Proceedings of the 2003 IEEE
International Symposium on Intelligent Control
Houston, Texas • October 5-8, 2003

Intelligent System Design with Fixed-Base Simulation Validation for General Aviation

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Abstract— This paper reviews research conducted in the Texas A&M University Flight Simulation Laboratory on intelligent systems for general aviation. Over the last eight years several intelligent cockpit systems and pilot decision-aiding tools have been created and developed for general aviation aircraft, using fix-based flight simulation validation and evaluation. This paper reviews these results, and also presents current research on advanced cockpit systems designed to satisfy the technological requirements posed by the general aviation Free Flight and Small Aircraft Transportation System concepts.

I. Introduction

Free Flight is an innovative air traffic management concept designed to enhance the safety and efficiency of the National Airspace System (NAS). It moves the NAS from a centralized command-and-control system between pilots and air traffic controllers, to a distributed system that allows pilots, whenever practical, to choose their own route and file a flight plan that follows the most efficient and economical route [1]. Since current Free Flight related research is focused ground controllers and commercial air transports, General Aviation (GA) Free Flight is an important missing piece at the present time. In parallel to GA Free Flight, another nation-wide project, the Small Aircraft Transportation System (SATS), requires an immense technology advancement in GA systems. The project, currently lead by NASA, aims at providing the nation with a small aircraft transportation system to relieve the safety and congestion problems currently on highways and in the air [2]. With over 5,000 small airports already in place across the country, SATS will satisfy the public demand for safe, high-speed mobility and increased accessibility[2].

For both GA Free Flight and SATS, advanced cockpit systems are required to assist pilots in decision making and information management. During the past eight years, extensive research work has been done in the Texas A&M University Flight Simulation Laboratory (FSL) on designing and developing intelligent cockpit systems and pilot decision-aiding tools for GA aircraft using fix-based flight simulation validation and evaluation [3]. The General Aviation Pilot Advisor and Training System (GAPATS), and the Hierarchical Agent Based System for GA conflict detection and resolution (CD&R) are two major systems created in these research projects, which have been or are funded by the NASA Langley Research Center, the State of Texas, and other industry partners. This paper first reviews previous recent research, and then details research projects currently underway.

II. Foundations

A. Engineering Flight Simulator

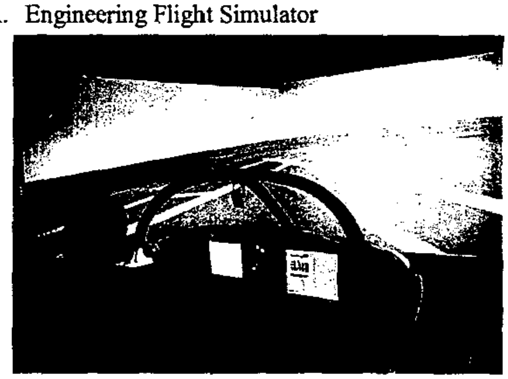

Fig. 1 Engineering Flight Simulator Cockpit and Environment

A real-time, nonlinear, six degree-of-freedom fixed base Engineering Flight Simulator (EFS), located in the FSL, serves as the platform for evaluation and validation of the various intelligent cockpit systems. It contains a cockpit with reconfigurable, multifunctional displays that can be rapidly modified and tailored to fit individual project needs for a wide range of general aviation, commercial, and military cockpit displays. The EFS is currently capable of simulating the Rockwell Commander 700, which is a light twin-engine, typical GA aircraft. This simulation model also possesses a three-axis autopilot with gain scheduling according to three different flight phases: cruise, takeoff, and power approach. Figure 1 depicts the simulation environment and a pilot operating the EFS.

B. Aviation Expert System

The General Aviation Pilot Advisory Training System (GAPATS) is a computerized airborne expert system, which infers the flight mode of an aircraft from sensed flight parameters using fuzzy logic methods. The pilot's flying performance is assessed based on the interpreted flight mode, an embedded knowledge base, and pilot inputs, and recommendations are issued for pilot actions. Such a system improves safety by enhancing the pilot's situational awareness, and by reducing the cost and time required to achieve and to maintain pilot proficiency [3]. Fig. 2 illustrates the modular layout of GAPATS and the interfaces between software components and hardware components. GAPATS is composed of several modules, primary of which are the Flight Mode Interpreter (FMI) and the Pilot Advisor (PA). These two core modules are key to realizing the designated intelligent behavior of the system, and are described in detail in the next few paragraphs.

