MULTI-AGENT FLIGHT SIMULATION WITH ROBUST SITUATION GENERATION

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Abstract[*]

Air traffic management systems, on-board aircraft systems, and proposed airspace management structures such as free-flight are often operated with human operators in a simulated environment. This is necessary for effective design and testing of these systems, as well as the training of the operators. For these experiments or training scenarios, success often depends upon human subjects experiencing one-or-more specific situations. Reliably generating these specific situations is often difficult because subjects may not act consistently or as expected; and these variations can affect the system. Generating specific situations in the presence of this uncertainty is referred to as robust situation generation, robust because the situations must occur within a range of possible actions by the subject. A robust situation generation architecture was developed to support flight simulation tests of air transport cockpit systems. Pseudo-aircraft maneuver within reasonable performance constraints, interact in a realistic manner, and make pre-recorded voice radio communications. The achieved robustness of this system to typical variations in the subject's flight path was explored. It was found to successfully generate specific situations within the performance limitations of the subject-aircraft, pseudo-aircraft, and the script used.

Introduction

An agent is defined here as a component of a system that has a relatively weak coupling with the remainder of the system; such as an aircraft, a helicopter, or an air traffic controller being elements in a simulated air transportation system. A multi-agent simulation mimics an actual system with at least two agents. Agents that a human subject controls are referred to as subject-agents. All other agents are pseudo-agents.

A situation consists of the trajectories and/or actions of one or more of the pseudo-agents over some period of time. The experimental situation may not involve all the pseudo-agents in the simulation. Also, the desired situation often does not fully constrain the trajectory of any particular pseudo-agent. In this context, a desired situation may involve anything from a single pseudo-agent doing a minor action to the complete state make up of every agent in the simulation for a period of time.

If pseudo-agents act autonomously, each with their own goals, knowledge, and processing, then the sequence of interactions between pseudo-agents and the human subject is sensitive to the initial conditions of the simulation and actions by the subject. For example, if a subject-aircraft flies five knots slower than expected over 90 minutes, then the subject-aircraft would be eight NM away from where it was expected to be. Had the desired situation been a collision hazard, a pseudo-aircraft intended to have a near miss might now safely pass as far as 8 NM away. Figure 1 shows both the desired situation (a collision hazard) and the resulting situation if the subject flies slower than expected.

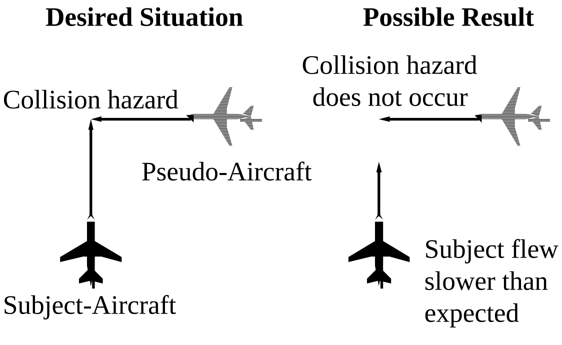

Figure 1 - Sensitivity to Subject Action

Tolerance to actions of the subject-vehicle implies the need for some form of feedback from the subject-vehicle. In current air traffic research, this is typically achieved by having the pseudo-aircraft 'flown' by another human[1]. Another approach is to have an experimenter or instructor change the flight plan of the pseudo-aircraft or subject-aircraft in real time to create

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specific situations, acting as an air-traffic controller. These options can be quite labor-intensive, and are inherently prone to inconsistent situations; which can confound experiments.

Given the power of computers used for real-time simulation, it has become possible to automate the pseudo-agents and generate specific situations using state feedback from the subject-vehicle. This approach is referred to as robust situation generation. The experimenter or instructor can, within limits, predetermine the situations that the subject is exposed to. These situations can then be replicated for multiple subjects.

In order for robust situation generation to be effective, pseudo-agents must also appear to maneuver realistically from the subject's point of view. The pseudo-agents must individually maneuver within performance constraints. Also, the pseudo-agents must interact with each other properly, in ways that would be normal in the actual system. In many cases, care must be taken only when the subject can perceive the pseudo-agents. These limits on the ability of the pseudo-agents to maneuver limits how robust the system can be.

Figure 2 illustrates how a situation generation system fits in to a multi-agent flight simulation. A subject-aircraft as a single subject-agent, and pseudo-aircraft and controllers are the pseudo-agents. The robust situation generator uses system state feedback to generate scripted situations by providing commands to the pseudo-agents in the form of desired trajectories and event plans, a process described in the next section.

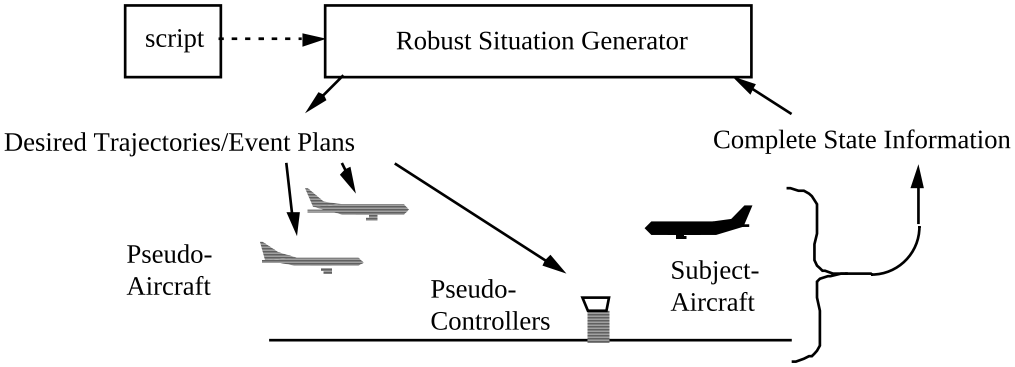

Figure 2 - Robust Situation Generation System

Approach

To generate specific situations, the robust situation generation architecture utilizes control over where the pseudo-agents go and what they do. The desired trajectory tells pseudo-agents where to go. An event plan tells them what to do and when.

