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A Technique for Testing and Evaluation Of Aircraft Flight Performance During Early Design Phases[1]

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ABSTRACT

A technique is proposed for examining complex behaviors in the “pilot – vehicle – operational conditions” system using an autonomous situational model of flight. The goal is to identify potentially critical flight situations in the system behavior early in the design process. An exhaustive set of flight scenarios can be constructed and modeled on a computer by the designer in accordance with test certification requirements or other inputs. Distinguishing features of the technique include the autonomy of experimentation (the pilot and a flight simulator are not involved) and easy planning and quick modeling of complex multi-factor flight cases. An example of mapping airworthiness requirements into formal scenarios is presented. Simulation results for various flight situations and aircraft types are also demonstrated.

INTRODUCTION

DEFINITION. Virtual testing and evaluation (VT&E) is an emerging method which employs mathematical modeling and computer simulation for examining vehicle dynamics and flight control (performance, controllability, stability, maneuverability, and other characteristics) under complex operational conditions. Key components of the VT&E method are (1) a situational model of the behavior of the “pilot – vehicle - operational conditions” system, (2) specification of flight situations or cases to be tested, e.g.: airworthiness requirements, test programs, a pilot’s manual, etc., and (3) computational resources (e.g.: a PC).

WHY VIRTUAL? The adjective “virtual” means that testing and evaluation (T&E) are performed on a computer with a mathematical model of the actual system. Because no test article is involved, VT&E can be conducted at any point during the vehicle’s life - from design to operation, provided that a dynamic model of the vehicle is available.

RATIONALE. The necessity for such substitution emerges from the following facts:

- flight tests are very expensive and require a long time to prepare and conduct
- it is difficult to exhaustively check the vehicle’s operational domain in flight tests and manned simulations
- as research tools, manned simulation and flight testing are limited in studying complex conditions of flight
- shortcomings identified in traditional T&E require substantial redesign work that may cause cost and schedule overruns.

As a result of these circumstances, a new vehicle may be undertested and have hidden weaknesses in the flight performance which are revealed only during operation. This may compromise flight safety. Statistics of flight incidents and accidents with highly automated aircraft reflect this situation [1, 2].

RESEARCH TASK FORMULATION

PROBLEM. The problem under study is as follows. How to check and evaluate flight safety or mission success standards for a new vehicle beginning from the earlier design phases?

Flight safety depends on the behavior of the “pilot - vehicle - operational conditions” system (the system) in complex situations. These situations normally occur as a result of unfavorable combination of several operational factors (multi-factor situations). Main contributors to flight safety are the three constituents of the system, namely [3]: the human pilot (60-70% of all flight accidents are attributed to so called “pilot errors”), a vehicle with its systems (17%), and external operational environments (5%). This implies that the flight safety problem must be addressed at the system level.

“CHAIN REACTION” ACCIDENTS. There is a correlation between so called “chain reaction” type flight accidents with highly automated aircraft and methodologies employed in design, testing and evaluation. The “chain reaction” is a quick and irreversible propagation of several operational factors linked by strong cause-and-effect relationships. Normally, each of these factors is not critical.

Fig. 1 depicts a “chain reaction” mechanism of a flight accident involving a modern airliner. The aircraft overran the runway and crashed after landing under heavy rain and, possibly, slight windshear conditions. A rainstorm during approach and landing (performed at an increased airspeed to cope with wind shear) caused a late spin-up of the wheels after a touchdown due to aquaplaning. Subsequent delay in spoilers deployment resulted in a 9-seconds’ delay in actuation of the

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thrust reversers. As a result, the airplane could not dissipate kinetic energy fast enough within the runway.

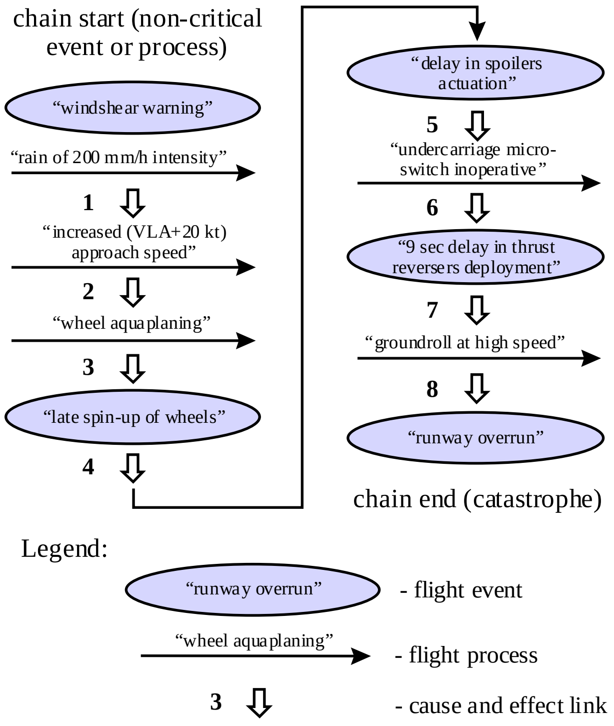


Figure 1: "Chain reaction" of a flight accident on overrunning after landing in rain and wind shear conditions

Each of the events and processes observed in this accident is not referred as critical alone. However, having been connected by cause-and-effect links they triggered an irreversible chain that led to a catastrophe.

SAFETY AND DESIGN. In the given example, flight envelope protection systems (i.e. the design) of the vehicle have contributed, to a large extent, to the development of this chain (links 4-7 in **Fig. 1**). A micro-switch, which prevents thrust reverser actuation while airborne, has become a trigger of the accident under non-standard landing conditions. Note that this micro-switch was introduced after an accident with a transport aircraft of other manufacturer occurred due to uncommanded in-flight deployment of thrust reversers.

Thus, a combination of several interconnected factors (heavy rain, possible wind shear, and errors in safety design logic) has become a prime cause of the accident. Obviously, these types of scenarios should be checked before operation. In particular, the vehicle's flight performance should have been re-examined after the modification (micro-switch installation).

SOLUTION. It is possible to expand the scope of studying complex operational domains of flight for new vehicles, including "chain reaction" type situations, to the earlier design phases. For this purpose an autonomous situational model of flight is proposed.

The words "autonomous" and "situational" mean that the pilot's decision making processes and complex flight situations are modeled mathematically along with non-linear dynamics of the vehicle. This allows flexible planning and execution of various flight test cases directly by the designer.