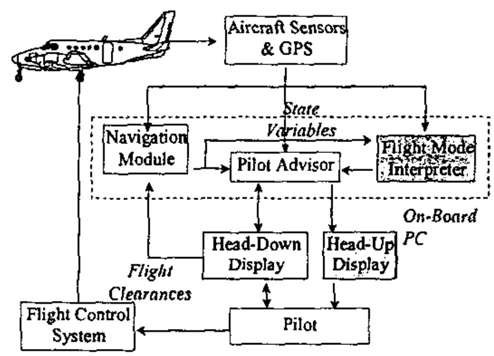

Fig. 2 GAPATS Architecture

Based on the observation of aircraft flight states obtained from the sensors, the FMI classifies the current operation of the aircraft according to a set of predefined "flight modes". A summary of the measurements accepted by the FMI and the flight modes is shown in Table I.

The six measurements may be regarded as "state variables," defining a state space for the airplane. The seven flight modes are modeled in terms of the six flight variables, which decompose the state space into seven partitions. When the six dimensional vector of flight variable measurements falls within the state-space partition defining one particular flight mode, that one is determined as the current flight mode of the aircraft.

Table 1 Aircraft Measurements And Interpreter Flight Modes

MEASUREMENT LIST	DEFINED FLIGHT MODES
Engine Power (%)	Taxi
Airspeed (knots)	Takeoff
Altitude (feet, AGL)	Climbout
Rate of Climb (FPM)	Cruise
Distance to Final Approach Fix (FAF)	Initial Approach
Distance to Missed Approach Point (MAP)	Final Approach
	Landing

Modeling the flight modes uses state-space partitions that are not always unique. A decision method based on Bayesian probability theory is used to resolve this ambiguity. Six-dimensional probability functions are defined for each flight mode, such that when called with a measured vector, they return a probability value between zero and unity. Some ideas from Fuzzy Logic were used to implement the Bayes decision algorithms.

The Pilot Advisor is a rule based expert system that works together with the Flight Mode Interpreter to determine the advice given to the pilot during takeoff and flight, concerning the manner the pilot should fly the airplane to accomplish the flight plan. The PA utilizes an embedded CLIPS programming language engine and rule base to analyze the data inputted from the sensors and the FMI. Based on the flight mode declared by the FMI, the current flight states, and specific navigation module outputs, it decides what advice should be presented to the pilot and at which alert level. The output of the PA displays various types of symbology sets and alarms on the Head Up Display (HUD) and Head Down Display (HDD).

A group of eight pilots participated in the simulator evaluations of GAPATS. The results showed that using GAPATS reduces pilot workload, increases situational awareness, and improves approach and landing performance.

C. Hierarchical Agent-based System

The hierarchical agent based system provides pilots with conflict free flight path guidance in situations where weather and traffic conflicts exist concurrently [5]. The agent system is composed of three independent intelligent agents: a Weather Agent, a Traffic Agent, and an Executive Agent, as illustrated in Fig. 3.

