Multi-Agent System for Airspace Control in the Combat Zone

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Abstract

Successful airspace control is one of the key factors maximizing the effectiveness of military air operations. It includes long and short-term planning and control that utilizes large and dynamic databases, and constitutes a combination of resource allocation, routing, scheduling, and deconfliction tasks performed repeatedly under information uncertainty to accommodate for the continuously arriving new information reflecting the dynamics of the battlefield. Combined with large volumes of data to be analyzed and stringent time requirements, these tasks place heavy burden on personnel, leading to costly inefficiencies. Modern computing technologies are capable of expanding the share of airspace control functions performed by computers resulting in numerically justified decisions that will enhance planning and reduce pressure on its personnel without freeing them from the ultimate responsibility. Computer-based planning, scheduling, and control are based on a mathematical formulation of the entire problem. Due to the high complexity, the problem solution is to be decomposed and its particular subsets are obtained in a decentralized, but coordinated fashion. This approach is best served by the "multi-agent" system technology that is deployed as the computational engine behind the airspace control system described herein. The paper features the distributed coordination mechanisms based on collective decision-making (voting) and sharing complex social knowledge (individual flight plans and aircraft status), design and implementation of the computational model, design and development of the algorithms and required knowledge structures for distributed coordination, the agent architecture and specific agents responsible for data collection/updating and planning/scheduling/deconfliction tasks, and the required visualization technology.

Key words

airspace control; air traffic; planning; multi-agent systems; software agents; deconfliction.

Introduction

Successful airspace control is one of the key factors maximizing the effectiveness of air operations and the entire combat operation. It includes long and short-term planning and scheduling, and real-time control. These functions utilize a large and dynamic database and constitute a very complex combination of resource allocation, space allocation, routing, scheduling, deconfliction, and control tasks that are to be solved under information uncertainty and rigid time constraint. In addition, these tasks must be solved periodically to accommodate for the continuously arriving new information reflecting the dynamics of the battlefield operation. The Airspace Control Authority (ACA) has highly trained personnel utilizing their knowledge, experience, and intuition to perform all necessary ACA functions. However, the complexity of the tasks, large volumes of data to be analyzed and stringent time requirements, place a heavy burden on individual planners that combined with the entire scope of issues labeled as “human factor,” may adversely affect the quality and timeliness of ACA decisions. Consequently, these could be among the factors limiting the success of the air campaign and preventing advanced military equipment and personnel to utilize their potential to the fullest. Availability of modern computing technologies creates the conditions when the share of ACA functions performed by computers could be expanded resulting in numerically justified decisions and reduced pressure on its personnel. This effort is aimed at the development of a computer-based system technology that will enhance ACA operation providing ever-increasing support to its personnel without freeing them from the ultimate responsibility.

An air traffic control system of the future is visualized as a fully decentralized, automated computer-based system. Such a system would allow for the utilization of the capabilities of personnel, equipment, and munitions to their full potential, as well as maximum safety of the air operation. A battlefield environment is highly dynamic. The decentralization results in the most flexible air operation control system that can easily accommodate for the rapidly changing situations providing that the necessary information is obtained and processed in a timely fashion. The latter could be achieved only by computer-based, fully automatic data acquisition and decision support. These considerations are implemented in the system for air traffic control in the battlefield zone presented herein with the goal of the maximum utilization of rapidly changing data and providing timely decision support to personnel of ACA (Wickens et al., 1998).

The solution to an air traffic control/planning problem is sought in the spatial, functional, and time domains. The *spatial aspect* of the problem deals with the geographical map, coordinates of the air bases, targets, airborne refueling stations and hazardous areas, and the utilization of airspace. It results in the definition of rational and safe routes for particular aircraft connecting the base of original deployment to the target or multiple targets, and to the designated landing base, when necessary through refueling areas. The f*unctional aspect* of the problem addresses the task assignment to particular pilots/aircraft, weapons-to-targets assignment, and the logistics of the entire air operation. The *time-domain aspect* of the problem includes the scheduling of the operation of particular aircraft at the take-off and landing stages, in-air refueling, and engaging targets. It could be seen that every aspect of the planning process is dictated by the tactical and intelligence information, affected by weather, and is consistent with the technical characteristics of aircraft, weapons, and targets. The system is expected to compile better-than-average air traffic control plans that will be presented for approval to ACA personnel in the enhanced, user-friendly format, which would complete the planning stage of the process.