The pseudo-agent model maneuvers along its desired trajectory, resulting in a real-time actual trajectory. Also, it executes an event plan. The event plan contains a list of actions at a criterion to cue each action. This relationship is shown in Figure 3 If the pseudo-agent is a vehicle, this model contains guidance and equations of motion for the vehicle. Otherwise, only the event plan is required.

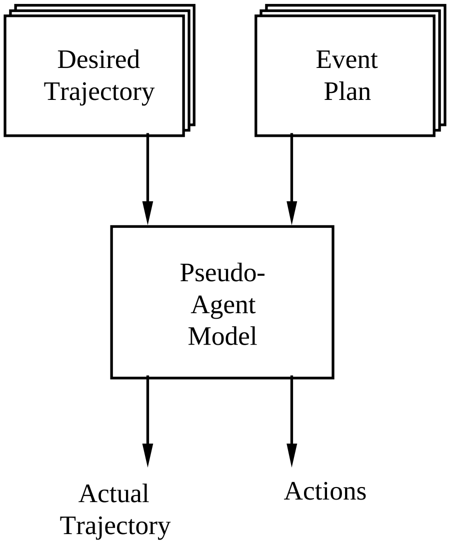

Figure 3 - Pseudo-Agent Model

Pseudo-agent actions need to be realistic when the subject can perceive them. Maintaining a model for each pseudo agent ensures that these agents individually behave in a realistic manner. By using processing that follows the desired trajectory as closely as possible within performance limits, realistic maneuvering of individual pseudo-agents is assured.

Desired Trajectories

Each pseudo-vehicle has a desired trajectory. This desired trajectory can be defined by a list of waypoints. There are many possible desired trajectories, or waypoint types, applicable to robust situation generation. Examples include: traditional position/time waypoints to 'maintain heading, use pitch and speed to collide with subject' or 'stay one mile behind subject'.

A fundamental type of waypoint applicable to robust situation generation is the 4-dimensional waypoint, referred to here as a 4D waypoint. A 4D waypoint is a position in space plus a desired time to be at that point. A series of 4D waypoints define a desired trajectory in space.

One way to use real time subject state feedback is to utilize waypoints that are defined to be relative to the subject-vehicle. A spatially relative waypoint specifies that the pseudo-aircraft is to be in a position relative to the subject-vehicle at a prescribed time. The use of two such waypoints is illustrated in Figure 4, where the pseudo-agent maneuvers to arrive on a parallel course with the subject-vehicle. In this case, the waypoints specify to be 5 NM South of the subject-vehicle at two moments in time.

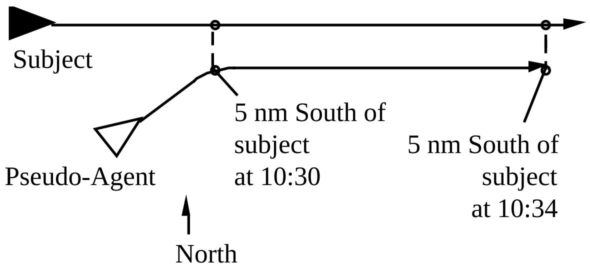

Figure 4 - Spatially Subject Relative 4D Waypoints

Depending on the type of multi-agent simulation experiment, other types of subject-relative waypoints may be useful. For example, rather than having the spatial elements relative to the subject-vehicle, it may be useful for the time element to be relative to the subject-vehicle. A waypoint could use normal spatial points, but use a time that is adjusted so the pseudo-agent maintains a prescribed distance from the subject-vehicle. Figure 5 illustrates such a waypoint. The first waypoint is a conventional 4D waypoint with a normal desired time. The second waypoint is a prescribed position with a desired time that is adjusted continuously so the pseudo-agent maintains a prescribed distance from the subject-vehicle. This waypoint uses speed changes to accomplish the specified range between the two vehicles.

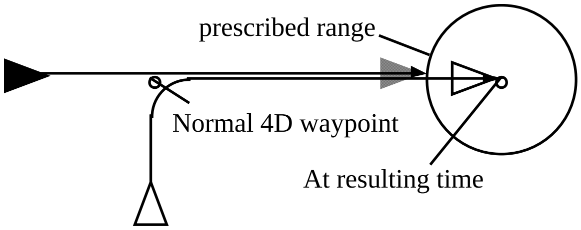

Figure 5 - Subject Range Relative 4D Waypoint

Clearly, many other possibilities for subject relative 4D waypoints exist. Any particular simulation may require one or more type of 4D subject relative waypoint to accomplish its goals.

Event Plan

Pseudo-agents need to do more than just maneuver relative to the subject-vehicle. Pseudo-agents that do radio communications, configuration changes, etc. may need to be a part of a simulation. Anything a pseudo-agent does beyond movement is referred to in this work as an event.