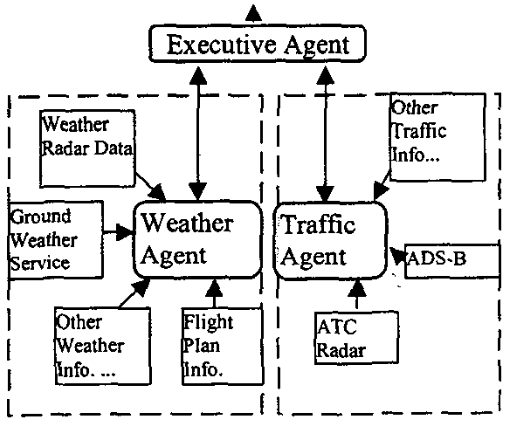

Fig. 3 Architecture of Agent Based Hierarchical System

Severe thunderstorms pose a significant threat to the flight safety of aircraft, primarily due to turbulence. The violent updraft and downdraft of the turbulence can destroy aircraft or even drive them into the ground. Other hazards related to the thunderstorms include icing and lightening. The Weather Agent detects hazardous thunderstorms based on data received primarily from onboard weather radar. Considering weather restrictions, the weather agent computes an optimal flight path that ensures the safety of the aircraft [6]. The Modified A* search method is the algorithm developed for the Weather Agent. It takes radar images of thunderstorms as input, and determines the safest path between two points in the flight with minimum detour. Passenger comfort and the aircraft operation limitations are accounted for, and the conflict avoidance path is subject to constraints such as maximum number of turns, maximum turn angle, etc.

An aircraft's protected zone surrounds the aircraft and should never overlay with another aircraft's protected zone. The Traffic Agent detects air traffic in the neighboring airspace and keeps the aircraft out of the protected zones of other aircraft [7]. The agent takes ADS-B state vectors of other aircraft in the immediate airspace as input, and the traffic conflict detection and resolution module uses a combination of a knowledge base expert system and optimal control theory to construct the conflict free flight paths. The knowledge base includes the expertise of pilots and Air Traffic Control (ATC), air traffic regulations, and Instrument Flight Rules (IFR). For the optimal control portion, the selected trajectory is optimized using an objective function consisting of the delta magnitude of acceleration, and the primary constraint is the required separation between aircraft. There are some secondary constraints including aircraft states limitation, aircraft performance limitation, and time to maneuver limitation. The optimizer applies a fixed step size 'Breadth First Search', such that the solution obtained is minimum acceleration, and satisfies all of the active constraints imposed on the system.

The Weather and Traffic agents are assumed to be independent of each other, and make individual formulations of the flight paths required to avoid conflicts. The highest-level agent, the Executive Agent, acts as an arbitrator when the altered flight paths recommended by the Weather and Traffic agents conflict [8]. Fuzzy synthetic evaluation is the method used to realize the designated intelligent attributes of the executive agent, such as reasoning, estimating, and decision-making. The Executive Agent performs the synthetic evaluation on the overall conflict situation based on two components: the current weather condition, and the current traffic scenario. Two sub-modules of the Executive Agent, the weather and traffic conflict evaluation modules, calculate respectively the severity of the weather and traffic conflicts in fuzzy terms such as "slight", "severe", etc. The qualitative values of weather and traffic conflicts are passed as inputs to the rule-based arbitrator that contains a Mamdani fuzzy rule inference system with 16 fuzzy rules. Weighing between the extent of the present weather and traffic conflicts, the arbitrator endeavors to avoid the potential collisions between the two agents. It controls the severity of both conflicts to an acceptable level, and provides an optimal solution to resolve both severe traffic and weather conflicts. The output from the inference system will decide whether the aircraft should completely follow the traffic conflict free flight trajectory provided by the traffic agent, or deviate from it and fly towards a new heading in case the recommended traffic conflict-free path may encounter a significant weather conflict. It must also determine how much the deviation should be if it is the latter case.

Integrating the agent system into GAPATS took advantage of the Navigation and Multi-Function Head Down Display (MFD/HDD) modules offered by GAPATS. The navigation information provided by the navigation module (present position and direction, etc.), is necessary for the agent system to detect potential conflicts and computing conflict-free flight trajectories. The moving map HDD is used to display several types of information provided by the agent system, such as radar images of squall lines, current traffic scenarios, potential conflicts warning messages and the ultimate recommended conflicts free flight. A snapshot of the moving map display is shown in Fig. 4. The small aircraft icon in the middle of the moving map represents the subject aircraft, and the weather radar image is represented by the fan-shaped area in front of the icon. The brown line shows the original flight path that encounters the weather or traffic conflict. The blue line indicates the recommended flight path by the agent system. Other icons on the moving map embody various types of navigation aids. Other aircraft in the neighboring airspace are also shown on the HDD. The circles around the aircraft denote their protected zones, which must not be overlapped with that of the subject aircraft. The interpreted flight mode is shown in the top left of the HDD, and the warning messages for the pilot are presented in the top-center.