OBJECTIVE. The objective in the solution approach is to fill the gap in a designer's knowledge about the vehicle performance under demanding flight conditions by identifying in advance potentially critical situations in the system behavior. For this purpose an exhaustive set of test scenarios is simulated in compliance with the airworthiness requirements or other specifications.

SUMMARY. Given non-standard operational conditions, the design of a highly automated aircraft may contribute to the development of a "chain reaction" type accidents. This occurs due to a lack of knowledge about the physics and logic of the "pilot – vehicle – operational conditions" system behavior in complex flight situations. A more thorough examination of multi-factor operational domains of flight is required. As a "knowledge generator", it is proposed to use an autonomous situational model of flight. The goal is to identify potential problems in the system behavior before operation.

PRESENT T&E PRACTICE

At present, the R&D cycle may be presented as four overlapping phases (**Fig. 2,** a): design, manned simulations, flight tests, and certification. In this scheme, the major share of knowledge about the vehicle flight performance under complex conditions is generated during manned simulations and flight tests.

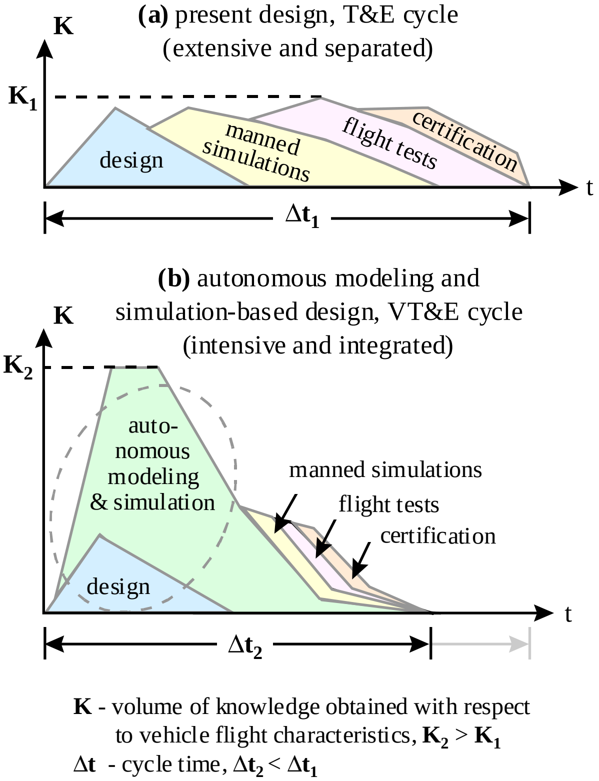
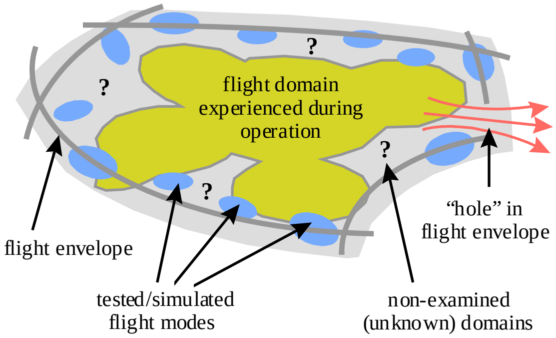


Figure 2: Present vs. proposed design, test and evaluation cycle

FLIGHT ENVELOPE. By using these methods, the flight envelope of a new vehicle is exemplified at certain points in a multi-dimensional flight space-structure (**Fig. 3,** a). After processing, these test points are then linked together and extrapolated under the assumption that the encapsulated domain is safe. As a result, some zones at the borders of the flight envelope may remain unexplored (i.e. unknown), especially in the presence of several operational factors.

(a) exemplification of the flight envelope in manned simulation and flight testing



(b) identification of the flight envelope through autonomous modeling and flight testing linked to design

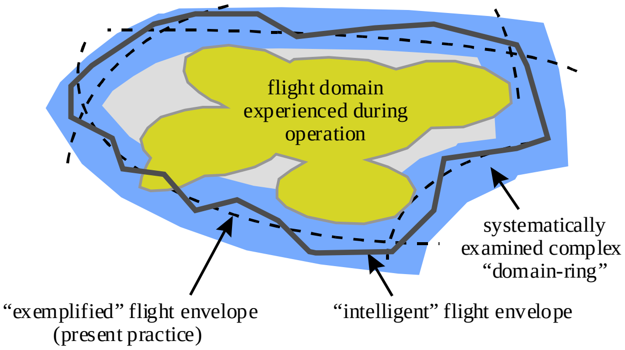


Figure 3: Exemplified vs. "intelligent" flight envelopes

Given a multi-factor flight situation, the position of constraints may unfavorably change compared with those ones specified for less demanding conditions. Alternatively, the flight envelope may reveal a "hole" (see **Fig. 3**, a), i.e. a zone of non-guarded transitions towards unsafe flight regimes. During operation, such deficiencies in the vehicle flight performance appear as incidents or accidents of a "chain reaction" type similar to **Fig. 1**.

LIMITATIONS. As a T&E methodology, manned simulation and flight testing have limitations which require rectification.

1. Flight experiments are very expensive and require a long time to prepare and conduct. The number of flight test and simulation hours needed for new vehicles is growing.

2. The vehicle flight performance is examined after a test article is built. This constricts and delays important feedback to the design process. Very little design freedom is thus left for radical changes in the vehicle if a problem is discovered during T&E.

3. Using these methods, it is difficult to exhaustively check the vehicle's future operational domain. Only a limited number of complex flight situation patterns, which the vehicle may encounter during future service, can be tested. The main obstacles are the heterogeneity, unpredictability, and combinatorial character of operational factors of flight.

4. It is problematic to plan and execute a large series of flight test or manned simulation experiments. Further, flight test modes under extreme conditions may be difficult to plan or unsafe to implement. It is also technically difficult to repeat a complex flight scenario in exact detail maintaining the required test mode and condition.

SUMMARY. At present, the burden of T&E of the aircraft flight characteristics in complex operational conditions rests with manned simulations and flight testing. These methods are expensive and require a long time to prepare and conduct. It may also be unsafe or technically difficult to examine complex operational domains. Thus, the flight envelopes of modern aircraft may not be protected reliably enough under multi-factor situations. As a T&E methodology, manned simulations and flight testing require enhancement to address the emerging flight safety problem.