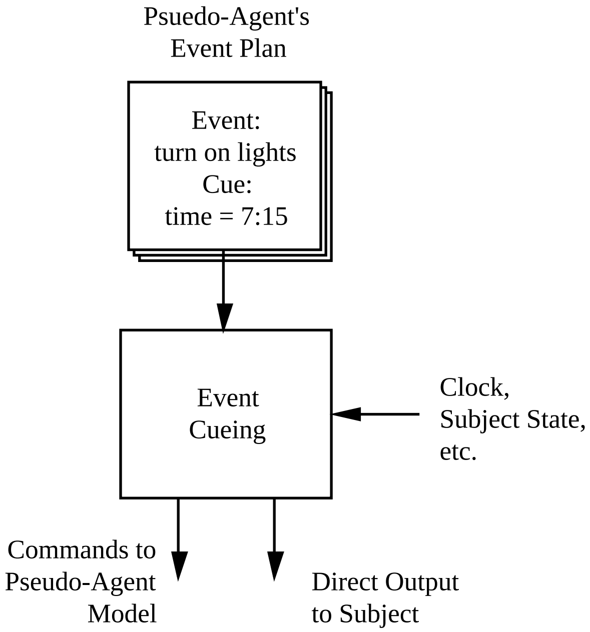

Figure 6 - Event Cueing, Single Pseudo-Agent

Events are cued by some criteria; such as time, subject-vehicle ETA to a key point, or subject-vehicle location. An event plan is assigned and maintained for each pseudo-agent, Figure 6. From this plan, events are cued and result in discrete actions by that pseudo-agent. By allowing events to be cued on criteria other than time, increased robustness to varied subject actions is obtained.

As illustrated in Figure 6, events can result in either direct output to the subject or commands to the pseudo-agent model or perhaps both. An example of the former would be a radio transmission on a frequency the subject is listening to. Examples of the latter are firing a cannon, lowering landing gear, or turning off lights.

Amendments

From time to time, the situation generation controller or human experimenter may want to make discrete changes to the desired trajectories and event plans of one or more of the pseudo-agents. In terms of the architecture presented, an amendment contains waypoints and events for one or more of the pseudo-agents in the simulation. The amendment also has a cueing criterion.

In general, an amendment cueing criterion is a logical expression. For example, an amendment could be scripted to occur when time is greater than 45 seconds, subject speed is less than 200 knots, or some distance is less than 5 nautical miles. The use of other amendment cues can be used to increase robustness.

There are a number of different ways to use amendments and amendment cues to facilitate robust situation generation. Some key examples are illustrated in Figure 7. As the subject-vehicle travels through space, its trajectory will be different than the expected subject trajectory. Amendment can be used to adjust the desired trajectories and event plans of all pseudo-agents based on the arrival time of the subject to an area of space, as shown for the first amendment in Figure 7.

A second example of an amendment is the collision hazard situation also shown in Figure 7. This amendment changes the desired trajectory of one of the pseudo-agents so it maneuvers relative to the subject-vehicle. By use of the amendment, this situation will only begin once the subject is in the proper position. If the subject is late or early, this is accounted for.

A third example of an amendment in Figure 7 is a blunder made by the subject. If the experimenter wants to allow the subject to take different discrete paths, or wants to design for different blunders the subject could make, then amendments could be made to account for these discrete variations.

A very flexible amendment cue is a manual one. This can simply be the experimenter hitting a button to trigger an amendment. Other aspects of the subject or pseudo-agent state, such as ETA, range, velocity, or others are also candidates. Amendment cues can also be logical operations of multiple cues.

Overall Configuration

Two fundamentally different uses are made of subject state feedback in this work. First, amendments and events can be cued based on subject state. Event cues allow pseudo-agent actions to occur at the proper time even when the proper time depends on what the subject does. Amendment cues are used to make changes to pseudo-agent trajectories based on subject state. A second, fundamentally different, use of subject

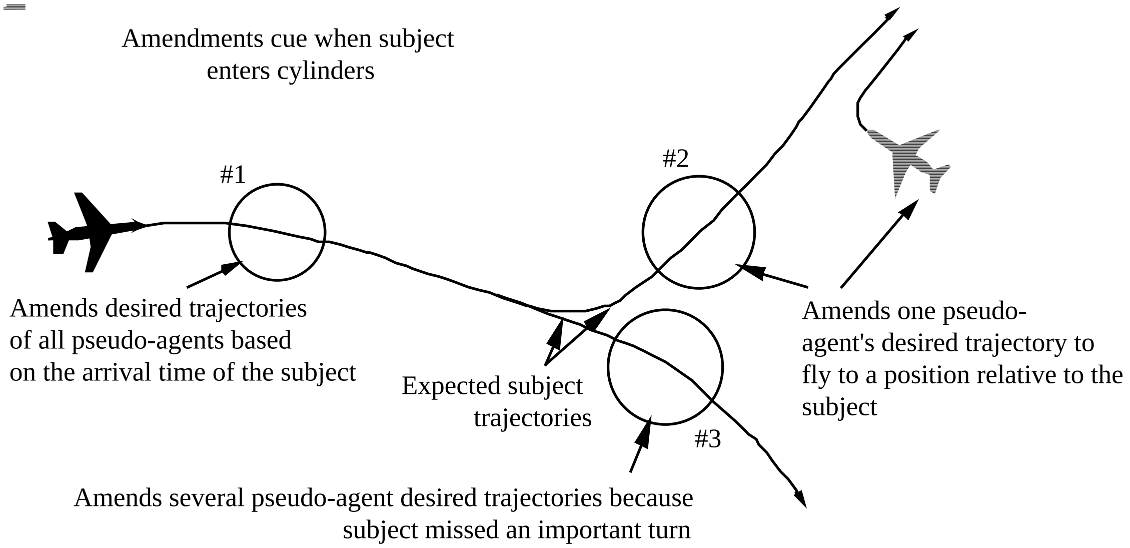

Figure 7 - Amendment Cueing Illustration

state feedback is real time adjustment of a pseudo-agent’s desired trajectory by use of subject relative waypoints.