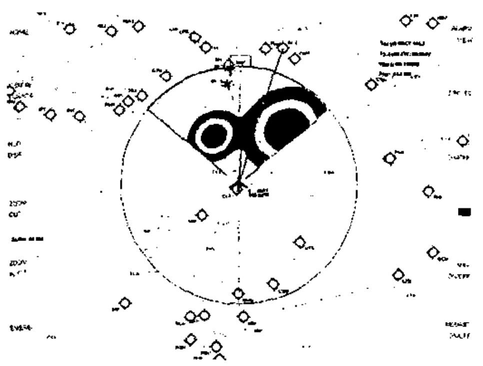

Fig. 4 Moving Map Display

The guidance solution for multiple conflict situations recommended by the agent system is directly inputted into the autopilot, which then flies the aircraft along the new, conflict-free flight path. Test results of the agent system show it to be an effective real-time conflict detection and resolution (CD&R) system for producing conflict-free flight path guidance in airspace subjected to co-existing individual weather and traffic conflicts.

D. Multi-Aircraft Agent System

A natural extension of the agent system described in the previous section is the Multi-Aircraft Agent System (MAAS). It uses multi-agent system approaches to solve the CD&R problem. Multiple aircraft in a neighboring airspace are regarded as independent agents in MAAS, especially when they encounter one or more conflicts. The environment of each aircraft includes the adjacent weather conditions, other aircraft in its neighboring airspace, and air traffic ground controllers. The CD&R problem is solved as a constraint satisfaction problem. An aircraft should always fly along a path that satisfies all of the constraints posed by its environment, e.g., avoiding the protected zones of other aircraft, the dangerous areas of squall lines, special usage airspace, and terrain. Among all possible flight paths, an optimal one is desired that produces the lowest cost in terms of time of flight, fuel consumption, passenger cost, etc. As the overall safety of the airspace is a global concern, collaboration among aircraft is required to search for appropriate solutions to conflicts. Thus, negotiation among aircraft in the airspace becomes a critical factor for multilateral agreement of the ultimate conflict resolution. Of course, negotiation between aircraft only occurs when traffic conflicts exist, since weather and terrain do not negotiate. In MAAS, aircraft adopt a pair wise, argument-based negotiation approach to search for multilateral acceptable resolutions to conflicts. In addition, real-time constraints such as response time and negotiation deadline are considered are considered in the negotiation. Although the test results for some simple conflict scenarios demonstrated that the proposed negotiation system and algorithm was capable of providing mutually acceptable solutions, it remains at the conceptual level and requires more research effort.

III. New Directions

As natural extensions of previous research projects, the current research work at the FSL focuses on two primary projects.

A. Aircraft Approach and Landing Assistant

The Aircraft Approach and Landing Assistant is a novel cockpit system, aimed at automating part of the pilot decision-making process and thus decreasing pilot workload and improving flight safety. Moreover, it acts as a study example for designing a pilot decision aid tool using data fusion methods.

The Assistant will benefit most pilots flying in the future Small Aircraft Transportation System (SATS). SATS is a new proposed transportation system that aims at relieving the safety and congestion problems currently on highways and in the air. By achieving multiple aircraft operation in non-radar airspace and non-towered airports, SATS would provide the public affordable and safe accessibility to most landing facilities throughout the nation in nearly all weather conditions.

Pilot decision-making is one of the most critical issues that related to the safety of SATS. In the last two decades, faulty pilot decision-making has become the most cited cause of general aviation accidents, most of which are due to high pilot workload and lack of pilot situation awareness under complex flight environments. This problem is potentially greater in SATS, since pilots will have to sustain more safety responsibility than today's IFR pilots do. Moreover, these pilots will need to deal with a large volume of raw data from various sources, such as the Flight Information Service Broadcast, the Weather Information Service Broadcast, and the Automatic Dependence Surveillance-Broadcast. Escalated flight tasks and increased data processing may also lead to information overload for pilots, and thus enhanced cockpit workload. This leads to decreased situation awareness, and increases the possibility of decreased flight safety.

