A Concept Of Hybrid Flight Simulator Based On Unmanned Aerial Vehicle And Autonomous Flight Situation Modeling[1]

Ivan Burdun[2]
Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150, USA.
Phone: (404) 894 8055. Fax: (404) 894 6596.
E-mail: ivan.burdun@aerospace.gatech.edu

Sergei Sadovnitchii[3]
National Politechnical Institute
Instituto Politecnico Nacional, ESIME-Ticoman,
Av. Ticoman No. 600 Col. San Jose Ticoman,
07340, Mexico D.F., Mexico.
Fax: (525) 586 33 94.
E-mail: sadovnic@vmredipn.ipn.mx

ABSTRACT

A hybrid technology of flight simulation for pilot training is proposed. The aircraft flight dynamics is represented by a flying model instead of a mathematical model implemented in a ground based simulator. The pilot controls the flying model remotely, from a ground station. The model is an unmanned aerial vehicle (UAV) which is dynamically similar to the modeled aircraft. It has video cameras to record out-of-the-cockpit views which are transmitted to and displayed in the ground station in real time. An autonomous flight situation model is employed as a flight scenario planning tool and a backup flight control method.

Two techniques are described: a method for securing the dynamic similarity between the base UAV and the modeled aircraft and a method for implementing the autonomous flight situation model. Several variants of hybrid flight simulator are proposed. Technical problems of concept implementation and possible solution approaches are discussed. The overall objective is to make flight simulators more affordable and increase the quality of training and the fidelity of flight modeling.

GROUND BASED AND FLYING SIMULATORS

In this section advantages and shortcomings of ground based and in-flight flight simulation methods are briefly analyzed.

Flight simulators and pilot training. The ideal method of pilot training is actual flight on the aircraft type which will be flown in operation. However, due to cost, safety and other constraints, flight simulators have to be used as a substitute. The role of training flight simulators is to develop basic airmanship skills and practical flight related knowledge in students, as well as to maintain and upgrade advanced flight control skills in professional pilots. (Sometimes the term 'flight management' is used instead of the 'flight control'.)

Training flight simulators can be divided into two classes: ground based and flying.

Ground based simulators. The simplest flight simulation technology is a software program for a personal computer equipped with a device to imitate flight control inputs. There is a variety of professional flight simulators[1] ranging from functional imitators of specific onboard systems to sophisticated full scale modeling complexes. The most advanced are flight simulators used by airlines and military and reconfigurable engineering research simulators.

Shortcomings. The ground based flight simulation technology is safe and less expensive training means compared with actual aircraft. However, it has a limited flight modeling capability. The shortcomings include the following: (1) limitations on out-of-the-cockpit view modeling, (2) a limited capability of flight scenario planning and execution, and (3) a limited fidelity of flight dynamics modeling.

---

[1] Burdun, I., and Sadovnitchii, S., "A Hybrid Flight Simulator Based on Unmanned Aerial Vehicle And Autonomous Flight Situation Modelling" (Paper AIAA-99-4184), *Proc. Of 1999 AIAA Modeling and Simulation Technologies Conference (MST-99), August _- _, 1999,* USA, 1999.
[2] PhD, Research Engineer II
[3] PhD, Invited Researcher

Flight visualization techniques. To address the first problem the following visualization techniques are employed. First, a mockup of some landscape is built in miniature. During simulated flight, this terrain model is scanned by a tele-/videocamera, and the image is projected on a screen in front of the simulator's cockpit. Second, a pseudo-realistic image of out-of-the-cockpit views can be generated on a computer using various graphic primitives, such as fields, trees, buildings, runways, towers, etc. Finally, a digital terrain map of a limited geographic region can be constructed based on the GPS data. Then, using advanced mathematical methods (e.g.: fractals) and computer graphics, realistic surface details are added. However, these techniques require a substantial amount of preparatory work or/and computer processing power and are very expensive.

Flight scenario planning techniques. In a flight simulator training scenarios are planned and controlled by a pilot instructor or/and using special software and hardware. (Note: we will consider two kinds of flight scenario - demonstrative and training.) A demonstrative scenario is basically an example of some flight situation-case (e.g.: correct/incorrect piloting tactics, incident or accident). Normally, these situations are pre-recorded and then demonstrated to the student. A training scenario is a plan of an interactive flight situation, which may include non-standard flight events and demanding operational conditions. Unlike demonstrative scenarios, student's responses to these circumstances constitute a part of training scenarios. One of the shortcomings of the scenario planning techniques used in flight simulation is a limited "what-if" experimentation capability and a lack of human pilot decision making models.

Flight dynamics modeling. At present, the equations of aircraft motion are available in the most generic form [10]. There are also efficient numeric techniques [11] to solve these equations. Models of the onboard systems which may affect the aircraft flight dynamics and flight control (sensors, actuators, avionics, etc.) are normally known, e.g.: from previous prototypes, etc. Empirical-theoretical models of external operational conditions, such as rain, ice, runway condition, wind, etc., are available as well [12,13].

However, the main method for achieving a higher fidelity of flight dynamics modeling is to improve the quality of the aircraft input characteristics. This is not always possible as aircraft manufacturers may not want to release all the characteristics of their products, especially the data related to extreme flight regimes.

In-flight simulators. There are several kinds of in-flight (flying) simulators. This list includes trainers, specially equipped operational aircraft, and flying laboratories. A trainer is the most popular kind of flying simulator. The role of trainers is to develop in students basic piloting skills and practical knowledge of flight dynamics and control.

The highest fidelity of in-flight flight dynamics modeling can be achieved when the base vehicle is of the same type as the operational aircraft or in a special flying laboratory. The principle of operation of all the flying simulators is to modify apparent stability and control responses of a base vehicle by feeding back response parameters into its electrical flight control system, and by shaping the pilot's inputs[2]. One of the advantages of in-flight simulation is that the pilot acts in his (her) natural operational environment with actual visual cues and actual motion stimuli of the modeled aircraft. Another advantage is that there is no need for a comprehensive mathematical model of the aircraft flight dynamics. Normally, the base vehicle has better dynamic characteristics than the modeled one. So it is not a technical problem to deteriorate its performance in order to match the behavior of the modeled aircraft.