The computer-based system represents the "big picture" of the airspace control problem in the *functional-domain*, *spatial-domain* and *time-domain* based on a mathematical model. Particular entities of the model "live" in the simulation environment and as such, obey laws of mechanics and aerodynamics, engage in communication among themselves and with the mission control, expend fuel and ammunition, experience various hazards, sustain battlefield damage, etc., and ultimately provide invaluable feedback for the enforcement of particular considerations and rules of engagement, detection of conflicts and deconflicting, and assessment of the "goodness" of the planning decisions. The system obtains numerical solutions of the particular subsets of the airspace control problem and coordinates "local," independently obtained solutions, thus resulting in conflict-free, long and short-term plans and schedules. The intermediate solutions are coordinated and deconflicted with the enforcement of specific considerations, and when possible, optimized. The entire solution task is visualized as an ongoing, iterative process driven by continuously updated databases reflecting the battlefield dynamics and newly arrived data. The capability of incorporation of human expertise presented in a formalized and intuitive fashion, and accommodation of new rules, considerations, and conditions is viewed as an important feature of the system. It could be further enhanced by inclusion of statistical analysis tools, and supervised and unsupervised learning capabilities.

Operation of the system includes planning and execution stages. At the planning stage, the plan of the entire air operation utilizing time-invariant data, such as geographical and performance characteristics of the aircraft, and a priory given information, such as the initial description of the air operation, is established. The execution stage addresses the effect of all factors preventing the implementation of the accepted plan of air operation, as well as the possible deviations from the plan. In order to assure the completion and overall success of the operation, the proposed system has the capability of rapid re-planning (deconfliction) achieved at the lowest possible cost. This process must employ some collaboration/negotiation between the involved entities. It facilitates the control of the air operation and is accomplished by providing updated assignments to individual pilots in a timely fashion. Consequently, the proposed system should perform the data acquisition task on a continuous basis and utilize reliable and secure communication channels with individual aircraft, as well as successful visualization techniques.

In many ways, the realization of the above capabilities is well served by the implementation of multi-agent system technology that has been successfully deployed for a number of large-scale software engineering projects for industrial and military applications (Wooldridge and Jennings, 1995) and specifically for airspace control (Tomlin et al., 1997), (Hill et al., 2005). Recent advancements in multi-agent system technology provide the means for the development of fully automated planning, scheduling, and operation control systems for complex, multivariable processes exhibiting hybrid (both continuous and discrete) behavior. Modern multi-agent systems emulate complex collaboration and information exchange processes taking place within a group of human experts engaged in finding a compromise solution of complex problems. Driven by mathematically justified procedures and utilizing high-speed computers, these systems consistently generate better-than-average and very prompt solutions that could be continuously updated on the basis of most recent information available. Unsurprisingly, multi-agent system technology has been chosen for the development of the ACA system featured in this paper.

Specifics of the airspace control problem

Solution of the airspace control problem results in an Airspace Control Plan (ACP) that allocates critical battlefield resources, equipment, space, and time reflecting

- Rules of engagement and disposition of air defense weapon systems,

- Air, land and maritime situations in the area of responsibility such as existing equipment limitations, electronic warfare, and C4 requirements that may adversely affect adherence to the ACP,

- Anticipated restricted area based on initial deployment of friendly forces and bases,

- Existing air traffic control areas, base defense zones, controlled or uncontrolled airspace, and overflight of neutral nations,

- Mission profiles, combat radii, and identification capability of aircraft operating in the area of responsibility,

- Enemy air defense weapons capabilities, deployment, and electronic attack/deception capabilities,

- Emergency procedures for aircraft experiencing difficulties,

- Procedures for day, night, and adverse weather conditions,

- Procedures for en route and terminal area air traffic control procedures for aircraft transitioning to and from the battle area that complement planned combat requirements,

- Procedures to support surge operations requiring high volumes of air traffic,

- Enemy offensive air capabilities, vulnerability of defensive counter aircraft to enemy surface-to-air missiles and vulnerability of friendly surface-based air defenses to enemy long-range artillery (Airspace…, 2005).