FLIGHT SITUATION MODEL

In this section, an introduction is made to an autonomous situational model of flight. This technique is proposed to complement manned simulations and flight testing when studying complex operational domains.

Basically, three formal concepts are sufficient to construct a comprehensive model of a complex flight situation. These are the flight event (**E**), the flight process (Π), and the flight scenario (**S**) [4]. Using this formulation, a human pilot's control tactics and heterogeneous operational conditions of flight can be described in an integrated fashion.

FLIGHT EVENT. The flight event is a characteristic state of the "pilot – vehicle – operational conditions" system. Flight events may be viewed as special "points" or nodes in a multi-dimensional flight space-structure. They are important to the pilot (or a control system designer) in terms of planning or executing flight in a particular situation.

Examples of flight events are $\mathbf{E}_2$: "on glide slope", $\mathbf{E}_4$: "speed VR achieved", $\mathbf{E}_{21}$: "engine #1 failed", $\mathbf{E}_7$: "low airspeed", $\mathbf{E}_1$: "bank angle within 25°-30°", $\mathbf{E}_{16}$: "go-around decision", $\mathbf{E}_9$: "altitude 1,000 ft", $\mathbf{E}_{15}$: "touchdown", $\mathbf{E}_3$: "wind shear warning", $\mathbf{E}_8$: "steep descent and low altitude", $\mathbf{E}_{11}$: "heading 175°", $\mathbf{E}_6$: "time 60 seconds", etc.

Flight events stand for discrete components of a flight situation model. A complete set of events, $\Omega(\mathbf{E})=\{\mathbf{E}_1, \ldots, \mathbf{E}_{N(\Omega(\mathbf{E}))}\}$, which may occur in a certain phase or mode of flight, is called the flight events calendar. The latter forms a logical framework of a human pilot's tactical decision making and a flight situation.

FLIGHT PROCESS. Unlike the event, the flight process is a continuous component of the situational model. It represents a distinctive non-momentary aspect (action, factor, input, etc.) of the system behavior. Depending on physical background, flight processes may be divided into three main groups:

- pilot's tactical decision making and pilot errors - "piloting task" (**T**), system "state observer" (**O**), "control procedure" (**P**), and some other processes
- external operational conditions – "wind" (**W**), "rain" (**R**), "runway surface condition" (**Y**), etc.
- onboard system functioning and system failures - "function" (**B**) and "failure" (**F**).

Typical examples of flight processes are as follows. $\mathbf{T}_2$: "keep pitch at about 10^o", $\mathbf{T}_8$: "perform right turn at a 25^c bank angle and zero sideslip", $\mathbf{O}_6$: "observe bank angle and roll rate", $\mathbf{P}_5$: "flaps - down from 0^o to 30^o", $\mathbf{P}_2$: "wheels - up", $\mathbf{W}_1$: "strong wind shear, accident 03/06/85", $\mathbf{R}_2$: "tropical shower of a trapezoid profile with the maximum intensity of 400 mm/hr", $\mathbf{Y}_3$: "wet runway", $\mathbf{B}_1$: "yaw SCAS inoperative", $\mathbf{F}_1$: "engine #1 failure", and $\mathbf{F}_{19}$: "uncommanded move of rudder to a $+25^o$ position".

In the flight situation model, every process Π_j runs between two events, the "source" event and the "target" event. The source event, $\mathbf{E}_{i*}$, opens Π_j, whilst the target event, $\mathbf{E}_k^*$, closes it during the flight; $\mathbf{E}_{i*}$, $\mathbf{E}_k^* \in \Omega(\mathbf{E})$. Sometimes, a flight process may not have a target event assigned; it means that the process is closed automatically. There may be several processes starting or/and finishing at the same event. An interrelated triplet $\{\mathbf{E}_{i*}, \Pi_j, \mathbf{E}_k^*\}$ is called the elementary flight situation, e.g.: a set $\{\mathbf{E}_9, \mathbf{T}_8, \mathbf{E}_{11}\}$ in the examples above. All the processes planned for a flight situation, or for a group of situations, constitute a united set of flight processes $\Omega(\Pi)$, $\Omega(\Pi) = \{\Pi_1, \ldots, \Pi_{N(\Omega(\Pi))}\}$, $\Pi \in \{\mathbf{T}, \mathbf{O}, \mathbf{P}, \mathbf{W}, \mathbf{R}, \mathbf{Y}, \mathbf{B}, \mathbf{F}, \ldots\}$.

FLIGHT SCENARIO. The flight situation scenario (flight scenario) is a plan for implementing a flight situation and the associated piloting tactics during simulation or in operation. It may be depicted as a directed graph, $\mathbf{S}=\Omega(\mathbf{E})\cup\Omega(\Pi)$. In the flight scenario, the events (vertices) $\Omega(\mathbf{E})$ and the processes (arcs) $\Omega(\Pi)$ are linked together forming a logical model of the particular situation. Note that the flight scenario graph may be represented as a union of its elementary flight situations.

Scenarios capture cause-and-effect and other key relationships between discrete and continuous elements of flight, thus mapping its invariant logical structure.

EXAMPLE. **Fig. 4** specifies a non-standard flight situation with an XV-15 tilt-rotor aircraft (a dynamic model of the vehicle has been extracted from the GTRSIM software package [5]). This hypothetical scenario may be called $\mathbf{S}_1$: "Transition from an airplane flying mode to a tilt-rotor mode via a helicopter mode under multiple control inputs".

The initial conditions of the maneuver (not trimmed) are as follows. H=2,500 ft, V_{CAS}=240 kt, $\varphi=85^o$ (airplane mode), $\vartheta=0^o$, $\gamma=-10^o$, ω=517.6, $\delta_F=0^o$, SCAS – on. The scenario $\mathbf{S}_1$ is briefly described below.