However, due to cost and safety constraints a high fidelity flying simulators have very limited applications. They are used mainly to finalize a training course, assess the flight performance of new aircraft, and for other unique purposes.

Therefore, both ground based flight simulators and flying (in-flight) simulators used for pilot training have advantages and shortcomings. The main problem is how to achieve a higher fidelity of flight modeling and improve the quality of pilot training with minimum expenses.

RESEARCH TASK FORMULATION

Problem. The problem under study can be formulated as follows. Given a task of flight simulation for pilot training, how to (1) increase the fidelity of modeling of the aircraft flight dynamics, (2) achieve a better quality of visualization of out-of-the-cockpit views, and (3) enhance the demonstrative and training scenario planning capability?

The overall objective is to reduce the cost of flight simulation and pilot training with a simultaneous increase in the quality of training.

The solution approach. A new method for addressing this problem is proposed. It is suggested to employ a hybrid flight simulator as a substitute for the "pilot – vehicle – operational conditions" system. The simulator includes a flying model (UAV), the pilot, a ground station, a situational flight model, a synthetic environment of actually present and simulated operational conditions, and auxiliary software and hardware.

Main principle. The central element of a hybrid simulator is an unmanned aerial vehicle, which is radio controlled by the pilot from a ground station. The flight control system of the UAV imitates the flight dynamic characteristics of a specific aircraft. Onboard digital video cameras provide a real-time picture of out-of-the-cockpit views of flight. This information, together with the current flight state parameters, is transmitted to the ground station via a radio channel. A virtual reality Head-Mounted Display[3] is used to present a realistic out-of-the-cockpit panorama of flight to the pilot. This picture is combined with a computer generated image of the instrument panel of the modeled aircraft.

Also, an autonomous flight situation model[8,9] is used on board the flying model and in the ground station. Its purpose is to provide a backup flight control in emergencies or under pilot's request and automate the process of planning of demonstrative and training flight scenarios. Depending on the scenario, the model can perform either autonomous or joint (i.e., together with the pilot) flight control.

Potential advantages. One of the potential advantages of hybrid flight simulators is that the pilot has almost unlimited freedom in executing flight maneuvers in any direction and over any terrain. The presence of the autonomous flight situation model in the control loop helps make training more flexible and safer. Also, external cues which the pilot receives from the flying simulator are almost identical to actual flight (perhaps, with the exception of the takeoff and landing modes – see the discussion section below).

Finally, the cost of the airframe and engine installation of a modern unmanned aerial vehicle (excluding onboard military or other special equipment or payload) is much lower compared with the price of a high-fidelity ground based flight simulator. Other expenses - for the ground station, HUD, onboard video cameras, etc. - are also relatively low.

SIMILARITY OF MOTION

The problem of securing the similarity of motion between the UAV and the modeled aircraft is a problem of finding a control law for the base UAV as a function of its motion parameters[4].

Equations of motion. Two systems of the equations of motion are considered: one is for the base UAV and another - for the modeled aircraft (the index *m* stands for the modeled aircraft):

$$\dot{x} = F(x, u, \varphi) \tag{1}$$

$$\dot{x}_m = F_m(x_m, u_m, \varphi_m) \tag{2}$$

where x is a state vector, u is a control vector, φ is a vector of external disturbances, and F is a vector-function.

It is assumed that the dimensions of the appropriate vectors in (1) and (2) are the same, and all the components of x can be measured without error.

Similarity conditions. The conditions of similarity of the flight dynamics properties for these two vehicles can be formulated as follows. Given the same initial conditions, i.e.:

$$x(t_0) = x_m(t) \tag{3}$$

- there exists a control $u(t)$, $u(t) \in G$, which provides for $\forall\ t \geq t_0$ the equality of the state vectors for the two vehicles, namely:

$$x(t) = x_m(t) \tag{4}$$

for $(\forall u(t_m))$ $(u_m(t) \in G_m;\ \varphi(t) \in \Phi,\ \varphi_m(t) \in \Phi_m)$, where G and G_m - are the domains of possible control inputs for the flying model and the modeled aircraft, respectively; Φ and Φ_m - are the domains of possible external disturbances. Therefore, the problem can be reduced to a study of the implementability of the motion $x(t)$, given the goal program $x_m(t)$. Note that the program $x_m(t)$ is a solution of the system (2), which describes flight dynamics of a specific (modeled) aircraft.

Thus, the task of securing the similarity of motion between the UAV and the modeled aircraft is to find a control law $u(t)$, which implements the relationship (4). It has been demonstrated[4] that if the UAV motion can be described by the system:

$$\dot{x} = Ax + Bu \tag{5}$$

and the motion of the modeled aircraft - by the system

$$\dot{x}_m = A_m x_m + B_m u_m \tag{6}$$

and if there exists a control law $u(t)$, then the following statement will be true:

$$\dot{x}(t) = \dot{x}_m(t) . \tag{7}$$

Thus,

$$Bu = A_m x_m + B_m u_m - Ax . \tag{8}$$

After adding $(Ax_m - Ax_m)$ to the right part of (8) and taking into account the condition (4), we get the following:

$$Bu = (A_m - A) x_m + B_m u_m . \tag{9}$$

Similarly, by adding $(A_m x - A_m x)$, we get:

$$Bu = (A_m - A) x + B_m u_m . \tag{10}$$

The equations (8), (9) and (10) give the following three variants of the control law to satisfy the condition (4):

$$u = B^+ A_m x_m + B^+ B_m u_m - B^+ Ax; \tag{11}$$

$$u = B^+ (A_m - A) x_m + B^+ B_m u_m ; \tag{12}$$

$$u = B^+ (A_m - A) x + B^+ B_m u_m . \tag{13}$$

where $B^+ = (B^T B)^{-1} B^T$ is a pseudo-inverse matrix and the index T means transposing.

