeling of radar controller (also called as R-side) operating an en-route air-traffic sector. Airspace is logically divided into sectors that provide air navigation services for flights within a particular volume of assigned airspace. A sector is a three-dimensional volume of airspace with defined boundaries and radio coverage for communication with airplanes. Each sector is covered by primary or secondary radar. Each radar controller has own radar display system providing current information about flights in his sector and surrounding area. The radar display system is a computer system which displays the sector map, airplanes positions linked with textual information containing key flight data (flight ID, altitude and ground speed) and provides access to the electronic flight strips.

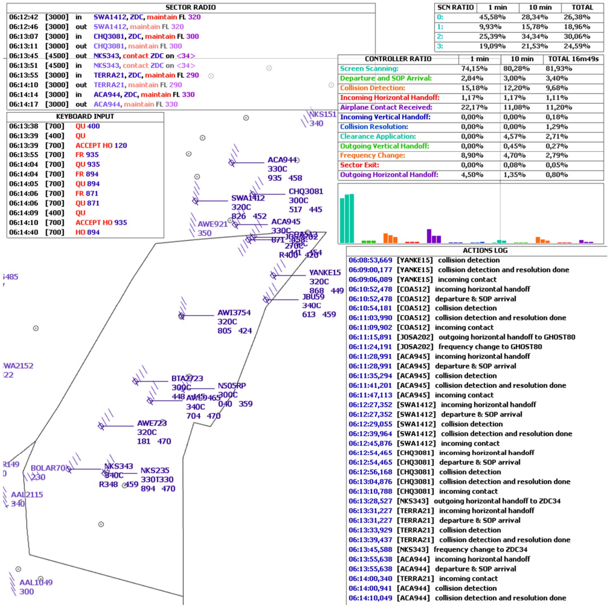

Figure 2: Modeled radar display and radar agent actions in a sector.

The radar controller monitors an en-route sector using his radar display. All duties performed by a controller are based on the situation awareness gathered from the radar screen or from communication with airplanes and other controllers. A controller is not able to work with precise airplane dynamic models as these are very complex and require information about internal state. Thus, all controllers' actions are based on the prediction built from the situation viewed on radar display. The agent-based model uses the same approach and uses its own display system for updating its situation awareness model, see Figure 2.

The radar controller agent model supports all key duties: (i) scan, monitor and analyze; (ii) handoff; (iii) standard operating procedures; and (iv) resolve predicted future conflicts. During *scanning*, the agent monitors its radar display to update its situation awareness. The model simulates complexity of the screen and thus controller is not able to notice new information immediately. Observed information is *analyzed* and based on the situation other tasks are initiated. *Handoff* is a procedure transferring airplanes horizontally or vertically to an adjacent sector. The model supports point-outs as well where usage of a part of other sector can be pre-negotiated with the respective controller. The *standard operating procedure* describes traffic flow restrictions including Letters of Agreement (LoA) among different ATM components.

During *conflict resolution*, the agent must find a suitable resolution maneuver for respective airplanes so that identified future separation issue is eliminated respecting required separation minima. Depending on the situation, the agent can resolve a conflict several ways: altitude change (climb/descent), vectoring (heading changes) and small speed adjustments. This is implemented as the search algorithm traversing state space of possible options and looking for an option based on selected optimization function.

5. Workload Model

The workload model is based on multiple resource theory (MRT) [11] which proposes to model a human operator with several different pools of resources. Depending on the task, resources may have to process information sequentially if the different tasks require the same pool of resource, or can process them in parallel if tasks require different ones. The performance decrement is viewed as a shortage of these different resources. Each human operator has limited capability for processing. Excess workload caused by a task using the same resource can result in slower task performance. The radar controller workload model uses four processing resources (VCAP model): (i) visual, (ii) cognitive, (iii) auditory and (iv) psychomotor. The *visual* and *auditory* components in the model are external stimuli that are attended to. The *cognitive* component describes the level of information processing required. The *psychomotor* component describes the physical actions required.

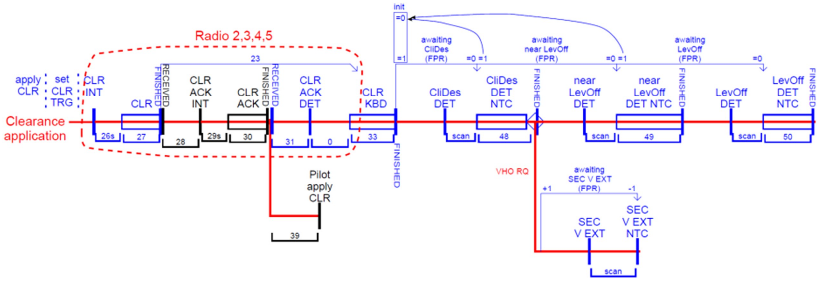

Figure 3: Modeled clearance application in work load model.