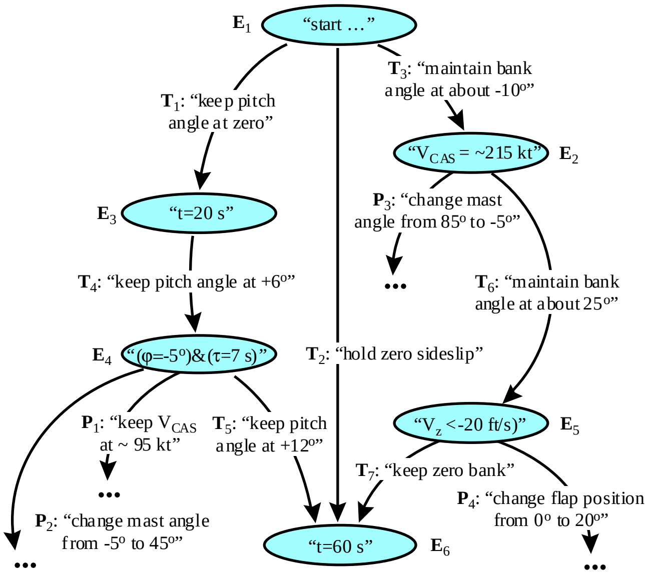


Figure 4: Flight scenario $\mathbf{S}_1$: "Transition from airplane mode to tilt-rotor mode via helicopter mode under multiple control inputs (XV-15 tilt-rotor aircraft)"

1. The flight situation starts at the event $\mathbf{E}_1$ and finishes at $\mathbf{E}_6$: "time is 60 seconds". At $\mathbf{E}_1$ three piloting tasks are initiated by the "silicon pilot", namely:

- $\mathbf{T}_1$: "keep pitch angle at zero" using elevator
- $\mathbf{T}_2$: "hold zero sideslip" by rudder
- $\mathbf{T}_3$: "maintain bank angle at about -10^o" by ailerons.

2. Then, at the event $\mathbf{E}_2$: "calibrated airspeed 215 kt", the task $\mathbf{T}_3$ is modified into $\mathbf{T}_6$: "maintain bank angle at $\sim+25^o$". One more control procedure is added at this point for execution, this is $\mathbf{P}_3$: "change the mast angle to a helicopter mode".

3. Beginning from the event $\mathbf{E}_3$: "time is 20 seconds", a higher command pitch is requested to maintain, so $\mathbf{T}_1$ is modified into $\mathbf{T}_4$: "keep pitch angle at about $+6^o$".

4. When the helicopter mode has been established, which is indicated by the event $\mathbf{E}_4$: "mast angle is at a -5^o position for 7 seconds", the control scenario is updated. The piloting task $\mathbf{T}_4$ in the longitudinal channel is being changed to further increase the command pitch, namely to $\mathbf{T}_5$: "keep pitch at about $+12^o$". Simultaneously, a control procedure is commenced to acquire a tilt-rotor flight mode, $\mathbf{P}_2$: "change the mast angle from -5^o to $+45^o$". Starting from $\mathbf{E}_4$, the "pilot" also attempts to keep the airspeed constant by applying collective inputs according to $\mathbf{P}_1$: "keep V_{CAS} at about 95 knots".

5. Finally, if a steep descent occurs (i.e. the event $\mathbf{E}_5$: "V_z<-20 ft/s" is recognized), two control processes will be added. These are a piloting task $\mathbf{T}_7$: "keep bank angle zero", and a control procedure to extend flap, $\mathbf{P}_4$: "δ_F: $0^o \rightarrow 20^o$".

Results of autonomous simulation of this maneuver according to the scenario $\mathbf{S}_1$ are depicted in **Fig**. **5**. Thus, complex interrelationships within the "pilot – vehicle – operational conditions" system can be formalized and modeled in a rigorous yet efficient way.

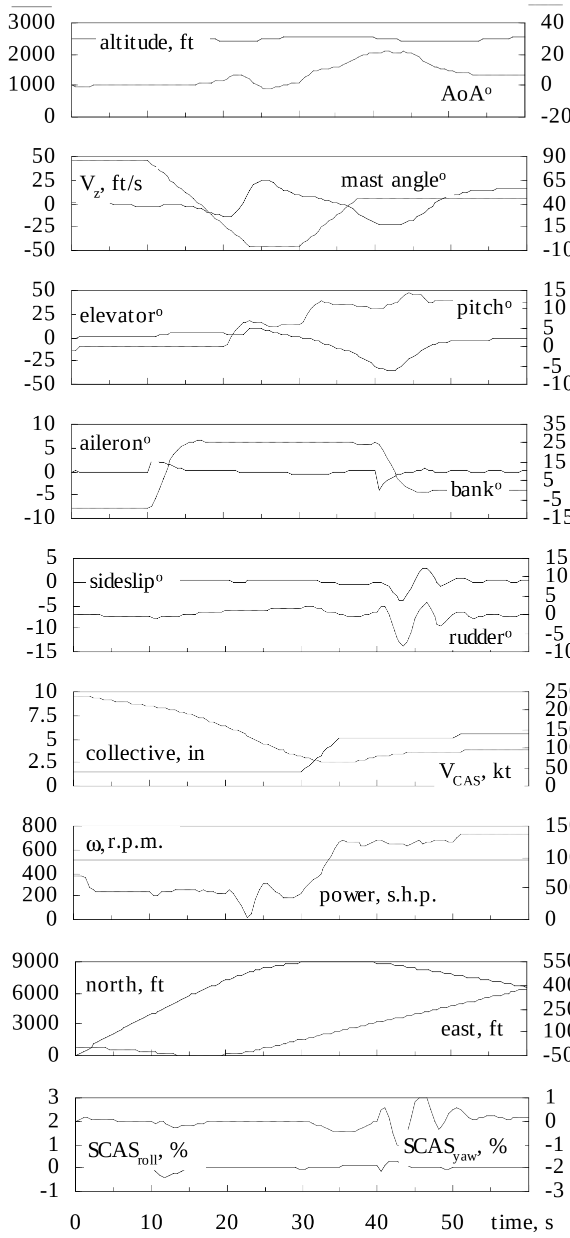


Figure 5: Transition from an airplane flight mode to a tilt-rotor mode via a helicopter mode under multiple control inputs (XV-15, scenario $\mathbf{S}_1$)

DISCUSSION. Note that only six events and 11 processes were used to plan and model this complex enough flight case on a PC within a few minutes.

Various modifications to the scenario can be introduced by blocking (“freezing”) some of the events or by adding, removing, or modifying the processes as required. For example, the removal of the event $\mathbf{E}_4$ from $\Omega(\mathbf{E})$ results in a modified scenario without the processes $\mathbf{P}_1$, $\mathbf{P}_2$, and $\mathbf{T}_5$. This means that the “flight” will be executed without, respectively, the helicopter mode, airspeed control, and an interim change in command pitch.