It important that a straight-forward attempt to plan/schedule the missions unavoidably requires that the following issues be addressed:

1. *Traffic hazards* i.e. potential conflicts with other objects on the surface or in flight such as other aircraft, missile launches, or other potential hazards characterized by the number, type, position, and intent available via surveillance.

2. *Current en route weather hazards* including hail, icing, turbulence, high winds associated with thunderstorm activity, thunderstorm activity over oceanic airspace, wind shear and microburst alerts, intensive precipitation, and areas of low visibility and tornadoes. This information is available from the Global Weather Information System.

3. *Rational airspace utilization* due to the fact that the value of the airspace for all users becomes increasingly critical as military operations, commercial operations, general aviation, rocket launches, and artillery shells compete for airspace. Airspace use/availability information

is dynamic; it allows utilizing available airspace to enhance flight operations for both mission and economic priorities.

4. *Aircraft-to-airspace separation* ensures that aircraft maintain a safe distance from special use airspace, such as hazardous and warning areas defined via intelligence and surveillance data and regulatory publications and specific control instructions. Separation standards ensure that aircraft remain at an appropriate minimum distance from such areas.

5. *Aircraft-to-aircraft en route separation* in airspace ensures that a safe distance is maintained between aircraft. Separation standards are defined for the different aircraft operating environments. They separate aircraft using standard rules for vertical, lateral, and longitudinal separation. When potential conflicts exist, an air traffic planner evaluates the situation and develops conflict resolution alternatives. Special rules exist for aircraft to aircraft separation services in oceanic airspace.

6. *Aircraft-to-aircraft separation in terminal airspace* ensures that a safe distance is maintained between aircraft. Within terminal airspace, requirements for separation vary by airspace Class. There are standard rules for vertical, lateral, and longitudinal separation methods. When potential conflicts exist, an air traffic planner evaluates the situation and develops conflict resolution alternatives.

7. *Aircraft-to-terrain/obstacle separation* that ensures that aircraft maintains a safe distance from terrain and obstacles.

8. *Current Surface Separation* that prevents taxi conflicts and runway incursions.

Consequently, the planning process constitutes a number of parallel, semi-autonomous tasks, utilizing common, continuously updated databases that are aimed at the detection and resolution of the conflicts. The solution process is typically decentralized and results in “local” solutions reflecting “local” criteria and constraints that must be coordinated in the interests of the overall solution (FAA 2005).

Existing practices of air traffic control

The air traffic control system is a vast network of people and equipment that ensures the safe operation of commercial and private aircraft. Air traffic controllers coordinate the movement of air traffic to make certain that planes stay a safe distance apart. Their immediate concern is safety, but controllers must also direct planes efficiently to minimize delays. Some regulate airport traffic through designated airspaces; others regulate arrivals and departures.

Although *airport tower controllers* or *terminal controllers* watch over all planes traveling through the airport’s airspace, their main responsibility is to organize the flow of aircraft into and out of the airport. Relying on radar and visual observation, they closely monitor each plane to ensure a safe distance between all aircraft and to guide pilots between the hangar or ramp and the end of the airport’s airspace. In addition, controllers keep pilots informed about changes in weather conditions such as wind shear, a sudden change in the velocity or direction of the wind, that can cause the pilot to lose control of the aircraft.

During arrival or departure, several controllers direct each plane. As a plane approaches a base, the pilot radios ahead to inform the terminal of the plane's presence. The controller in the radar room, just beneath the control tower, has a copy of the plane's flight plan and already has observed the plane on radar. If the path is clear, the controller directs the pilot to a runway; otherwise, the plane is fitted into a traffic pattern with other aircraft waiting to land. As the plane nears the runway, the pilot is asked to contact the tower. There, another controller, who also is watching the plane on radar, monitors the aircraft the last mile or so to the runway, delaying any departures that would interfere with the plane's landing. Once the plane has landed, a ground controller in the tower directs it along the taxiways to its assigned gate. The ground controller usually works entirely by sight and/or relies on radar information if visibility is very poor.

The procedure is reversed for departures. The ground controller directs the plane to the proper runway. The local controller then informs the pilot about conditions at the airport, such as weather, speed and direction of wind, and visibility. The local controller also issues runway clearance for the pilot to take off. Once in the air, the plane is guided out of the airbase's airspace by the departure controller.