The radar controller duties described in the previous section are modeled as procedures consisting of actions organized into dependency chains, see Figure 3. Each particular action has defined which component from the VCAP model it requires, duration and priority. An action can be performed if its predecessor(s) are completed and the respective VCAP components are available. If multiple actions are ready for execution, the action with the higher priority is selected. Ready, but not selected, actions are automatically postponed until they can be processed. The duration of each action can be fixed or can use probabilistic model. Long-running procedures are decomposed in many actions with short duration. The procedure decomposition and processing is implemented using event-driven simulation described earlier.

The visual stimuli are connected to radar display model. The radar display is partitioned into several regions and the controller focus cycle among these regions. Time spent in the region depends on the number and complexity of performed visual stimuli in that region. The selection of the next region for focus is based on the priority model. The described model of radar controller perform cognitive actions only based on information from the available ATM tools and does not have access to the internal states and plans of other components in the system. For conflict detection and resolution, the agent builds an internal flight model for each flight which is updated based on the processed external stimuli, taken and planned control actions, see Figure 4. This mental flight model integrates controller predictions and uncertainainess. The controller procedures using the sector radio models precisely all situations including interferences. Each time before a radio transmission, the agent checks whether the channel is free for some short duration. All broadcast radio communication is followed by acknowledgement by the receiver thus a sender further secures transmission by timeout for acknowledge of the message. If there is no acknowledgement until timeout, the message is repeated again and application of desired action is delayed.

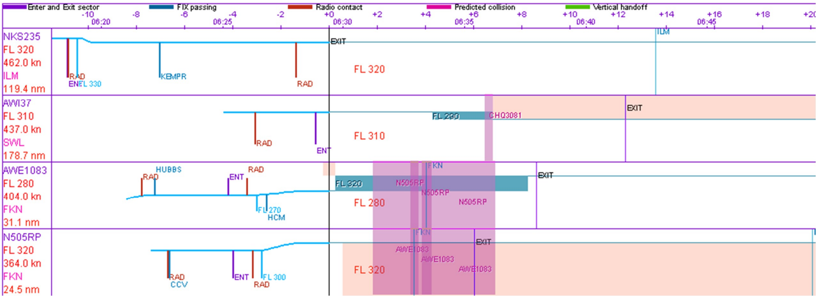

Figure 4: Mental information about flights used by the model.

The precise modeling of air-traffic controller procedures and their parameterization is based on many discussions with real air-traffic controllers in U.S. and other ATM experts from U.S. Federal Aviation Administration (FAA), studying their work while they were providing ATM services to airplanes. The parameterization of the model has been configured based on cooperation with the Human Factor laboratory in FAA where the largest human-in-the-loop simulations of air-traffic are performed.

6. Model Verification and Evaluation

The agent-based air-traffic model (implemented in AgentFly system) has been verified and evaluated [12] by TASC Inc., leader company having expertise in U.S. air-traffic services and methodology. The verification and evaluation was focused on two main goals: (i) verify the flight model based on top of BADA parameters and how well the system simulates real-world flight data; (ii) validate the accuracy of the agent-based model in predicting human controller behaviors in various traffic conditions. The flight model verification has been done by validation the model's ability to predict flight performance metrics under conditions of varying complexity comparing with real world data. On other hand, the validation of the accuracy of the agent-based model predicting human behaviors was based on comparison of output from agent-based simulation against results from a representative data source obtained from human-in-the-loop simulation running on the same sector and same air-traffic pattern. The key question for the validation was to provide an assessment of the theoretical soundness of the agent-based human air-traffic model.