The final robust situation generation architecture must include amendments and amendment cueing, and is depicted in Figure 8. Each amendment contains a desired trajectory update and/or event plan updates for one or more of the pseudo-agents. It also contains a cueing criterion. This cueing criterion can be based on system state or can be triggered by an experimenter. Also, cued amendments can adjust several interacting pseudo-agents simultaneously.

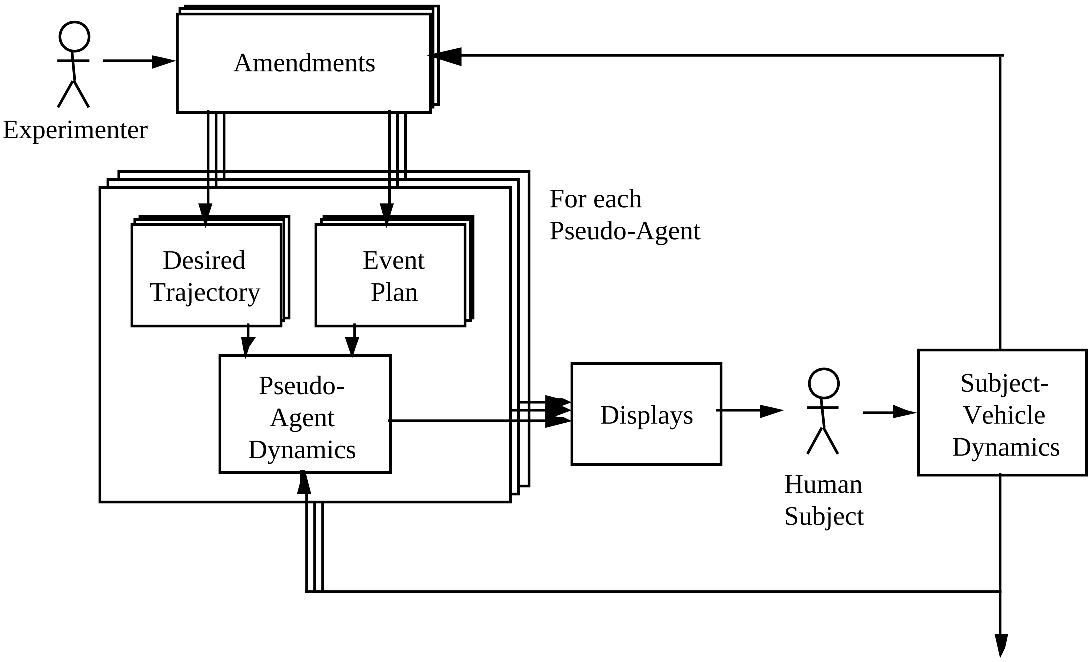

Figure 8 - Overall Configuration

Implementation

This section describes a specific implementation of the robust situation generation architecture. The facility is a tool used for air transportation systems research.

For research involving collision avoidance systems, such as the Terminal alert and Collision Avoidance System (TCAS), and other air transportation concepts such as free-flight, many different types of pseudo-aircraft traffic situations are needed. These include collision and near collision situations, collision hazard situations, and other traffic related situations. Other traffic related situations include expected sequencing around weather, expected holding, etc. to test pilot situation awareness.

Simulator Setup

The simulation experiments were to be conducted on the Aeronautical Systems Laboratory (ASL) Advanced Cockpit Simulator (ACS). The simulator is centered around a graphics workstation, used to integrate the subject aircraft's dynamics and provide the desired displays. The simulator also provides a Control Display Unit (CDU), Mode Control Panel (MCP), sidestick, and throttle quadrant, shown in Figure 9.

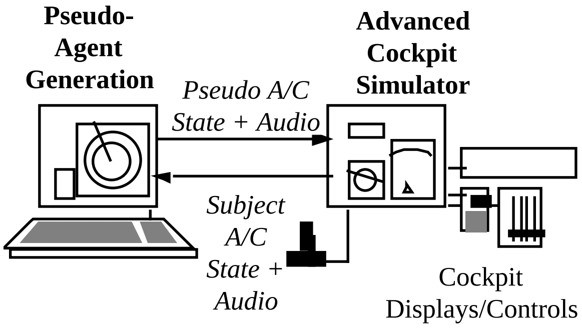

Figure 9 - Simulator Setup

Pseudo-aircraft were generated on a machine separate from the cockpit simulator, also shown in Figure 9. This created an experimenter's station that could be placed away from the pilot’s display, in another room if desired. A display of all aircraft in the simulation was developed for use in writing the scripts and monitoring progress during an experiment. The result is the experimenter's display, shown in Figure 10.