On other hand, by adding a new process-arrow to the initial scenario-graph, for example the wind-type process $\mathbf{W}_1$: “strong windshear identified from an accident dated 03/06/85”, between $\mathbf{E}_1$ and $\mathbf{E}_6$, the vehicle behavior specified in $\mathbf{S}_1$ can be tested under demanding weather conditions encountered in some accident.

Using the directed graph form, construction and modification of a flight scenario, as well as its propagation during simulation, can be automated and visualized. More examples of flight scenarios and simulation results will be demonstrated below (see also [4]).

BENEFITS. The proposed “events-processes” formulation of flight scenarios provides a practical tool for quick and flexible planning of various test cases on a computer. The modeling experience demonstrates that the content and logic of a flight situation of any complexity can be mapped into a compact set of data structures, simulated and retained on a computer for future reuse and modification. Piloting or programming skills are not required. The complexity of the scenario planning and simulation task does not increase with the complexity of the flight situation under study. These conclusions have been checked for several aircraft types and various operational conditions of flight.

SUMMARY. Using the flight scenario concept, complex flights situations can be represented in the form of directed graphs. This formulation allows capturing cause-and-effect and other invariant relationships between discrete and continuous elements of flight. Flight situations of practically any complexity can be coded into compact input data structures for autonomous simulation. The modeled cases range from test certification programs to flight accidents and special maneuvers. Piloting or programming skills are not mandatory for the experimenter.

AUTONOMOUS FLIGHT SIMULATION

DEFINITION. Autonomous flight simulation is an engineering technique developed to reconstruct the behavior of the entire “pilot - vehicle - operational conditions” system using the situational model of flight and a computer.

The overall purpose of this technique is to keep the number of flight test and manned simulation hours for a new vehicle within the reasonable bounds. This can be achieved through a more comprehensive coverage of complex operational domains where the traditional T&E approach fail.

BASIS. This technique combines complementary properties of several theoretical, experimental and computational disciplines. This list includes flight mechanics, aerodynamics, flight control, propulsion, human pilot decision making and situational (tactical) control, flight dynamics simulation, numerical methods, graph theory, and computing. Through such integration, complex behaviors of the “pilot – vehicle – operational conditions” system can be simulated.

OBJECTIVE. The objective is to examine potentially critical situations in the system behavior, including a “chain reaction” type phenomena, before the vehicle is built and flown. During “what-if” experimentation with the situational model on a computer, various test scenarios can be applied to thread the vehicle’s operational domain.

EXAMINED OPERATIONAL DOMAIN. In general, two components contribute to the vehicle's operational domain: (1) specified phases or modes of flight, and (2) anticipated operational factors of flight, their combinations and levels. The operational factors may be presented as flight processes and grouped accordingly, i.e.:

- pilot errors and piloting methods (delays, objectives, gains, patterns, etc.)
- onboard system failures (engines, primary and secondary controls, undercarriage, autopilots, etc.)
- demanding weather conditions (wind gusts, windshear, crosswind, rain, icing, runway, atmosphere, etc.).

The flight scenario formulation described in the previous section allows uniform representation and processing of these factors. A concise and meaningful "events-processes" data structure implementable on a computer can be associated with any multi-factor flight situation.

INPUT REQUIREMENTS. A pre-requisite for successful application of autonomous flight simulation to the VT&E processes is the availability of a non-linear mathematical model of vehicle flight dynamics.

The fidelity of autonomous modeling and simulation is determined by the quality and completeness of vehicle input characteristics. These input characteristics and their arguments must cover the flight modes and operational factors under examination. Some "exotic" characteristics may also be needed to account for special regimes and conditions of flight. Also required is a general (verbal, qualitative) description of test cases under study.

PREVIOUS APPLICATIONS. The autonomous flight situational model has been used to study the flight performance for 17 aircraft types and two design projects. This list includes turbojet and turboprop transport airplanes, helicopters, a tilt-rotor aircraft, a high-speed civil transport project, and transatmospheric vehicles. Over 30 practical problems were studied in the sectors of flight safety, flight control, and practical aerodynamics. These include the following groups of tasks:

- studying combined effects of failure modes, pilot errors and weather conditions on vehicle dynamics and control
- validation of new piloting methods and automatic control systems under multi-factor conditions
- virtual testing of an aircraft flight performance in the earlier design phases
- rehearsal of complex test programs and reconstruction of recorded flight test modes
- reconstruction of flight accidents; examination of operational domains around a flight accident/incident
- implementation of a "silicon pilot" model in a training flight simulator for an aerospace vehicle.

COMPARISON WITH CURRENT APPROACH. Compared with flight testing and manned simulation (**Table 1**), the proposed technique offers an inexpensive and accessible source of knowledge about complex behaviors of the "pilot - vehicle - operational conditions" system. It allows quick examination of multi-factor operational domains for new vehicles in a more systematic and manageable way.

Table 1: Flight testing and manned flight simulation vs. autonomous flight simulation

Comparison criterion	**1**	**2**	**3**
Studying complex (extreme) operational domains	$+^{**}$	$+^{*}$	$+^{*}$
Systematic examination of flight envelope	-	$+^{**}$	+
Inexpensive to establish and run	-	-	+
Flexibility and sensitivity of experimentation	$+^{**}$	$+^{**}$	$+^{*}$
Accessibility in research and education	-	-	+
Accuracy and fidelity of results	+	$+^{*}$	$+^{*}$
"What-if" experimentation capability	$+^{**}$	+	+
Autonomy (independence of the human pilot)	-	-	+
Retention and automation of test scenarios	-	$+^{**}$	+
Faster-than-real-time flight experimentation	-	-	+
Safety of experimentation	$+^{**}$	+	+
Suitability for pilot training	+	$+^{*}$	$+^{**}$

Notes:

1	Flight testing
2	Manned flight simulation
3	Autonomous flight modeling and simulation
+/-	"Yes" or "no" in matching the criterion
*	Depends on the fidelity of a dynamic model
**	Limited capability

Thus, provided that a dynamic model of the vehicle exists, the autonomous modeling and simulation technique may complement the present T&E practice, namely:

- increase the volume and improve the quality of knowledge about complex operational domains of flight
- reduce the volume (or prevent excessive growth) of required flight tests and manned flight simulations
- accelerate and virtualize the overall T&E process.