After each plane departs, airbase tower controllers notify *enroute controllers* who will now take charge. Nationally, there are 20 air route traffic control centers located around the country, each employing 300 to 700 controllers, with more than 150 on duty during peak hours at the busiest facilities. Airplanes usually fly along designated routes; each center is assigned a certain airspace containing many different routes. Enroute controllers work in teams of up to three members, depending on how heavy traffic is; each team is responsible for a section of the center's airspace. A team, as exemplified by commercial aviation, might be responsible for all planes that are between 30 and 100 miles north of an airport and flying at an altitude between 6,000 and 18,000 feet.

To prepare for planes about to enter the team's airspace, the radar associate controller organizes flight plans coming off a printer. If two planes are scheduled to enter the team's airspace at nearly the same time, location, and altitude, this controller may arrange with the preceding control unit for one plane to change its flight path. The previous unit may have been another team at the same or an adjacent center, or a departure controller at a neighboring terminal. As a plane approaches a team's airspace, the radar controller accepts responsibility for the plane from the previous controlling unit. The controller also delegates responsibility for the plane to the next controlling unit when the plane leaves the team's airspace.

The radar controller, who is the senior team member, observes the planes in the team's airspace on radar and communicates with the pilots when necessary. Radar controllers warn pilots about nearby planes, bad weather conditions, and other potential hazards. Two planes on a collision course will be directed around each other. If a pilot wants to change altitude in search of better flying conditions, the controller will check to determine that no other planes will be along the proposed path. As the flight progresses, the team responsible for the aircraft notifies the next team in charge of the airspace ahead. Through team coordination, the plane arrives safely at its destination.

Both tower and enroute controllers usually control several planes at a time; often, they have to make quick decisions about completely different activities. For example, a controller might direct a plane on its landing approach and at the same time provide pilots entering the airport's airspace with information about conditions at the airport. While instructing these pilots, the controller also might observe other planes in the vicinity, such as those in a holding pattern waiting for permission to land, to ensure that they remain well separated.

In addition to airbase towers and enroute centers, air traffic controllers also work in flight service stations operated at more than 100 locations nationally. These *flight service specialists* provide pilots with information on the station's particular area, including terrain, preflight and inflight weather information, suggested routes, and other information important to the safety of a flight. Flight service specialists help pilots in emergency situations and initiate and coordinate searches for missing or overdue aircraft. However, they are not involved in actively managing air traffic.

Some national air traffic controllers work at the FAA's Air Traffic Control Systems Command Center in Herndon, VA, where they oversee the entire system. They look for situations that will create bottlenecks or other problems in the system, then respond with a management plan for traffic into and out of the troubled sector. The objective is to keep traffic levels in the trouble spots manageable for the controllers working at enroute centers.

The FAA has implemented an automated air traffic control system, called the National Airspace System (NAS) Architecture. The NAS Architecture is a long-term strategic plan that will allow controllers to more efficiently deal with the demands of increased air traffic. It encompasses the replacement of aging equipment and the introduction of new systems, technologies, and procedures to enhance safety and security and support future aviation growth. The NAS Architecture facilitates continuing discussion of modernization between the FAA and the aviation community (Nolan, 1990).

While the above description primarily reflects the operation of commercial aviation, it provides sufficient detail for the purpose of this project.

Multi-agent planning and execution processes

In the nearest future, the advanced methods of computer science and artificial intelligence will play a pivotal role in air traffic control of military and civilian as well as manned and unmanned aerial vehicles. We have been investigating the use of agent based technology and the multi-agent algorithms for deployment in this specific application domain.

Multi-agent system is a collection of loosely coupled autonomous programs that perform collective behavior and collective decision making by means of interaction, negotiation, cooperation but also methods of teamwork, competition or social dominance. Multi-agent system domain provides a wide selection of ready to use COTS or open source integration platforms as well as various techniques and algorithms suitable for different coordination tasks.

The use of this highly innovative technology is appropriate in the situations where the data required for decision making are not available centrally. As air traffic control domain needs to move to less human driven problem and a problem more suited for automated decision making, we expect that substantial amount of computation and data maintenance will be onboard of the aircraft. Similarly, the future air-traffic operation (especially in battle-field or surveillance operations) will require techniques implementing safe, fast and robust deconfliction algorithms and would allow for other replanning scenarios in highly dynamic and unpredictable environment.