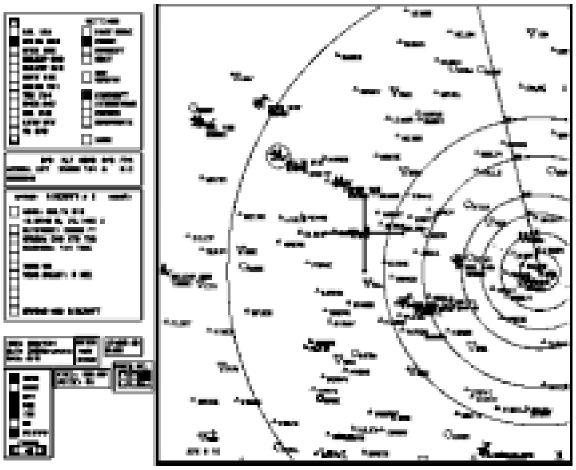

Figure 10 - Experimenter's Display

The experimenter's display is essentially an electronic map of an area. All aircraft, including the subject-aircraft, are shown as symbols at their proper locations. Airports, navigation fixes, intersections, and radio navigation aids are shown. In a separate window on the screen, a variety of information about the subject-aircraft is displayed. This information is received from the ACS and is shown as a reference for the experimenter. Information about pseudo-aircraft can be displayed, including the waypoints the pseudo-aircraft is flying through

Pseudo-Aircraft Modeling

Multi-agent flight simulation relies on realistic modeling of the pseudo-aircraft. This includes equations of motion, performance limitations, and a guidance model. The specifications of planned experiments directly determine the fidelity and accuracy required of this model.

The requirements for a TCAS display imply that pseudo-aircraft states must result in realistic update of latitude, longitude, and altitude. Many proposed enhanced traffic displays, as well as useful TCAS alerts, imply that airspeed, vertical speed or Flight Path Angle (FPA), and heading should also be outputs. Because these experiments do not require any information about pseudo-aircraft conventional control locations (aileron, elevator, rudder), a rather simple aircraft model can be used.

Different aircraft types are modeled through database of aircraft performance parameters. The parameters are then used in a generic performance limits structure for all pseudo-aircraft, summarized in Table 1.

	lower bound	upper bound
Ground speed	stall speed & bottom of power curve based on current environment	regulations & cruise mach number based on current environment
Flight path angle	best attainable in steady state at current altitude within speed limits	
Roll angle	arbitrary	
Ground speed rate	best available given altitude, airspeed, and flight path angle	
Flight path angle rate	lift coefficient & structural load factor	
Roll rate	best available at current airspeed	

Table 1 - Performance Limitations Summary

The performance limitations, in general, need only be active for a particular pseudo-aircraft when that vehicle can be perceived by the subject. This has the potential to improve situation robustness. For this implementation the benefit is small due to the range of the TCAS traffic display.

Voice Generation

Pseudo-aircraft PLI is accomplished by organizing individual pseudo-aircraft voice radio transmissions as events. This is done by digitally recording them ahead of time, and then using the robust situation generation architecture to play them back at the proper time.

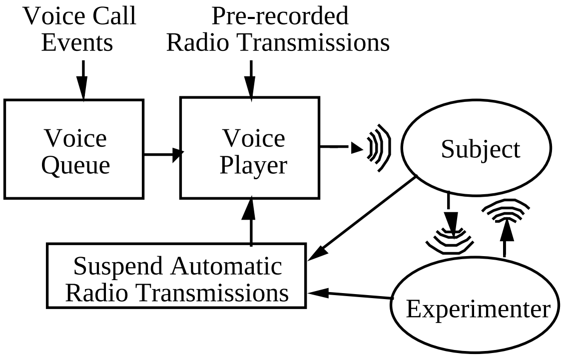

Figure 11 - Voice Generation

Once a radio transmission event is cued, it goes into a voice queue. It is used in combination with the voice player, Figure 11, to prevent more than one call from occurring at the same time, to suspend voice calls when a human is transmitting, and to ensure that the subject hears only those transmissions on the frequency selected. Included in the definition of each voice call is a frequency that it is transmitted on, a priority value, a maximum wait time, and the identification of the digital recording to play back.

The priority value prevents important transmissions from having to wait too long. Transmissions with higher priority simply skip those of lower priority when entering the queue. A maximum wait time is used to delete a radio communication event when it is no longer relevant, to prevent clearances for unimportant aircraft from occurring after the time period during which they make sense.

An experimenter acts as the controller that the subject is currently communicating with. Although most of the controller's voice calls can be scripted and pre-recorded, all of the possible requests of the subject cannot be realistically prepared for.

Transmissions by the controllers to other aircraft are normally pre-recorded and scripted as events. These voice calls are normally tied to pseudo-aircraft transmissions such that one is played immediately after the other. For example, the sound recording:

KBOS Tower: *United 111, you are cleared to land, runway 4 left.*

would be immediately followed by:

United 111: *United 111, cleared to land 4 left.*

without interruption. This is accomplished simply by having the second transmission cue be the execution of the first. The only way they can be split up is if a higher priority message enters the cue while the first one is playing, as desired.

The subject has a communications radio control console where the transmitting/receiving communications frequency and volume can be changed. The voice queue is suspended when the subject or experimenter-controller transmits, and restarted manually by the experimenter. At this point, radio transmission events would resume playback.

Script Development

To script the flight of numerous aircraft over a significant length of time is not a trivial task. Add to this the creation of specific situations for a subject with varied actions, and it is clear that a critical aspect of this approach to multi-agent simulation is writing the script for the experiment.