SUMMARY. Autonomous flight simulation is an inexpensive and accessible source of knowledge about the "pilot – vehicle – operational conditions" system behavior in multi-factor flight situations. This technique can be used for systematic examination of the flight envelopes of new aircraft to identify potential problems, which may affect flight safety. Thus, autonomous flight modeling and simulation may complement and reduce the volume of flight testing and manned flight simulations when studying complex operational domains for advanced aerospace vehicles.

MAPPING AIRWORTHINESS REQUIREMENTS INTO FLIGHT SCENARIOS

This is an example of mapping of the airworthiness requirements into formal flight scenarios for virtual testing and evaluation.

NOTE. The material presented in this section is illustrative. It must not be used as a citation or reference to any aviation regulatory document or in conjunction with any particular vehicle type or test certification procedure.

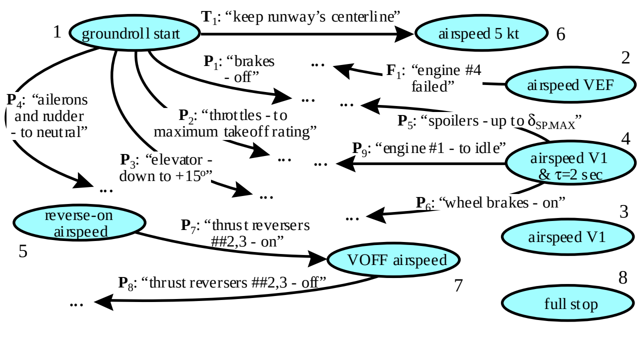
PURPOSE. The purpose of this example is to demonstrate that verbal specifications of flight test/certification cases can be translated into formal scenarios for autonomous simulation. It will be shown that such mappings help reduce the ambiguity when interpreting and implementing the airworthiness requirements or other qualitative descriptions of flight standards.

SOURCE SPECIFICATION. A typical verbal description of the airworthiness requirements, similar to FAR Part 25, "Flight and Performance. Takeoffs. Accelerate-stop distance" [6], is presented in Appendix 1.

Specified are the requirements to the flight performance of a four-engine jet airplane during aborted takeoff. Two test cases are considered: aborted takeoff with a critical engine out (Case A), and aborted takeoff with all engines operating (Case B). Anticipated operational factors (e.g.: weight, C.G., ambient air temperature, altitude, runway surface condition, etc.) are also regulated to be tested during the given flight modes. Some special requirements are also outlined.

OUTPUT SCENARIOS. Flight scenarios, which implement these two cases, have been constructed. An algorithm for experimentation with the situational model was also designed (but not covered in this paper), based on the anticipated operational factors and the special requirements outlined for these modes. Basically, this algorithm defines the sequence in which modifications (i.e. the requested operational factors, as well as their levels and combinations) are to be introduced into the initial scenarios. Design of experiment methods may also be applied to achieve the best coverage of the operational domain with the minimum number of autonomous "flights". Finally, based on the simulation results, the accelerate-stop distance is calculated [6].

Fig. 6 and 7 depict flight scenarios which implement the two test certification cases (A and B), respectively the scenario $\mathbf{S}_2$: "Aborted takeoff of a four-engine airplane with critical engine #4 out", and the scenario $\mathbf{S}_3$: "Aborted takeoff of a four-engine airplane with all engines operating".



Note: isolated events are for information only

Figure 6: Scenario $\mathbf{S}_2$: "Aborted takeoff of a four-engine airplane with critical engine #4 out"

These structures are concise and clear: only eight events and 11 processes are used to map the specified flight test certification modes. Note that the scenario $\mathbf{S}_3$ is derived from $\mathbf{S}_2$ by simply erasing the event $\mathbf{E}_2$: "airspeed VEF", which results in automatic cancellation of the process $\mathbf{F}_1$: "engine#4 failed". In addition, the process $\mathbf{P}_9$: "engine#1 to idling" is removed, and the processes $\mathbf{P}_7$ and $\mathbf{P}_8$ are to be modified.

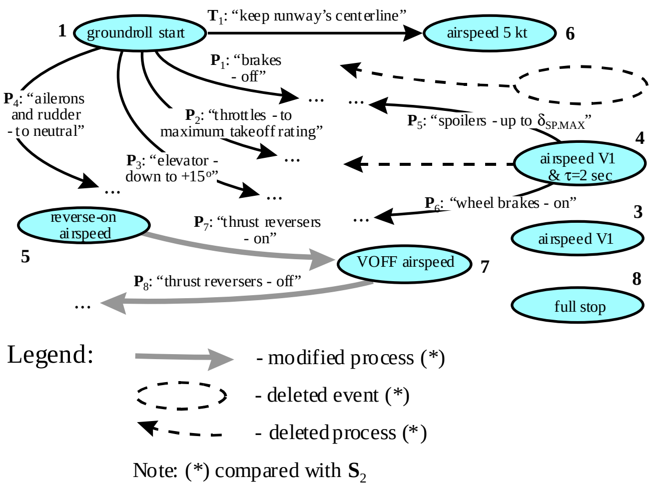


Figure 7: Scenario $\mathbf{S}_3$: "Aborted takeoff of a four-engine airplane with all engines operating"

DISCUSSION. The described test certification scenarios are generic. They capture the cause-and-effect structure of the tested flight mode and the pilot's tactics associated with it. Given a specific aircraft type, only the parameters of some events and processes (in this case, VEF, V1, VOFF, and $\delta_{S.MAX}$) are to be adjusted accordingly.

Test scenarios similar to **Fig. 6-7** may be accumulated in the form of a library and repeated in exact detail at any point in the future. Through this capability, VT&E receive the status of physical experiment. Note that in flight testing or manned flight simulation it may be difficult to repeat a complex test scenario in exact detail.

Thus, the mapping process exemplified above has three benefits. First, it associates a unique set of formal data structures (a flight scenario) and an appropriate experimentation algorithm with the airworthiness requirements, thus capturing their meaning. Second, it provides an affordable tool for applying these requirements to "test" the vehicle flight performance on a computer in a rigorous way. Finally, through autonomous simulation, the VT&E process can be automated and accelerated.