The choice of control laws from the list (11)-(13) depends on the application task. The first law provides the invariance of the UAV to wind disturbances by converting the equations of its motion to the equations of a neutral body. The law (12) differs from the first one in the use of signals from the model, which implies that measurements of flight parameters for the UAV are not required during flight. In the third law (13) there is no need to solve the equations of motion (6) for the modeled aircraft – it is sufficient to measure flight state parameters for the UAV.

Similarity by airspeed. One of the problems of securing the similarity of motion between the UAV and the modeled aircraft is the similarity by speed. Many UAVs (such as “Pioneer”, “Hermes”, etc.) have a maximum cruise speed of up to 300 km/h. This covers the majority of flight regimes for general aviation aircraft, as well as the takeoff and landing phases for other airplane types. To model flight of large (subsonic) aircraft, special UAVs are required to be able to address other flight regimes, such as climb, descent and cruise. Nevertheless, the production cost of such UAVs is expected to be much lower than for military UAVs.

One of the most complex tasks is to adequately model flight of highly manueverable airplanes, such as F-18, Sukhoj-27, Rafale, and F-22. The use of special electronic modules adjusting the dynamic characteristics of the vehicle control system does not help meet the similarity criteria for such aircraft types at high angles of attack, during rapid turns, etc. In these cases, it is required in addition to secure the aerodynamic similarity between the UAV and the modeled aircraft. For this purpose a large scale dynamically similar [flying] model, or DSM, can be used as a base vehicle. At present, DSMs are broadly used for advanced flight control concept research [5,6]. For example, DSM X-36 has a full set of equipment to remotely control the vehicle by the pilot from the ground.

A DSM has the same aerodynamic configuration as the modeled aircraft. Normally, the structure of its control system is similar to the original aircraft system. In all cases, the coefficients required to obtain model's gains from the aircraft’s ones depend on actual dimensions and are defined by the following equations[7]:

$$\mathrm{K} = 1, \ \text{for dimension} \left[\frac{\text{degree}}{\text{degree}}\right]$$

$$\mathrm{K} = \sqrt{\mathrm{K_L}}, \ \text{for dimension} \left[\frac{\text{degree}}{\text{degree / s}}\right]$$

$$\mathrm{K} = 1/\sqrt{\mathrm{K_L}}, \ \text{for dimension} \left[\frac{\text{degree / s}}{\text{degree}}\right]$$

where $K_L = \frac{L_M}{L}$; K_L is the linear dimension scale.

To achieve the required stability and controllability characteristics in a DSM-based flying simulator the Froude similarity criterion must be met. The equation expressing the required relationship between inertial and gravity forces is as follows:

$$\frac{V_N^2}{gL_N} = \frac{V_M^2}{gL_M} = Fr; \ \text{and } Fr = idem \tag{14}$$

where V is the velocity, g is the acceleration due to gravity, and L is the characteristic length. Finally, the following conditions of compliance with the Froude criterion for the velocity and time complete the system:

$$V_M = V \cdot K_V = V \cdot \sqrt{K_L}$$
$$t_M = t \cdot K_t = t \cdot \sqrt{K_L} \ .$$

Note that because K_L is always less than 1, all the processes in the flying model run faster. Thus, if a DSM is used, special modules must be introduced into its flight control system to slow down the dynamics of control surfaces (the rates of deflection, etc.). This issue requires a more detailed study.

Thus, employing a dynamically similar flying model, a higher fidelity of physical modeling of the aircraft aerodynamics and flight dynamics can be achieved. In addition, various failures in the flight control system (e.g.: actuator's malfunctions), as well as mechanical damages to the airframe and control surfaces, can be imitated.

AUTONOMOUS FLIGHT SITUATION MODEL

In this section an introduction is made to the autonomous flight situation model. This model is proposed as a method for flight scenario planning and backup flight control in a hybrid flight simulator. An example of flight scenario will be given to demonstrate how this method can be implemented.

The autonomous flight situation model. Basically, the autonomous flight situation model is a system of data structures and generic computational algorithms which model a flight situation as a discrete-continuous cause-and-effect structure.

The object of autonomous flight modeling is the behavior of the ‘pilot - vehicle - operational conditions’ system in a complex flight situation. Modeled phases and modes of flight include: take-off (normal, aborted, and continued), landing (normal, continued, and go-around mode), climb, descent and landing approach (any profile), en-route flight modes (any profile), groundroll motion, and special/test maneuvers (e.g.: stall, spin, power-off flight, etc.).

Components. The autonomous flight situation model includes the following components:
- a situational, or tactical, pilot model (‘silicon pilot’)
- models of selected external factors (e.g.: wind shear, rain, icing)
- models of selected internal factors (e.g.: engine failures, control surface hardovers, pilot errors).

In this paper the first component, a situational pilot model, will be introduced.

Situational pilot model. The situational pilot model is a system of input flight scenarios and computational algorithms that imitates a limited subset of a human pilot’s knowledge and decision making functions required to perform situational (tactical) flight control.

The pilot’s control tactics are formalized at the level of cause-and-effect relationships between flight events and control processes. These are the only two object types, which are required to plan and simulate flight situations of practically any complexity [9].

Limitations. The proposed pilot model has the following limitations. Pilot’s sensor-motoric functions are not modeled. Pilot’s strategic decision making functions are not modeled with the exception of the flight scenario planning function. Situational decision making is formalized as a multi-stage control process based on flight scenarios.

Why to model the human pilot? The role of adequate situational models of the human pilot in training is very important. Situational models provide a link between the perceptual-motor and strategic levels of a human pilot’s decision making mechanism. Situational (tactical) control is largely responsible for safe and unsafe outcomes of a particular flight. Using such models, pilot’s tactics and errors can be analyzed as an integral part of the system behavior. Finally, the situational pilot model is a powerful tool for studying an emerging class of flight safety problems - multi-factor operational domains of flight and “chain reaction” flight accidents [9].