For this implementation, an effective way to write and edit scripts was to include tools specifically for this purpose in the experimenter's station, Figure 10. A list of all aircraft is shown at the left of the screen, allowing the user to select specific aircraft. Four other menus can be brought up to modify the robust situation generation script: aircraft, amendment, event, and waypoint. An organized way to record the numerous digital audio recordings to be played back is a necessary component of this type of system. Due to the large number of calls from any individual, it was effective to make an interactive program for the specific purpose of recording.

Achieved Robustness

A test script, or flight, was used to evaluate the robust situation generation architecture and the implementation developed. The expected flight path of test script subject-aircraft is depicted in Figure 12. The subject-aircraft starts at 23,000 feet above LVZ (Wilkes Barre) VOR and proceeds to a landing at New York's JFK airport runway 31 Left. The expected flight path is defined by a series of 4D waypoints. Each point has a latitude, longitude, altitude, and time. The subject receives clearances as necessary to match the expected flight path as closely as possible. The robust situation generation architecture causes specific situations to happen even when the subject varies from the expected path or speed. The general locations of the three situations are labeled on the figure as A, B, and C.

There are three situations included in the test script. First, the subject is to see and hear aircraft ahead request lower altitudes due to turbulence at 19,000 feet. This requires several pseudo-aircraft to fly similar flight paths as the subject while maintaining a scripted separation from the subject and each other. It also requires radio communications from the pseudo-aircraft. It is scripted to occur in area A shown on Figure 12.

The second situation is a TCAS Traffic Advisory (TA) caused by an aircraft passing below. This is to appear normal to the subject. A pseudo-aircraft is to pass 2000 feet below the subject on a perpendicular course while the subject is in area B in Figure 12.

The final situation is a collision hazard while on final approach to runway 31L at JFK, shown as area C in Figure 12. The intruder pseudo-aircraft flies to a scripted location relative to the subject-aircraft on its parallel approach to runway 31R. It deviates from its

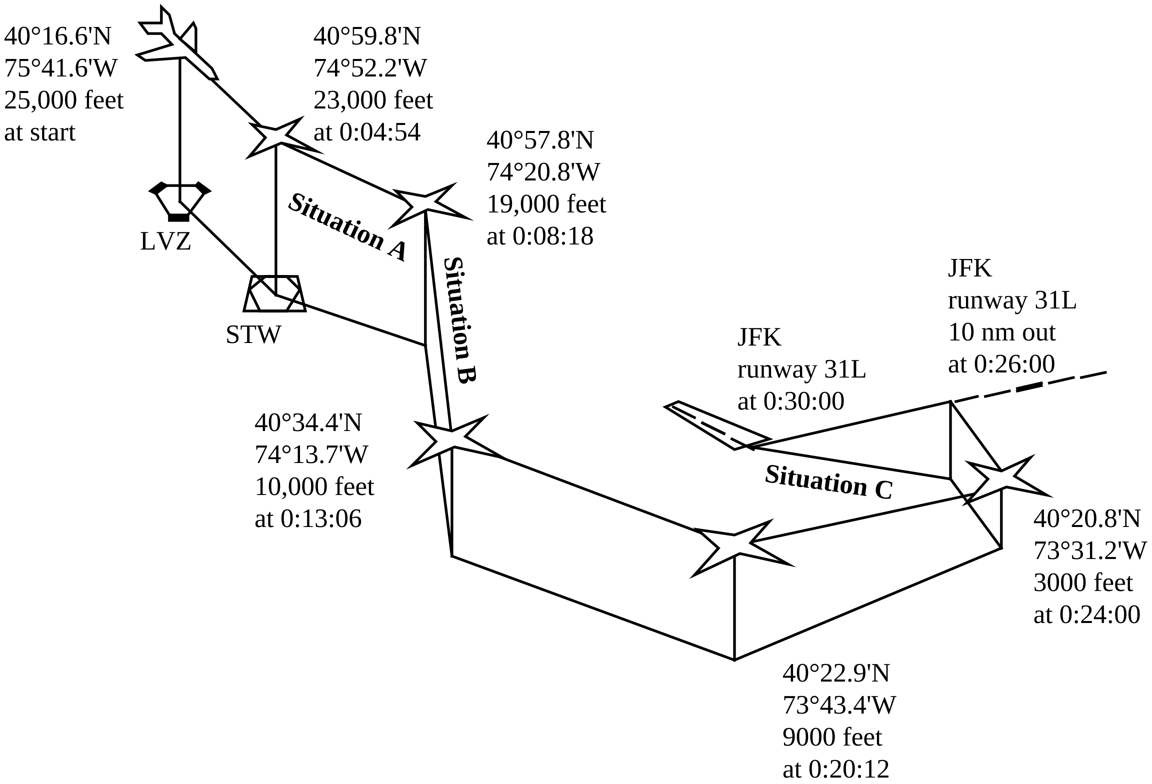

Figure 12 - Nominal Subject Flight Path

flight path and creates a collision hazard at five NM from touchdown. The intruder and subject each get a TCAS Resolution Advisory (RA) that will generate avoidance commands for both aircraft.

Reasonable background traffic, in the form of pseudo-aircraft not directly involved in any of the above situations, were also used. All aircraft, including this background traffic, must perform within reasonable performance limits and interact properly for an individual flight to be a success.