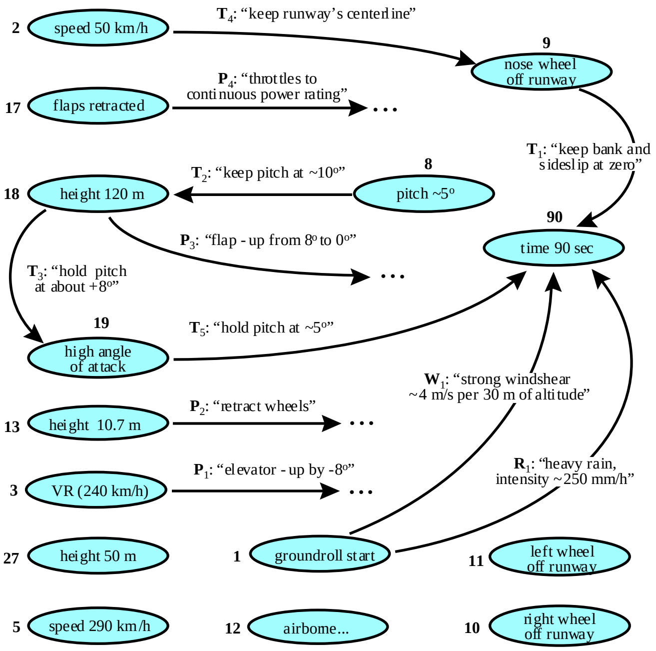
It is estimated that each page of a regulatory document, which specifies the airworthiness requirements, can be mapped into 2-6 flight scenarios similar to $\mathbf{S}_2$ or $\mathbf{S}_3$. Appropriate experimentation algorithms (plans) are to be designed as well.

SUMMARY. The FAR or other specifications of the aircraft flight performance can be mapped into a library of test scenarios and an appropriate experimentation plan (algorithm) for autonomous simulation. Based on these inputs, VT&E is then performed as a series of experiments with the autonomous situational model of flight. Test certification “flights” can be repeated for the same vehicle or for other aircraft from the same class using the initial scenarios with parametric adjustment of flight processes and flight events.

SIMULATION EXAMPLES

FLIGHT SCENARIOS. **Fig. 8-13** depict more examples of various flight scenarios:

- S_4 Take-off under strong wind shear and heavy rain conditions (FLA)
- S_5 Rough landing under strong wind shear and heavy rain conditions (FLA)
- S_6 Go-around with two right-hand engines out (FLA)
- S_7 Elevator pulse input in cruise flight (FLA)
- S_8 Aileron/elevator pulse inputs and airspeed control at low altitude and airspeed, cruise configuration (HSCT)
- S_9 Reconstruction of flight test modes (new medium-range turboprop airplane)

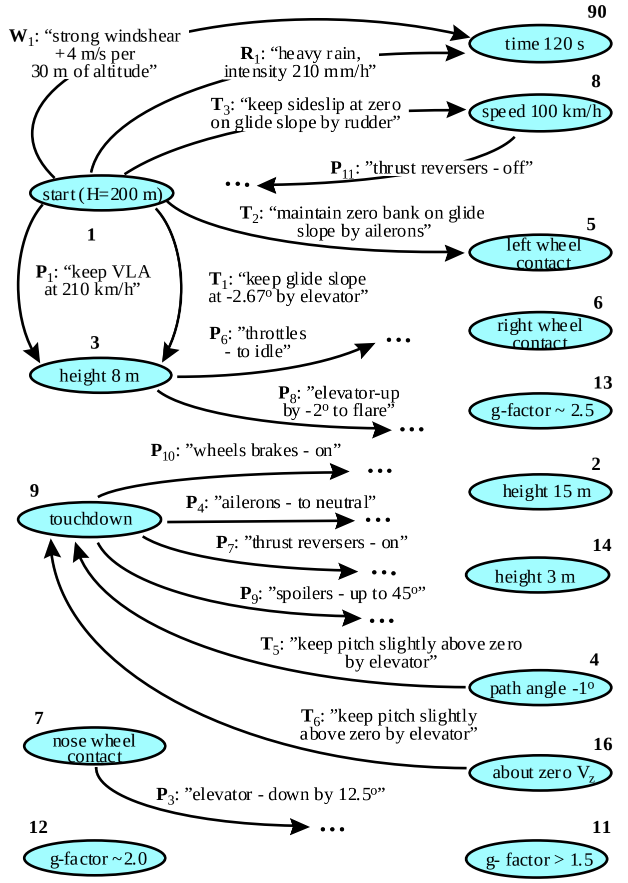


Note: events $\mathbf{E}_5$, $\mathbf{E}_{10}$, $\mathbf{E}_{11}$, $\mathbf{E}_{12}$, $\mathbf{E}_{27}$ are used only for information

Figure 8: Scenario S_4: “FLA take-off under strong wind shear and heavy rain conditions”

In the scenario S_4 a FLA prototype [7] is virtually tested under the microburst conditions encountered during a severe flight accident [4]. The correct piloting techniques are applied. The scenario S_5 formalizes a rough landing situation with the FLA under strong windshear combined with heavy rain (the weather conditions are similar to S_4).

The scenario S_6 models a go-around maneuver for FLA with two engines failed from one side of the wing. The approach is conducted at VLA=210 km/h. The examined piloting tactics employ a combination of bank and sideslip command angles and thrust control required to unload ailerons and avoid unrecoverable roll due to thrust asymmetry. Note that initially S_6 repeats S_5 (i.e. motion on the glideslope).



Note: events $\mathbf{E}_2$, $\mathbf{E}_6$, $\mathbf{E}_{11}$, $\mathbf{E}_{12}$, $\mathbf{E}_{13}$, $\mathbf{E}_{14}$ are used only for information

Figure 9: Scenario S_5: “FLA rough landing under strong wind shear and heavy rain conditions”