This expectation leads to investigation of a highly decentralized decision making systems that will make an important use of the available multi-agent technologies. Operation of a multi-agent air traffic control system is supposed encapsulate the following 3 decision making phases:

Data acquisition

Time-invariant data includes geographical information (digital map); performance characteristics of aircraft, primarily operational speed ranges and fuel burn rates given for various Standard Configuration Loads (STL); coordinates of the friendly airbases; and airspace design (aircraft separation) criteria that could be defined for various visibility conditions (i.e., sizes of the air corridors and tunnels, and communication, alert, safety, and collision zones around aircraft). Airspace design criteria are established based on the capability of aircraft to accurately fly and maintain pressure altitudes in higher altitude cruise and based on the capability of the aircraft and the relationship to separation criteria in lower altitude situations. Airspace design criteria for flight objects for a special use (hazardous/restricted) airspace activity include the time duration and volume of airspace around the trajectory required to execute the mission. This addresses dynamic airspace restrictions with variable separation for security, military operations, remotely operated aircraft, and reusable launch vehicles. *Time-varying data* includes the plan of the air operation that designates targets for particular aircraft (pilots) and assigns weapons to target and defines the NET (not earlier than) and NLT (not later than) times for particular target; weather-related information; coordinates and status of particular targets; and hazardous areas, also known as special use airspace (areas defended by SAMs, areas occupied by flying artillery shells, rocket launches, etc.). It could be seen that this information reflects the battlefield dynamics, i.e., changing goals of the air operation, neutralization of targets and detection of new targets and hazardous areas, changing weather conditions, etc. Finally, *reported data* represents the current status of the particular aircraft, such as payload, technical status, available fuel status, and actual aircraft position.

Initial planning

The first step of the initial planning process begins with establishing a logical time schedule for the neutralization of particular targets that constitute a subset of the air operation plan. This is followed by assigning aircraft/weapons to targets, selection of take-off airbases, and the bases where aircraft are to return after the completion of the mission. Temporal coordinates of the rest of the node points are to be calculated based on the average speed of the aircraft and the geometrical distance between the appropriate locations. At the next step of the initial planning, all intermediate points of the aircraft paths are to be calculated by interpolation, assuming that the node points are connected by straight lines in the four-dimensional space. The number of intermediate points is defined according to some chosen time step and average speed of the aircraft.

Deconfliction

The flight plans that are results form the initial planning process may contain possible conflicts and collision situations. Collision avoidance is not solved during the initial planning process due to high computational requirements related to this process and due to high dynamics of expected flight traffic. The detection and resolution of the conflicts criteria utilized in this process are defined based on the capability of aircraft to accurately fly and maintain required altitudes. Criteria for flight objects for a special use (hazardous/restricted) airspace activity include the time duration and volume of airspace around the trajectory required to execute the mission. This addresses dynamic airspace restrictions with variable separation for security, military operations, remotely operated aircraft, and reusable launch vehicles. It should be emphasized that detection and resolution of the conflicts takes into consideration weather conditions, time of the air operation, and the geographical region that dictates the size of the air corridors, air tunnels, communication, and alarm and danger zones surrounding aircraft.

The deconfliction process can be physically embedded in the initial planning phase or fight execution phase, described below. If deconfliction is to be executed during initial planning it needs to be implemented on top of a multi-agent simulation of the flight-plans elaborated during the initial planning process. Possible collisions will be resolved by the multi-agent deconflcition methods and log of the resulting operation will provide the final non-conflicting plans. More natural alternative is to implemented deconfliction within the flight execution process. The aircraft would follow their mission plan and carry out deconfliction process up in the air. This concept is referred to as *free-flight* and is particularly suitably for unmanned aerial vehicle operation.

Flight execution

The execution stage addresses the effect of all factors preventing the implementation of the accepted plan of air operation. These factors include unexpected changes in weather conditions, damage sustained by particular aircraft, actual fuel status, newly detected targets and hazardous zones, failure to neutralize targets according to the plan, failure to follow the required schedule, failure to stay within the designated corridor/tunnel, etc. It could be seen that in addition to making the goals of air operation unattainable, these factors can result in additional conflicts. In order to minimize the effect of these factors on the completion and overall success of the operation, the proposed system has the capability of rapid re-planning (deconfliction) achieved at the lowest possible cost. This process must employ some collaboration/negotiation between the involved entities. It facilitates the control of the air operation and is accomplished by providing updated assignments to individual pilots in a timely fashion. Unlike the initial planning, conflict resolution at this stage implies a decision process that takes into account when reported (real) data on technical status of the involved aircraft is available, amount of fuel on board, and the aircraft position.