The first step in writing the test script was determining a nominal flight path for the subject-aircraft, shown in Figure 12. If branches of significantly different flight paths are to be allowed, these other branches should also be determined. In the case of the test script, the only branch allowed occurs during situation A. If the subject requests a lower altitude, it is given. If not, the new altitude will be given at the end of situation A.

The 4D waypoints for the pseudo-aircraft are then created based on the subject-aircraft expected flight path. This approach ensures that the highest fidelity pseudo-aircraft generation occurs were it is needed, in view of the subject. In this case, standard arrival and departure waypoint sets are stored for JFK, Newark, and La Guardia runways. These sets were used repeatedly to eventually define the flight paths of 34 pseudo-aircraft.

The next step taken in this demonstration flight was to split the flight into 15 amendments. The first 14 amendments are designed to cue approximately every two minutes. They provide waypoint updates for all active pseudo-aircraft. The amendment cue for each will be subject-aircraft ETA of less than one minute to a point on the map. By using this approach; if the subject travels slower or faster than expected, amendments will be cued later or earlier respectively. This effectively adjusts the pseudo-aircraft waypoint times every two minutes to variation in subject-aircraft speed.

The complete test script amendment list is shown in Table 2. The flight contains three situations that are critical to the experiment. The turbulence reports situation corresponds to the third amendment in the list. The TA corresponds to the fifth. The parallel approach RA begins when the 14th amendment is cued, and an additional amendment is cued so that the RA occurs at 5 NM from the runway threshold. The RA amendment updates only the pseudo-aircraft that will cause the RA. The other amendments are necessary to maneuver the pseudo-aircraft realistically and place them for the three experiment critical situations in a robust manner.

Amend-ment	Expected cue time	note:
1	0:00:00	Active at start-up (initial set of waypoints and events)
2	0:02:00	
3	0:04:00	Turbulence reported at 19,000 feet from pseudo-aircraft situated ahead of the subject-aircraft
4	0:06:00	
5	0:08:00	TA situation; TA aircraft gets a subject relative waypoint 2000 feet directly below the subject-aircraft
6	0:10:00	
7	0:12:00	
8	0:14:00	
9	0:16:00	
10	0:18:00	
11	0:20:00	
12	0:22:00	
13	0:24:00	
14	0:26:00	Intruder aircraft gets subject relative waypoints on the parallel approach in order to get in the proper position
RA	0:26:45	Collision hazard (RA); intruder flies directly into the subject-aircraft until RA occurs

Table 2 - Test Script Amendments

Achieved robustness was evaluated by varying the subject's flight path to extremes of speed and lateral position error, as well as subject blunder errors. They were varied to the point that the test script and the robust situation generation architecture could no longer adequately control the pseudo-agents, generate desired situations, or when the extreme of the subject-aircraft's performance envelope has been reached. Speed and lateral position errors are differences between the expected subject-aircraft flight path and the actual flight path. Blunder errors were wrong turns and incorrect altitude commands made by the subject.

Speed Error

The achieved robustness to speed variation was explored by varying the speed of the subject by a multiplicative factor. The system was tested by flying the subject-aircraft at 120, 110, 90, and 80% of the expected speed profile, which contained speed near both the upper and lower bounds of the subject-aircraft's speed envelope.

The resulting amendment cue times are shown in Figure 13. Early in the 110 and 120% cases the subject-aircraft was performance limited. This is shown by the curves lying roughly on top of each other in the first 5 amendments. Though not apparent from the figure, the subject-aircraft flew unrealistically close to stall speed for much of the later part of the slowest test, 80% speed.

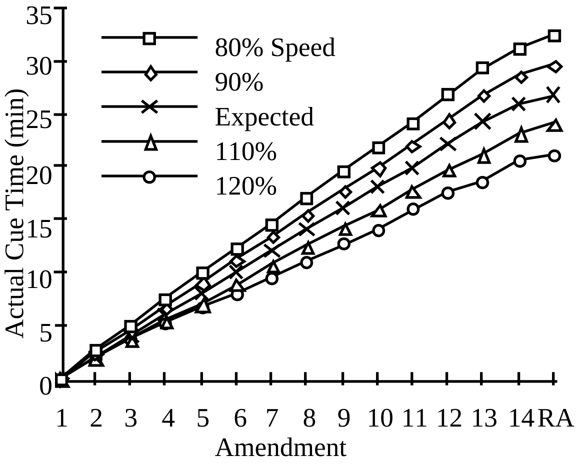

Figure 13 - Actual Cue Times for Different Subject Speeds

For these tests, the three experiment critical situations and the background traffic were observed. For all but the fastest test, 120% speed, experiment critical situations occurred as scripted and background traffic appeared to maneuver properly.

For 120% case, it was observed that some background traffic could not keep up with the experiment due to the 250 knots speed limit below 10,000 feet. As a result, some turns were cut short and trailing distance in some landing sequences became unreasonably small. For the same reason, the pseudo-aircraft involved in the parallel approach RA could not arrive in time to cause a collision hazard at 5 NM from the runway as scripted. A summary of these results is shown in Table 3.

Speed	Turbulence Reports	TA	RA	Back-ground
80%	yes	yes	yes	yes
90	yes	yes	yes	yes
110	yes	yes	yes	yes
120	yes	yes	no	no

Table 3 - Results of Subject Speed Variation

Although the subject is highly unlikely to fly the 120% trajectory, it is possible that the waypoints given to offending pseudo-aircraft could be modified to allow the system to work under these conditions. The approach would be to have these aircraft fly slower when the subject is on the expected flight path. Clearly, there is a balance between tolerance allowed at the bottom and top of the subject's speed range. The experimenter can shift the range of speeds up and down by adjusting pseudo-aircraft waypoints. As shown, this speed range available to the experimenter in this implementation is approximately the same as the subject-aircraft's performance limits.