There are three basic concepts of the autonomous flight situation model: the flight event, the flight process, and the flight scenario. These concepts permit a uniform formalization of the majority of phases, modes and conditions of flight for all aircraft types [9].

Flight event. The flight event is a special state of the “pilot - vehicle - operational conditions” system, which is important to the pilot and stands for a substantial change in the current flight situation. Examples of flight events are as follows: *“left engine out”, “speed VR achieved”, “altitude 360 ft and speed*

180 kn", *"on the runway"*, *"high angle of attack"*, *"30^o left bank"*, *"go-around decision"*, etc.

Main classes of flight events include: independent and dependent (in the latter case an "if-event", or event-condition, is checked first), simple and compound (determined by the number of components in the event recognition criterion), precise and fuzzy (determined by the type of variable in the criterion), momentarily recognizable and recognizable with a delay, unique and periodical (repeating), single and serial. These class pairs may have non-empty intersections.

Calendar of flight events. The list of all the events which may occur in a particular situation, or in a group of situations, is called the flight event calendar, $\Omega(\mathbf{E})$:

$$\Omega(\mathbf{E}) = \Omega^{NR}(\mathbf{E}) \cup \Omega^{JR}(\mathbf{E}) \cup \Omega^{F}(\mathbf{E}) \cup \Omega^{P}(\mathbf{E}), \qquad (15)$$

where $\Omega^{NR}(\mathbf{E})$ is a subset of "not recognized" events, $\Omega^{JR}(\mathbf{E})$ - "just recognized" events, $\Omega^{F}(\mathbf{E})$ - "frozen" events, and $\Omega^{P}(\mathbf{E})$ - "past" or "recognized" events. The symbols {NR, JR, F, P} stand for the four possible subset-states of a flight event during simulation. Note that $\Omega^{A}(\mathbf{E}) = \Omega^{JR}(\mathbf{E}) \cup \Omega^{F}(\mathbf{E})$ is a subset of "active" events.

The flight event calendar may be viewed as a discrete logical framework to which various flight processes are attached. Graphically, flight events are depicted as ellipses or circles with the event name and code.

Event recognition criterion. A flight event becomes active in the situational model if its recognition criterion is true:

$$(((x\square R)_1\, l_{12}\, (x\square R)_2\, l_{23}\, (x\square R)_3 \ldots) \text{ - true}) \Rightarrow (\mathbf{E} \in \Omega^{A}(\mathbf{E})), \qquad (16)$$

where x is a flight variable, $x \in V$, V is a vocabulary of all the flight variables; ij $\in$ {12, 23, ...} - pair number; $l_{ij} \in$ {OR; AND} - logical link between the elementary criteria $(x\square R)_i$ and $(x\square R)_j$; $\square \in$ {GT, LT, EQ, BEL, GE, LE, NE, AE, NA} - relation type[8]; R - right part of the criterion, $R \in \{\mathbf{a}; [\mathbf{a}; \mathbf{b}]\}$, **a** and **b** - real numbers, **a**<**b**.

For example, a compound event $\mathbf{E}_4$: *"at circuit altitude"* can be activated using the following recognition criterion: `(H = 1200) AND (V`$_Z$` BEL [-1.0; 1.0])`.

Flight event specification. In the situational model flight events are defined using the following generic frame-specification:

$$R[\mathbf{E}_i] = \{\ i,\ j^{IF},\ N,\ (x_1, \ldots, x_n),\ (x\square R),\ \Delta t,\ \tau\ \}, \qquad (17)$$

where i is the event code, i $\in$ {1, 2, ...}; j^{IF} - code of the "if-event" (event-condition), $j^{IF} \neq i$; N - event name, $(x_1, \ldots, x_n)$ - list of variables to be memorized when the event is recognized, $x_i \in V$, $(x \square R)$ - recognition criterion, Δt - time period (for periodic events), $\Delta t \geq 0$; τ - required delay in the event recognition process (after the recognition criterion becomes true), $\tau \geq 0$.

Example. The following input frame specifies an event E_3 for modeling: $R[\mathbf{E}_3]$ = `{ 3, 1, "speed VR", (3,19,14,1), (77 AE 290.0), 0.0, 0.5 }`. It means that the event $\mathbf{E}_3$: *"speed VR"* will be recognized when the indicated airspeed (the variable $x(77)$) will reaches some 290 km/h. Current values of the flight variables $\{x(3), x(19), x(14), x(1)\}$, or $\{\delta_e, L, \theta, \alpha\}$, will be memorized when the event is recognized. There is also a required 0.5 s delay in recognizing the event.

Flight process. The flight process (Π) is basically a time-history of one or several flight state variables, which characterize a certain aspect of the behavior of the "pilot – vehicle – operational conditions" system. Flight processes are used to formalize dynamic properties of the vehicle, flight control tactics including human piloting and errors, functions and malfunctions of onboard systems, and weather conditions. Every flight process has its specific purpose in the cause-and-effect structure of a flight situation. Unlike the events, the processes are continuous components of the situational model.

The following phrases represent various flight processes: *"keep to runway centerline"*, *"keep pitch at 10^o during initial takeoff climb"*, *"windshear 10 ft/s per 30 ft of altitude"*, *"r.p.m. decay after engine #1 failed"*, *"flaps down from 0^o to 15^o"*, *"turn at 20^o bank and zero sideslip"*, *"wet runway"*.

Flight processes are graphically depicted as arrows marked with process main attributes (type, name, code, and other).

Flight process types. Flight processes can be organized by their nature and purpose into the following groups: vehicle dynamics (**D**), flight control processes (**T**, **O**, **P**), airborne systems functioning and failures (**B**, **F**), external operational conditions (**A**, **R**, **W**, **Y**, ...), and some other[8,9].