Status of the Implementation

The agent-based air traffic based on the architecture listed in the previous section has been designed recently and has been implemented on top of the **𝒜-globe** multi-agent platform (Sislak et al., 2005) and has been presented at (Pechoucek et. al, 2006). The system features technology for agent based flight modeling, air-traffic planning mechanism for a single plane, rule-based and utility based deconfliction mechanisms (See Fig. 1.). Specific negotiation-based conflict resolution procedures have been developed and implemented in multi-agent environment originally suggested by (Schulz et al. 1997), (Tomlin et al. 1997), and further developed for airspace deconfliction by (Pechoucek et al. 2006). The deconfliction mechanism is distributed by its nature that allows for addressing the high volume of computations associated with the solution of this problem.

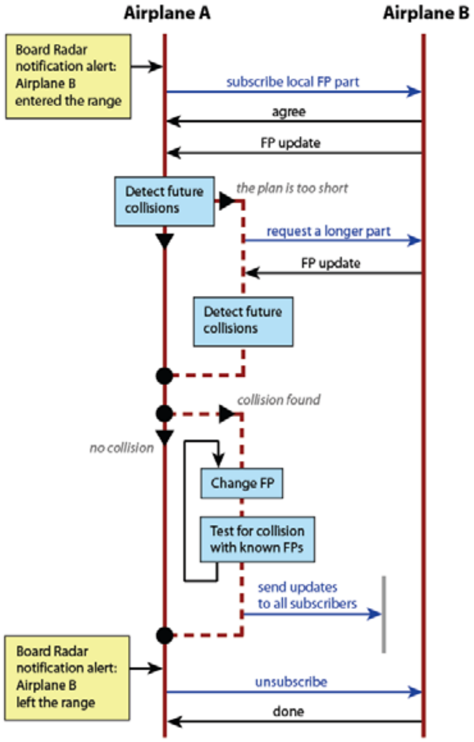
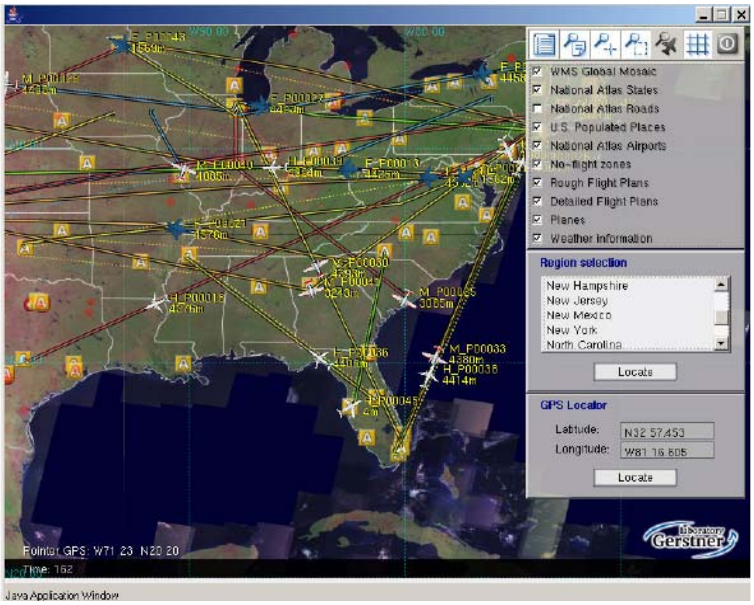


Fig.1. Deconfliction negotiation protocol

Currently, massive scalability tests are under development. The developed system also provides 3-dimensional and web-accessible 2-dimensional presentation (GUI) layer (see Fig. 2). The system performs data-fusion on top of various data from freely available data-sources that have been integrated in the system (e.g. mosaic of Landsat7 images, USGS geographical data, GNIS name-related data, but also almost real-time data from the airport traffic monitors of major U.S. airports).