Position Error

Another way the subject can vary flight path from expected, beyond speed, is to fly slightly off the expected course. This can manifest itself as being slightly left, right, above, or below the expected flight path.

Achieved robustness to position error was tested by flying the subject-aircraft one, two, and four NM right of the expected flight path. These errors are extreme for a transport category aircraft following an ATC clearance, but were chosen in order to test the limitations of this robust situation generation system. No position error was included once the subject was established on the localizer.

Position errors of one and two NM right of the expected course had no effect on the system. This was not the case with a position error of four NM. In this case, using the ETA of one minute amendment cue meant that amendments would not cue if the subject was flying slower than four NM per minute. This corresponds to a ground speed of 240 knots. Once the subject-aircraft speed dropped below this value, which happened shortly after the TA situation, new amendments were not properly cued. This caused the simulation to longer be tolerant to subject actions, so the parallel approach situation and the background traffic were no longer assured. A summary of these results is shown in Table 4.

Error	Turbulence Reports	TA	RA	Back-ground
1 NM	yes	yes	yes	yes
2	yes	yes	yes	yes
4	yes	yes	no	no

Table 4 - Results of Subject Position Error

If an experiment requires tolerance to position errors of this magnitude, four NM, a different amendment cue should be used, perhaps a larger ETA value.

Blunder Error

The final type of subject variation explored is the blunder error. Tolerance to blunder errors was tested by having the subject-aircraft make a key turn at two levels of delay. In all cases the experimenter was assumed to intervene, acting as ATC, and clear the subject to a new heading that will put the subject back on the desired flight path. Achieved robustness was also tested by having the subject-aircraft descend too far when capturing a cleared altitude, and then remain at this lower altitude until it returned to the expected flight path.

The first test was to have the subject aircraft fly 2.5 NM beyond the point at which the base turn was to be initiated, the 9000 feet 0:20:20 waypoint in Figure 12. This could be caused because the subject did not hear the new clearance. This blunder had no effect on the system. When the blunder distance was increased to five NM amendment #12 in Table 2 did not cue. This *might* cause a problem if the subject were to fly at a very different speed than expected during this period of time, which would be unusual for this particular phase of flight, because the pseudo-aircraft had to wait four minutes between trajectory updates rather than the normal two minutes. A summary of these results is shown in Table 5.

Blunder Error	Turbulence Reports	TA	RA	Back-ground
• 2.5 NM late turn to base	yes	yes	yes	yes
• 5 NM late turn to base	yes	yes	yes	see text
• descent to 17,000 rather than 19,000 feet	yes	yes	yes	yes
• descent to 6000 rather than 10,000 feet	yes	yes	yes	yes

Table 5 - Results of Subject Blunder Error

Altitude blunder errors were also tested. The descent to 19,000 feet shown in Figure 12 was lowered to 17,000 feet. In a separate test, the descent to 10,000 feet was increased to 6000 feet. These blunder errors represent extremes of possible mistakes to be made by subjects. Also, these two cases are among the few possible scenarios where the subject-aircraft can descend significantly too far using a reasonable descent rate. In both cases, the system performed as expected, also shown in Table 5.

Summary and Conclusions

A robust situation generation approach has been developed. This approach utilizes subject feedback in two fundamental ways. First, the trajectory of a pseudo-agent can be adjusted continuously in response to the motion of the subject. Second, discrete qualitative amendments to the agents' trajectories can be cued by some aspect of the subject's current state. In addition, discrete actions can be similarly cued for the pseudo-agents, such as turning on lights or lowering landing gear.

The robust situation generation approach was implemented for an air transportation system research facility. Experiments required voice communication to be heard by a human subject from other aircraft. It also required specific types of collision hazards between the subject and other aircraft. A pseudo-aircraft model and other related software was developed to implement the situation generation architecture for use in this type of research.

A test situation generation script, designed to be a part of an air transportation research experiment, was developed. This script contained three situations that were critical to present to the subject. The script included fifteen amendments, where these amendments organized background aircraft and led aircraft involved in the three experiment critical situations to their proper positions. The achieved robustness of this test script to variations in subject actions was explored. This analysis included varying the subject-aircraft speed and position accuracy, as well as testing blunders by the subject, such as missing a turn.

Achieved robustness indicated that the system allows specific situations to be generated for subjects who perform within a reasonably large envelope of possible action. In cases where the system failed, the subject was performing at an extreme of possible action or a limitation was found in the script that could be rectified if needed.

The development of a script is an important element of the system presented. Scripting the flight of multiple aircraft in a crowded sky is not a trivial task even before attempting to generate specific situations. This effort can be reduced using software specifically developed for the purpose of script writing.

Triggering voice communications using the robust situation generation architecture, with the implementation of a voice queue, was found to be a powerful technique. It allows pseudo-aircraft radio transmissions to be pre-recorded. This eliminates the need for a large number of 'pseudo-pilots' that would normally provide these transmissions from manned remote stations.

The architecture developed has proven to be effective for air transportation research. It could also be applied other applications, where the details of the implementation would differ. Any system that must coordinate one or more pseudo-agents to give specific situations to a maneuvering subject-vehicle is a candidate for a robust situation generation scheme.

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