The united list of flight processes, $\Omega(\Pi)$, can be written as follows:

$$\Omega(\Pi) = \Omega(\mathbf{T}) \cup \Omega(\mathbf{P}) \cup \Omega(\mathbf{O}) \cup \Omega(\mathbf{B}) \cup \Omega(\mathbf{F}) \cup \Omega(\mathbf{W}) \cup \Omega(\mathbf{R}) \cup \Omega(\mathbf{Y}) \ldots \quad (18)$$

where $\Omega(\mathbf{T})$ is a subset of piloting tasks, $\Omega(\mathbf{P})$ - control procedures, $\Omega(\mathbf{O})$ - state "observers", $\Omega(\mathbf{B})$ - onboard system functions, $\Omega(\mathbf{F})$ - onboard system malfunctions, $\Omega(\mathbf{W})$ - wind conditions, $\Omega(\mathbf{R})$ - rain conditions, $\Omega(\mathbf{Y})$ - runway surface conditions, etc.

In the situational pilot model the first four types are used, namely: piloting tasks, flight state observers, control procedures, and onboard system malfunctions. Obviously, a subset of flight control processes includes piloting tasks, state 'observers', and control procedures.

Piloting task. The piloting task (**T**), or the task, is a manual flight control process. It is carried out using primary controls (elevator, ailerons, rudder, etc.). Piloting tasks represent control with feedback. Every piloting task requires observation of the current flight state modeled by state 'observers' (see below). The examples of $\mathbf{T}_j$ are as follows: $\mathbf{T}_4$: *"keep to the centerline during groundroll"*, $\mathbf{T}_5$: *"make coordinated turn at bank +15°"*, $\mathbf{T}_8$: *"keep pitch at 10° and zero bank during initial climb after liftoff"*.

Input specifications of piloting tasks and other control processes are described in [8].

State 'observer'. The flight state 'observer' (**O**) is the process of evaluation of current states of the system and comparison of these states with the relevant tactical objective (goal state). The aim is to detect an error between these two states sufficient to change the performance of the piloting task. For example, the piloting task $\mathbf{T}_8$ listed above is provided with a state 'observer' $\mathbf{O}_1$ to monitor the vehicle motion in pitch. This 'observer' may include the following three components (elementary state 'observers'[8]) used to monitor pitch angle, pitch rate and pitch acceleration: $\mathbf{O}_1$ = (`PitchObs`, `PitchRateObs`, `PitchAccelObs`).

Control procedure. The use of secondary controls (flaps, spoilers, etc.), as well as single movements with the primary controls, are described by the process type called control procedure (**P**). For example, $\mathbf{P}_1$: *"wheels – up"*, $\mathbf{P}_2$: *"unstick"*, $\mathbf{P}_3$: "flap 30°→15°", $\mathbf{P}_6$: *"engines - to MCPR"*.

Failure. The onboard system's failure is a process which imitates abnormal function of some onboard system. The examples are as follows: $\mathbf{F}_2$: *"left engine failure"*, $\mathbf{F}_8$: *"uncommanded deployment of thrust-reverser"*, $\mathbf{F}_{27}$: *"elevator jammed at 17.5°"*. In the situational pilot model, failures are formally described as artificial control procedures and thus may constitute a part of a demonstrative or training scenario.

Flight process states. During simulation every flight process from $\Omega(\Pi)$ can be in one of the following three subset-states: $\Omega^{NO}(\Pi)$, $\Omega^{O}(\Pi)$, or $\Omega^{CL}(\Pi)$, i.e.:

$$\Omega(\Pi) = \Omega^{NO}(\Pi) \cup \Omega^{O}(\Pi) \cup \Omega^{CL}(\Pi), \quad (19)$$

where $\Omega(\Pi)$ is the united list of flight processes, $\Omega^{NO}(\Pi)$ - "not open" processes, $\Omega^{O}(\Pi)$ - "open" processes, and $\Omega^{CL}(\Pi)$ - "closed" processes; $\Omega^{O}(\Pi) = \Omega^{A}(\Pi) \cup \Omega^{F}(\Pi)$, $\Omega^{A}(\Pi)$ - "active" processes and $\Omega^{F}(\Pi)$ - "frozen" processes.

Flight scenario. The flight scenario (**S**) is a plan of a flight situation. It formalizes the content and the logic of flight including flight control. The flight scenario **S** is formed of two sets of objects - flight events, $\Omega(\mathbf{E})$, and flight processes, $\Omega(\Pi)$. They represent, respectively, discrete and continuous components of the flight situation model.

Scenarios may be depicted as directed graphs with the flight events as vertices and the flight processes as arcs. Examples of scenarios are as follows: $\mathbf{S}_1$: *"Normal takeoff"*, $\mathbf{S}_3$: *"Aborted takeoff with left engine out"*, $\mathbf{S}_{12}$: *"Groundroll on wet runway"*, $\mathbf{S}_7$: *"Takeoff with two right hand engines out"*, $\mathbf{S}_{10}$: *"Stall in takeoff configuration"*, $\mathbf{S}_{19}$: *"Cruise mode at 500 kn and 30,000 ft"*.

Example. The event-process flight description language can be used to program both demonstrative and training scenarios. A realistic example of such a scenario is shown in Fig. 1.

This is a complex flight situation $\mathbf{S}_7$: *"Takeoff of a four engine airplane with two right hand engines out"*. Both correct and incorrect control tactics are shown. Following is a description of a correct piloting method under the given conditions.

The situation starts on the runway, at the flight event $\mathbf{E}_1$: *"ground roll start"*, with brakes released and throttles at full power. When the airspeed reaches about 50 km/h (event $\mathbf{E}_2$), a piloting task $\mathbf{T}_4$: *"keep to* *runway centerline"* is initiated by means of rudder and a nose wheel control system until the nose wheel is on the ground (event $\mathbf{E}_9$).