☑ WMS Global Mosaic
☑ National Atlas States
☐ National Atlas Roads
☑ U.S. Populated Places
☑ National Atlas Airports
☑ No-flight zones
☑ Rough Flight Plans
☑ Detailed Flight Plans
☑ Planes
☑ Weather information

Latitude: N32 57.453
Longitude: W81 16.605

Pointer GPS: W71 23 N20 20
Time: 162

Fig.2. Presentation layer

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References

Marik, V., Pechoucek, M., Stepankova, O. (2001). Social Knowledge in Multi-Agent Systems, In (M. Luck et. al, eds.) *Multi-Agent Systems and Applications*, LNAI 2086, Springer-Verlag, Heidelberg, 2001, pp. 211-245.

Pechoucek, M., Marik, V., Barta, J. (2002). A knowledge based Approach to Coalition Formation. In: *IEEE Intelligent Systems*. vol. 17, no. 3, IEEE Computer Society, New York, pp. 17-25.

Pechoucek, M., Marik, V., and Stepankova, O. (2001). Towards Reducing Communication Traffic in Multi-Agent Systems. In: *Journal of Applied System Studies*, Cambridge International Science Publishing, No.1, Cambridge, UK.

Pechoucek, M., Marik, V., Stepankova, O., Macurek, F., Tichy, P. (1999). Meta-agent: A Workflow Mediator in Multi-Agent Systems. In: *Intelligent Workflow and Process Management: The New Frontier for AI in Business*. Vol.1. San Francisco: Morgan Kaufmann Publishers.

Riha, A., Pechoucek, M., Vokrinek, J., Marik, V. (2002). ExPlanTech: Exploitation of Agent-based Technology in Production Planning, In: *Multi-Agent Systems and Application II*, (Marik, V. et. al., eds.), LNAI 2322, Springer Verlag.

Sandholm, T. (1999). Distributed Rational Decision Making, In: (Weiss, G. ed.) *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*, pp. 201-258, MIT Press.

Tambe, M. (1997). Towards Flexible Teamwork. In: *Journal of Artificial Intelligence Research*, AI Access Foundation and Morgan Kaufman Publishers, Vol. 7, pp. 83-124.

Wooldridge, M., Jennings, N. (1995). Intelligent Agents: Theory and Practice. In: *The Knowledge Engineering Review*, Vol. 10, No. 2, pp. 115-152.

“Airspace Control in the Combat Zone,” Air Force Doctrine Document 2-1.7, 13 July 2005.

Wickens, C.D., Mavor, A.S., Parasuraman, R., McGee, J.P. (1998). *The Future of Air Traffic Control: Human Operators and Automation*, The National Academies Press.

Smith, P. G. (Smith, P. G. ed.), "Concept of Operations in the National Airspace System in 2005", FAA, 1999.

FAA List of all Operational Improvements in the NAS Architecture 5 database, Oct 2005.

Nolan, M. S. (1990). *Fundamentals of Air Traffic Control*, Wadsworth Inc.

Tomlin, C., Pappas, G., and Sastry, S. (1997). Conflict resolution for air traffic management: A case study in multi-agent hybrid systems. *IEEE Transactions on Automatic Control*.

Zlotkin, G. and Rosenschein, J. S. (1989). Negotiation and task sharing among autonomous agents in cooperative domains. In: N. S. Sridharan, editor, *Proceedings of the Eleventh International Joint Conference on Artificial Intelligence*, pp. 912–917, San Mateo, CA, Morgan Kaufmann.

Sislak, D., Rehak, M., Pechoucek, M., Rollo, M., and Pavlicek, D. (2005). A-**globe**: Agent development platform with inaccessibility and mobility support. In: *Software Agent-Based Applications,Platforms and Development Kits*, pp. 21-46, Berlin, Birkhauser Verlag.

Pechoucek, M., Sislak, D., Pavlicek, D., and Uller, M. (2006b): Autonomous Agents for Air-Traffic Deconfliction. In: *Proc. AAMAS-06 – Industry Track*, ACM Press, pp. 1498-1505

Hill, J. C., Johnson, F. R., Archibald, J. K., Frost, R. L., and Stirling, W. C. (2005). A cooperative multi-agent approach to free flight. In *AAMAS*, pp. 1083-1090.