One solution for the problem described above is to develop an intelligent pilot decision aid tool using data fusion techniques. Generally, the pilot's decision-making process starts with the perception and recognition of cues in the environment, followed by an evaluation of these pieces of information. A pilot is able to make an appropriate response based on a correct diagnosis of the situation, which makes this diagnosis crucial. In general, data fusion is an automated deduction process, which detects known patterns or signatures in real-time or stored data. By automating the situation diagnosis and risk assessment process of a pilot, the decision-aid tool may greatly assist pilots in processing information and making decisions. Consider the following example. Given inputs consisting of raw weather data, the prescribed approach procedure, aircraft states, and other information, the tool must perform the following: discern the hazardous airspace of high thunderstorm intensity, estimate the severity of the weather threat to the approach, and indicate the potential dangerous phases along the approach path. This information will allow the pilot to decide whether or not to continue the approach, or find an alternate airport. Using data fusion techniques to design a cockpit system is a novel idea that has not been investigated for general aviation (GA).

Of all the flight phases, approach and landing has the highest task requirements for a pilot since several jobs must be carried out simultaneously. Conducting approaches and landings completely unassisted may be difficult for SATS pilots, since responsibility for most of the current ground based controllers duties (avoiding severe weather conditions and maintaining safe separation intervals) will be delegated to the airborne system. The Assistant is designed as a real-time decision-aide tool for pilots in these kinds of high workload situations. The proposed structure of the Assistant is a multi-agent system composed of a collection of intelligent agents, as illustrated in Fig. 5. The primary data fusion techniques used to develop the Assistant are Artificial Intelligence methods, including rule-based expert systems, fuzzy logic, and artificial neural networks.

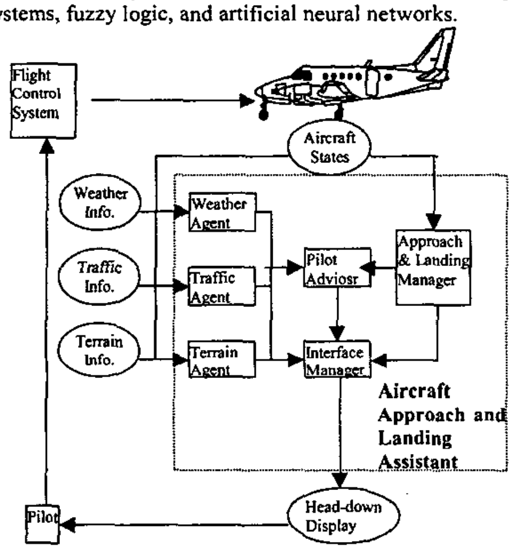

Fig. 5 Overall Architecture of the Assistant

The proposed functions of the Assistant are:

1) Reducing Pilot Monitoring Tasks

Monitoring tasks include detection of severe weather conditions, possible collision with other aircraft, Controlled Flight into Terrain (CFIT), deviation from the prescribed instrument approach procedure, abnormal aircraft states, and malfunctions of on-board systems.

2) Preprocessing of Information

Raw data from various sources must be filtered so as not to overwhelm pilots. Some data should be further interpreted into information that is more useful, or a recognizable pattern based so the pilot may respond immediately.

3) Issuing Warnings and Advice

Warning messages remind pilots of hazards in the environment, operations errors, and aircraft malfunctions. Advice based on the flight rules or emergency procedures provide pilots with normative operations to deal with specific situations.

4) Managing Information Display

Good information display management can improve pilot situational awareness. A poorly organized display often adds additional workload, and increases the possibility for pilot error.

B. Air-Traffic Information Management System

The current simulation system in the FSL is not able to satisfy the requirement of validating an advanced cockpit system design. Additionally, another ongoing research project named "Automation Capability Analysis for Non-Controlled Airports" also needs testing and verification tools to validate the operation concepts and procedures which are introduced [9]. One promising solution is the use of distributed interactive simulation. There are various air traffic simulation systems designed for evaluating future ATM models and concepts, as listed in [10]. Based on these existing systems, an Air Traffic Information Management System (AIMS) will be developed in the FSL to implement the simulation requirements for ongoing research in GA Free Flight and SATS. In order to make AIMS an open simulation platform that satisfies the comprehensive simulation requirements for different kinds of ATM research projects, it will be built as an agent-based and plug-in modular simulation system. Fig. 6 shows the hierarchy architecture of AIMS.