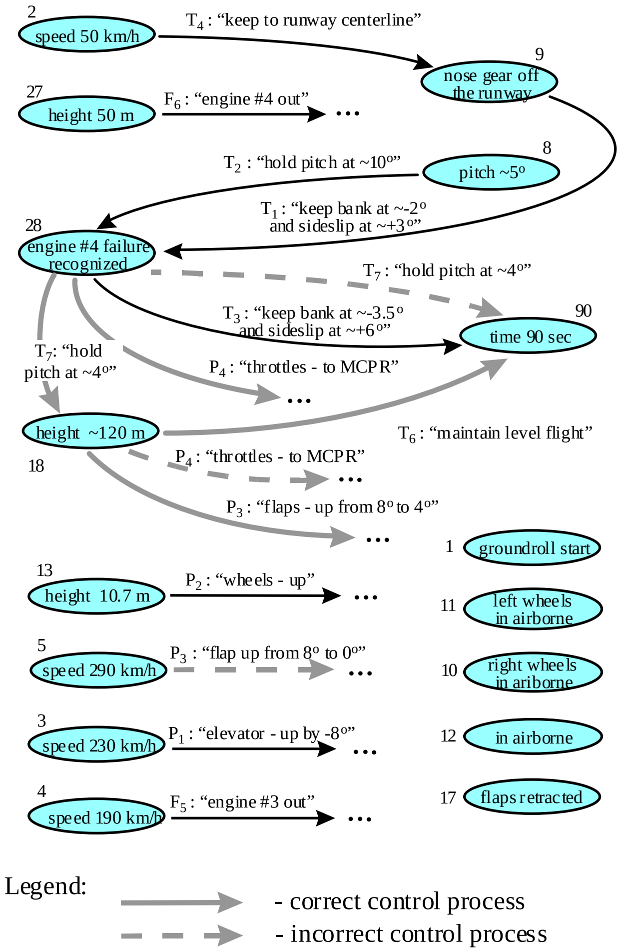

Fig. 1. Training flight scenario example $\mathbf{S}_7$: "Takeoff with two right hand engines out"

At the airspeed of ~190 km/h (event $\mathbf{E}_4$) an artificial control procedure-failure $\mathbf{F}_5$: *"engine #4 failed"* is introduced. At a rotation point (event $\mathbf{E}_3$: *"speed VR = 230 km/h"*) the appropriate action is applied by elevator, $\mathbf{P}_1$: *"move elevator up by -8°"*. When the pitch angle exceeds ~5° ($\mathbf{E}_8$) the 'silicon pilot' initiates a piloting task $\mathbf{T}_2$ to hold pitch attitude at about 10° by elevator.

Also, after the nose wheel leaves the ground ($\mathbf{E}_9$), the pilot tries to maintain the command bank and sideslip angles required to help counteract the effect of thrust asymmetry ($\mathbf{T}_1$: *"keep bank at -2° and sideslip at +3°"*) by ailerons and rudder. Wheels are retracted at event $\mathbf{E}_{13}$: *"height 10.7 m"* by means of control procedure $\mathbf{P}_2$: *"wheels - up"*.

When the engine #4 failure is planned to occur (at event $\mathbf{E}_{27}$: *"height 50 m"*) another artificial control procedure is activated, $\mathbf{F}_6$: *"engine #4 failure"*. In two seconds (at event $\mathbf{E}_{28}$: *"engine #4 failure recognized"*) the 'silicon pilot' sets throttles ## 1 and 2 to a maximum continuous power rating (procedure $\mathbf{P}_4$). Simultaneously, the model decreases the command pitch angle to reduce drag (task $\mathbf{T}_7$: *"hold pitch at +4°"*). Also, it further adjusts the command bank and sideslip angles to account for deteriorated thrust asymmetry (task $\mathbf{T}_3$). After reaching the altitude of about 120 m (event $\mathbf{E}_{18}$), a process of flap retraction from 8° to 4° (procedure $\mathbf{P}_3$) is commenced. Also, at this point the model changes the piloting task $\mathbf{T}_7$ to $\mathbf{T}_6$ in the attempt to maintain level flight (to increase the aircraft kinetic energy).

Note that this scenario diagram depicts, clearly and concisely, a difference between correct and incorrect control tactics at the level of cause-and-effect relationships between main events and processes constituting this complex enough flight case.

An example of autonomous simulation of flight according to scenario $\mathbf{S}_7$ is shown in Fig. 2.

<u>Algorithm</u>. A generic algorithm for executing a flight scenario in the situational model is as follows:

$$(\forall \mathbf{S})(\mathbf{S} = (\mathbf{E}_i, \mathbf{E}_k, \Pi_j)\ (((\mathbf{E}_i \in \Omega^P(\mathbf{E}) \wedge \mathbf{E}_k \notin \Omega^P(\mathbf{E}) \wedge \Pi_j \notin \Omega^{CL}(\Pi)) \wedge (t \geq t\,[\mathbf{E}_i \in \Omega^P(\mathbf{E})] + \tau)) \Rightarrow \Pi_j \in \Omega^A(\Pi)) \vee ((\mathbf{E}_k \in \Omega^P(\mathbf{E}) \Rightarrow \Pi_j \in \Omega^{CL}(\Pi)). \qquad (20)$$

The relationship (20), together with the algorithm (16) which models flight events, and algorithms which model flight processes constitute a computational basis for the autonomous flight situation model.

<u>Advantages</u>. There are several advantages of using the autonomous flight situation model as a part of the hybrid flight simulator.

A flight scenario is a concise and clear mapping of key cause-and-effect relationships of flight and control in the form of directed graph. Complex flight situations, which are usually a dynamic superposition of several operational conditions, can be formalized in the most rigorous yet efficient way using the concepts of flight event, flight process, and flight scenario. A library of such scenarios can be constructed and retained for future reference or modification.