First, there were selected human-in-the-loop scenarios consistent with agent-based model conditions. The selected 45 minutes high-traffic flight scenarios included multiple en-route sectors with ten air-traffic controllers. Radar controller workstations were equipped with a high-resolution radarscope, keyboard, trackball and sector radio. During HITL simulation there were recorded: (i) inter-computer communications, (ii) variety of system and human behaviors, and (iii) eye tracking data. The log from *inter-computer communication* contains airplanes' radar positions and handoffs information among sectors. *Human performance data* capture keyboard activity, on-screen activities and radio interaction between air-traffic controllers and pseudo-pilots. Pseudo-pilots are human operators controlling simulated airplanes and communicating with ATM services. Data contain complete set of actions performed by the participants and subjective workload obtained using the Air Traffic Workload Input Technique (ATWIT) where participants regularly press one of seven buttons to indicate instantaneous workload collected every 2 minutes. *Eye tracking data* are collected with an eye tracker consisting of infrared pupil capture and magnetic head tracking device. Such measurement provided eye movement recordings like fixations, saccades (short, coordinated, ballistic movements of eyes scanning the screen) and dwell time. For each fixation a timestamp, pixel coordinates and fixation target (onscreen object) was recorded. The same data were collected from the agent-based model running over the same scenario. The precise visual stimuli model described in the previous section was configured with hundreds of regions to be comparable with collected data. For the lack of space only few comparison metrics are presented here.

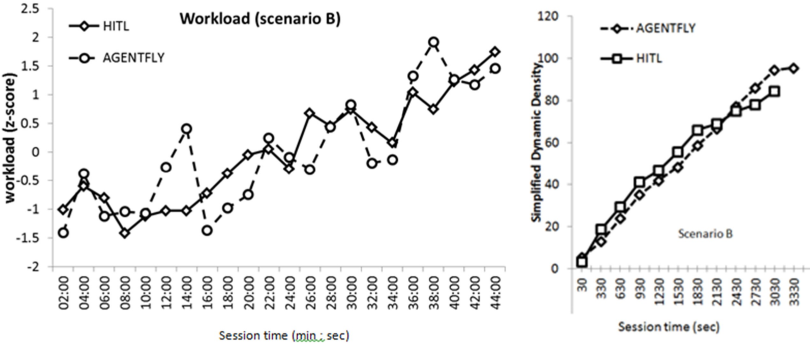

Figure 5: Workload (left) and Simplified Dynamic Density (right).

Figure 5 presents comparison from one of the scenario comparing human-in-the-loop simulation with the agent-based model. Left chart presents workload comparison using standardized outputs as z-scores to enable comparison. Results in all scenarios showed a significant correlation between collected results from HITL and simulated ones from agent-based simulation. Right chart presents metrics not based on subjective air-traffic controller workload measurement. Dynamic Density [13] is an accurate and robust indicator of a measure of control related workload that is a function of the number of aircraft in the complexity of traffic patterns in a volume of airspace. Simplified Dynamic Density consist of weighted sum of the following components: sector occupancy counts, proximities in a sector altitude transitions, transfers across sector boundaries, variance of sector headings in sector and variance of cruising aircraft speeds in sector. Parameter was sampled every 300 seconds and computed correlation show that measured simplified dynamic density on agent-based model perfectly correlate with values from HITL simulations.

One of the major sources of air-traffic controller activity is communication via sector radio with airplanes. Table 1 presents averaged incoming (air-to-ground) and outgoing (ground-to-air) calls per minute. The rates measured during human-in-the-loop simulation and agent-based simulation seems very close.

	RT rate outgoing calls (calls / min)	RT rate incoming calls (calls / min)
HITL	3.12	3.78
AGENTFLY	3.63	3.12

Table 1: Radio transmission rate comparison.

7. Conclusions

The work presents a multi-agent model of air-traffic domain composed of variety of agents representing human actors and system components. One set of agents precisely emulates behavior of human air-traffic controllers integrating their workload model and interaction with ATM tools and system. The presented model is implemented as the software tool which is actively used by U.S. Federal Aviation Administration (FAA) where it is used as a tool for study of new concepts for air-traffic control.

The model preciseness has been verified and evaluated by third-party company having strong expertise in U.S. air-traffic services. The key component of the agent-based model evaluation was based on comparison of the model output with data measured during human-in-the-loop simulation with respective sector air-traffic controllers. The result of the agent-based model evaluation states that the model demonstrated an excellent ability to predict controller workload and it could be used by FAA as much faster tool for determining standards for sector control instead of using expensive and time consuming human-in-the-loop simulation especially under early developmental research. The agent-based model seems to be an excellent candidate for a fast-time work load prediction methods. Various scenarios with different workload patterns that the agent-based model has strong correlation with measured values in human-based simulations. Other metrics show that overall agent-based decision-making patterns were compatible with those of human air-traffic controllers.

The agent-based model of air-traffic modeling has strong potential to be used within many studies evaluating new concepts and tools for air-traffic control. Now, the model provides precise modeling of en-route part of the flight and should be later extended to include terminal areas and airport operations know as gate-to-gate models but including workload models for human operators in respective positions as well.

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Patent

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