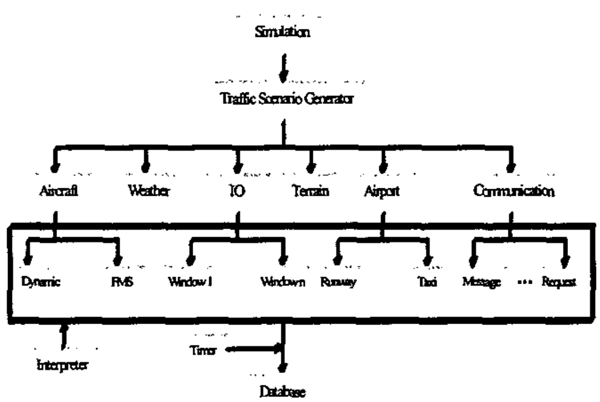

Fig. 6 AIMS Hierarchy Architecture

AIMS is composed of four components:

1) Traffic Scenario Generator

The traffic scenario generator is the key element of AIMS. It sets up the initial conditions and settings for each simulation, such as the initial configuration and conditions of each aircraft, the aircraft models, CD&R model, position, velocity, etc.; the airspace domain, either en-route airspace or terminal airspace; the weather and terrain configuration; and the simulation mode, either fast-time or real-time mode. The traffic scenario generator generates traffic scenarios based on either a combination of actual congested air traffic data, and simulated traffic data created by some known traffic distribution functions. Realistic traffic data can be obtained by using flight plans filed at the Air Route Traffic Control Center (ARTCC) host computer. Simulated traffic data is complemented to real traffic data to create some reasonable level of air traffic volume in future GA Free Flight or SATS.

2) Intelligent Aircraft Agent

Each aircraft in AIMS is implemented as an intelligent aircraft agent. As shown in Fig. 7, an intelligent aircraft agent is has a six-degree-freedom dynamical model, a pilot model, a Flight Management System (FMS) model (including autopilot), a CD&R model, an ADS-B model, and a model reserved for future research.

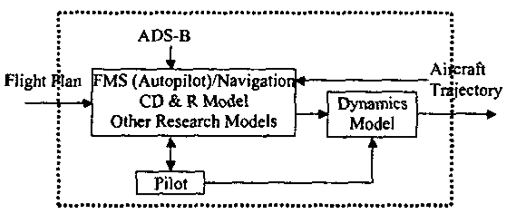

Fig. 7 An Intelligent Aircraft Agent

3) Airport Model

Implementation of an airport model is divided into four steps. First, the terrain configuration of an airport and its surrounding area is generated based on its one-degree U.S. Geological Survey (USGS) Digital Elevation Models (DEM). Second, weather-constrained airspace in the terminal area of an airport is generated based on real-time weather conditions. Third, data transfer and data interpretation functions are developed to take responsibility for the interactive actions between the intelligent aircraft agent and the airport. Finally, future research will be focused on improved terminal area traffic flow management functions. These will include an arrival runway load balancing function, an arrival sequencing algorithm, and arrival flow re-planning, given a perturbation such as runway change or severe weather.

4) Weather Model

Real weather data can be obtained from resources on the Internet. This data is either recorded data in the form of historical databases, or actual real-time data, e.g., those provided by National Oceanic and Atmospheric Administration (NOAA) or National Weather Service (NWS). Since most of the weather data is discrete data points, the weather model is established by applying interpolation/extrapolation methods and ruled-based model identification methods.

IV. Conclusions

Results presented in the paper demonstrate that intelligent cockpit systems are promising candidates to address the technology requirements of General Aviation Free Flight and Small Aircraft Transportation Systems. Acting as pilot decision aid tools, these intelligent systems show promise for decreasing pilot workload, enhancing situational awareness, improving approach and landing performance, and providing conflict-free flight guidance in complex environments. Moreover, the use of high fidelity simulation as an evaluation and validation method appears to be of particular use and importance to the development of such an intelligent cockpit system. Future researcg efforts are focused on developing advanced decision aid tools pilots, and a high fidelity terminal air traffic simulation system.

Acknowledgment

This research is funded by the State of Texas Advanced Research Technology Program, under grant number 000512-0301-1999. The authors gratefully acknowledge this support.

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