Verbal or other descriptions of various flight situations, such as Pilot's Manuals, flight accidents or

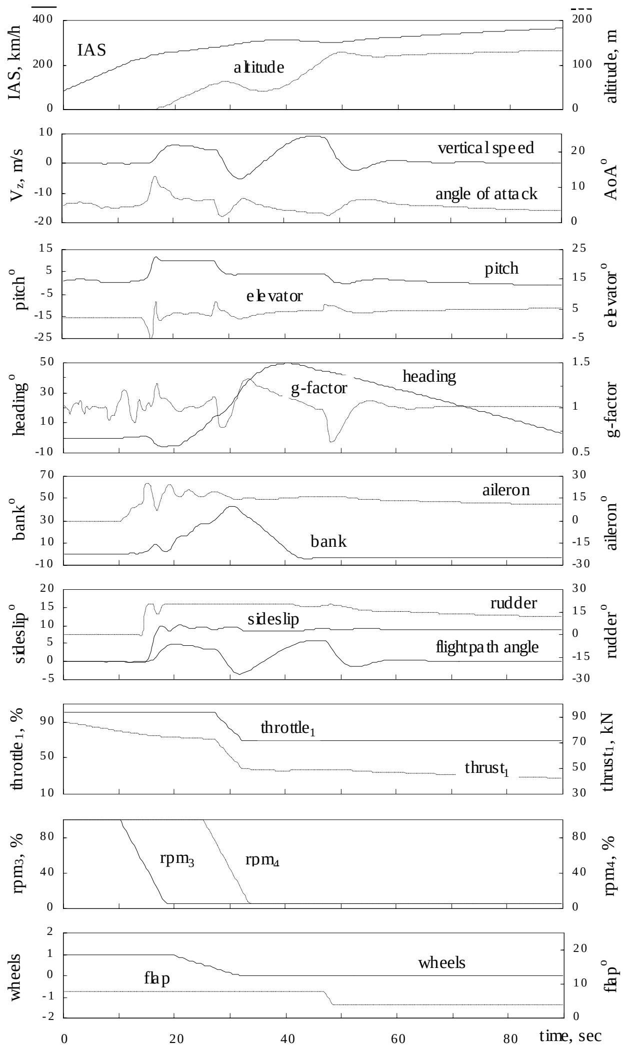

Fig. 2. Example of autonomous modeling of a flight situation $\mathbf{S}_7$: "Takeoff with two right hand engines out"

incidents can be formalized and then modeled systematically using this model. By applying a "what-if" method, various actual, hypothetical and mixed flight situations can be constructed and analyzed directly by the pilot. Programming and piloting skills are not mandatory for using the model.

The situational model allows flexible planning and execution of a large volume of systematic flight training experiments. It can run faster or slower than the actual flight time. Finally, an important feature is that the complexity of flight situation planning and modeling does not depend on the complexity of a situation under study.

IMPLEMENTATION VARIANTS

There are several possible variants for implementing the hybrid flight simulator concept. The choice depends on training objectives, modeled aircraft types and funds available.

Fixed base control station. In this case a fixed base ground station is equipped with a control system to remotely control the UAV. Real-time images of out-of-the-cockpit views from the onboard camera are displayed on the Head-Mounted Display together with a computer generated image of the cockpit instrument panel. This option can be used, for example, for light airplane simulation.

Light-weight movable control station. This variant repeats the first one, but in this case the control station is installed on a six-degree-of-freedom dynamic platform. The main difference compared with a 6DOF ground based flight simulator is that there is no need to move the entire cockpit with its equipment which is very heavy. Only the pilot and a control panel is to be installed on the platform. In this case the weight of a loaded platform does not exceed 100-150 kg. This allows to use simple, energy efficient and relatively inexpensive dynamic platforms. The information obtained from the UAV attitude sensors is also used as command signals to drive the platform.

A fixed base cockpit is used as the control station. In this option the pilot station is arranged as a fixed base aircraft simulator's cockpit. By means of a HUD or other virtual reality system, the pilot observes both a natural out-of-the-cockpit panorama and virtual controls located in the cockpit.

Partial use of ground based flight simulator hardware. In this case all the equipment of an existing ground based flight simulator can be employed, excluding the hardware which models the aircraft flight dynamics and the visualization system. Cockpit flight controls (e.g.: stick, pedals, throttles, etc.) are used to control the UAV via a radio channel. The instrument panel imitators display the actual flight state parameters transmitted from the UAV. The data obtained from the UAV attitude sensors are simultaneously used as command signals to drive the platform.

DISCUSSION

In this section, several issues associated with concept implementation are briefly discussed.

One of the advantages of the hybrid simulator concept is a realistic portrayal of out-of-the-cockpit views. Also, this technology is compatible with existing ground based simulation complexes. The only components which should be changed are the visualization system and the flight dynamics modeling system. This allows a gradual and two-way transition from one configuration to another.

Modern telemetry and command systems can secure reliable communication with a UAV at a distance of 100 km and more. If communication satellites are used, this distance can be increased significantly. Modern UAVs have the maximum endurance between 4 and 10 hours. This allows to conduct training flights over remote territories located several hundred kilometers and farer from the base.

One of the pluses of this technology is the capability to naturally model various malfunctions and failures, including mechanical damages to the airframe and control surfaces.

The use of the autonomous flight situation model onboard and in the ground station can significantly expand the freedom of performing demonstrative and training scenarios. It also helps automate the process of flight scenario planning. The 'silicon pilot' model, which is a part of the situational model, supports various forms and methods of vehicle control, e.g.: recorded control tactics, autonomous scenarios (conducted by the model), and mixed control of the vehicle (by the model and the pilot), etc.

The supported training scenarios range from standard and non-standard flight situations described in the Pilot's Manual to flight accident and incident reconstructs and 'what-if' cases around some accident and various hypothetical maneuvers. In fact, the pilot can construct and retain a library of such scenarios for future reuse according to his (her) specific needs. Finally, the 'silicon pilot' model can be used as a backup flight control method for the UAV in case of a loss of communication between the vehicle and the ground station.

As UAVs are light vehicles they can be equipped with a parachute rescue system. This provides the flying model with a dual protection capability in emergencies (the first one is backup flight safety control of the situational model). Thus, if the student has made a piloting error, or has applied an incorrect recovery tactics, he (she) can observe realistic consequences of these actions without a fear to loose the vehicle. Also, the situational model can be used by the instructor to automate the process of planning and simulation of various internal and external operational factors.

Finally, in military aviation this technology opens a new avenue for sophisticated and realistic combat training. For example, air-to-surface attack scenarios have practically the same appearance as in reality, because all the targets may be real objects. This method also allows heterogeneous training scenarios which may involve multiple UAV and other systems (ships, tanks, etc.).

However, as any new technology this method may have potential problems and other unresolved issues which require a more thorough analysis.

One of the problems is how to integrate the external picture (out-of-the-cockpit view) recorded by onboard cameras and displayed on the HUD together with the cockpit's instrumental panel. Each of the implementation variants discussed above may require a special solution approach. Another problem is how to control these video cameras to account for dynamics of the pilot's head.

There is a problem of adequate modeling of takeoffs and landings and other flight regimes in close ground proximity. To secure adequate visual cues, the pilot's eyes (i.e. the onboard video camera) should be located at the same level above the ground as in the modeled aircraft. However, the height of the UAV's undercarriage system is much lower than in actual aircraft. One of possible solutions could be to dynamically adjust the camera's optical focus distance to visually 'increase' it. Also, for these models of flight the takeoff and landing speeds should be the same as in modeled aircraft. This poses additional requirements to the UAV's undercarriage system, because originally it was designed for much lower takeoff and landing speeds.

If a dynamically similar [flying] model is used as the base vehicle, the problem is also how to expand the time scale without violating the dynamic similarity criteria. One of the approaches is to introduce into the DSM flight control system special devices to control its mass and inertial characteristics.

Several problems are to be addressed in order to integrate the situational flight model with the UAV and the human pilot. One of them is the identification of a set of the flight conditions (in an emergency or in case of loss of ground-vehicle communication) when the control authority should be transferred to the 'silicon pilot'. Another problem is visualization of the flight scenario dynamics in the ground station.

A special graphic interface program is also needed for construction, modification and selection of flight scenarios by the pilot/instructor. Finally, though memory requirements to run the situational model and retain a flight scenario are very modest (~50-100 K and ~5-10K, respectively), an onboard computer is required for this purpose. There are some technical problems associated with the implementation of joint (model-pilot) flight control.

Finally, one of possible drawbacks of this technology compared with the ground based flight simulation method is the necessity to actually fly the vehicle. In other words, a runway is required for takeoffs and landings together with a special zone in the air space to perform training flights. However, flying schools and training centers are normally located close to airfields.

CONCLUSION

For the last few years the cost of flight simulators for pilot training has increased significantly. The expansion of operational domains of flight of new aircraft requires pilots to receive more training at the edge of the flight envelope and under multi-factor conditions. As a result, pilot training is becoming less affordable than it should be, and it requires to address more complex flight situations.

The proposed technology of hybrid flight simulation is a feasible solution to these problems. The cost of flight simulation for pilot training can be reduced and the fidelity of flight modeling and the quality of pilot training can be improved. Some of the technical issues associated with the hybrid simulator concept require a more detailed analysis.

REFERENCES

1. “Trainers & Simulators”, *Aviation Week & Space Technology*, December 2, 1996.
2. J.M. Rolfe, K.J. Staples, “Flight Simulation”, Cambridge University Press, 1986.
3. Jeffery R. Hogue, R. Wade Allen, “Virtual reality entertainment technology applied to military parachute simulation flight training”. Collection of Technical Papers of the AIAA Modeling and Simulation Technology Conference, New Orleans, LA, 1997, pp. 83-89.
4. L.M. Berestov, V.V. Gorin, “Simulation of flight dynamics by means of a flying laboratory”, Moscow “Mashinostroenie”, 1988 (in Russian).
5. Michael A. Dornheim, “X-36 To Test Agility of Tailless Design”, *Aviation Week & Space Technology*, March 4, 1996, pp. 20-21.
6. Patuxen River, “NASA Drop Model Sinks”, *Aviation Week & Space Technology*, January 20, 1997, p. 59.
7. S. Sadovnitchii, V. Ryabkov, A. Rushenko, J. Sandoval, "Modeling of Aircraft Flight by Means of Dynamically Similar Models with Flight Control System Similarity", *Proc. of AIAA, Modeling and Simulation Technology Conference’97*, New Orleans, 1997, pp. 326-332.
8. I.Y. Burdun, "An AI Situational Pilot Model for Real-Time Applications", *Proceedings of the 20th Congress of the International Council of the Aeronautical Sciences, Sorrento, Napoli, Italy, 8-13 September 1996 (ICAS'96)*, Volume 1, AIAA, 1996, pp. 210-237.
9. I.Y. Burdun and D.N. Mavris, “A Technique for Testing and Evaluation of Aircraft Flight Performance During Early Design Phases” (Paper No. 975541), *World Aviation Congress (WAC’97), October 13-16, 1997, Anaheim CA*, SAE Aerospace - AIAA, 1997, 12 pages.
10. P.G. Thomasson, “Flight Dynamics Simulation”, Cranfield University, Cranfield, 1993.
11. R.W. Hamming, “Numerical Methods for Scientists and Engineers”, McGraw-Hill, 1962.
12. V.V. Vyshinsky, “Aircraft Vortex Wake and Airport Capacity”, (Paper No. 975519), *World Aviation Congress (WAC’97), October 13-16, 1997, Anaheim CA*, SAE Aerospace - AIAA, 1997, 13 pages.
13. Gamon M. A., “Airplane dynamic wheel loads during ground maneuvering”, *AIAA/ASME/ AHS 20th Struct., Struct. Dyn. and Mater. Conf.*, 1979, New York, pp. 95-101.