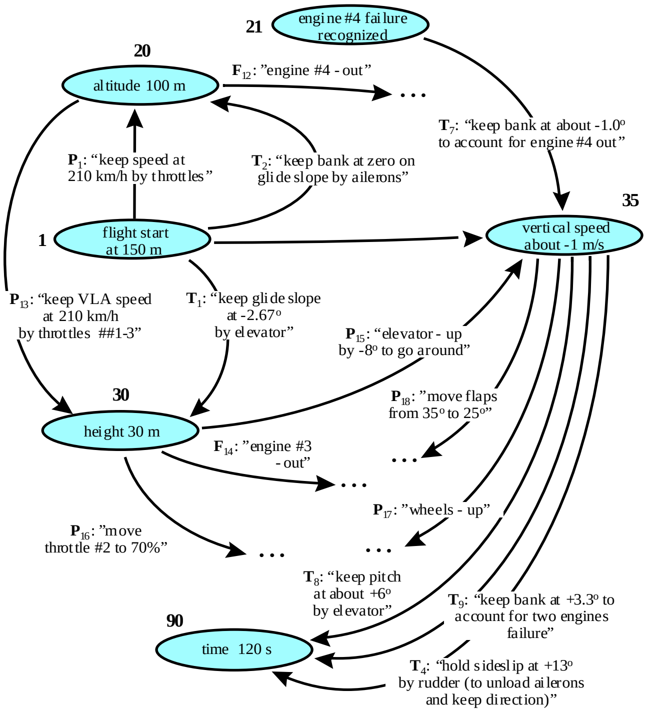


Figure 10: Scenario S_6: “FLA go-around maneuver with two right-hand engines out”

The scenario $\mathbf{S}_7$ demonstrates how to implement in the model a single pulse by the elevator in a cruise flight at H=10,000 m and M=0.75. Initially, a constant speed is maintained for about 25 seconds. Then a $+5^{\circ}$ elevator input is applied followed by a -5° reverse action.

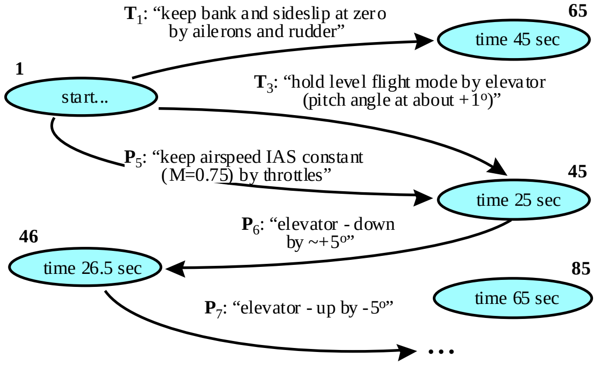


Figure 11: Scenario $\mathbf{S}_7$: "Elevator pulse input to FLA in cruise flight (H=10 km, M=0.75)"

A non-standard maneuver of an HSCT prototype [8] flying at low Mach number (M=0.3) and low altitude in cruise configuration is programmed in the scenario $\mathbf{S}_8$. A thick line denotes a special engine control procedure imitating an authothrottle system employed to keep the indicated airspeed constant.

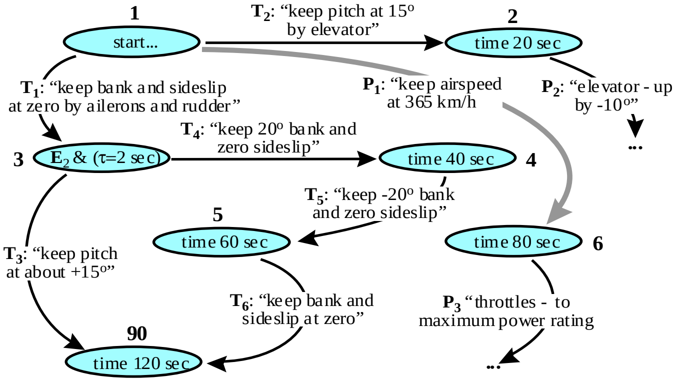


Figure 12: Scenario $\mathbf{S}_8$: "Aileron/elevator pulse inputs and airspeed control in HSCT (H=900 ft, M=0.3)"

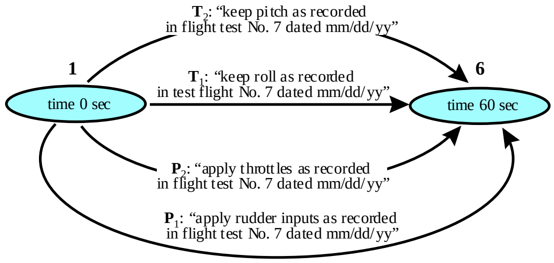


Figure 13: Scenario $\mathbf{S}_9$: "Reconstruction of flight test modes of a new turboprop airplane"

Finally demonstrated is the scenario $\mathbf{S}_9$ which reconstructs flight test modes of a new turboprop commuter airplane in autonomous modeling. Note that this real flight case is coded and modeled as an elementary flight situation.

SIMULATION RESULTS. Results of autonomous simulation of flight situations according to the scenarios $\mathbf{S}_4$ - $\mathbf{S}_9$ are presented in **Fig. 14-19** in Appendix 2.

SUMMARY. The autonomous situational modeling and simulation technique is capable of studying the flight performance of various aircraft types under demanding and standard operational conditions. The flight scenario formulation helps better understand and manage, during the process of experimentation with the model, complex physical and logical interrelationships in the "pilot – vehicle – operational conditions" system. Extreme or rare combinations of anticipated operational factors which may lead to a flight accident can be reproduced, quantified and evaluated. This technique can be used to track potential problems with the vehicle flight performance in advance and thus help focusing flight test and manned flight simulation programs.

DISTINGUISHING FEATURES

Below this is a summary of the distinguishing features of the technique discussed above.

The autonomous flight modeling and simulation technique can be applied to a broad range of flight vehicles. Complex relationships between a human pilot's control tactics and operational factors of flight are described at the level of invariant cause-and-effect links. Effects of weather conditions, pilot errors, and onboard system's failures can be combined and studied in a rigorous way. Both hypothetical and actually occurred flight cases are possible to model.

The airworthiness requirements or other verbal descriptions of test or complex flight cases can be mapped into concise input data structures (directed graphs). An exhaustive set of virtual test scenarios can be constructed and simulated. Special piloting knowledge, programming skills, or a flight simulator are not required. Thus, VT&E experiments may be planned and executed directly by a designer who, in fact, will act as a test pilot or a certification professional.

Once constructed, flight scenarios can be repeated in exact detail for a new design configuration. After parametric adjustment the flight scenario library may be reused for other vehicles belonging to the same class.

Finally, an important feature is that autonomous flight models run 20-40 times quicker than real time (on a 200 MHz PC).

CONCLUSIONS

A technique has been developed for virtual testing and evaluation of the vehicle flight characteristics using an autonomous situational model of flight. This technique may be used from the earlier design to operational phases of the vehicle's life cycle. This model integrates a human pilot's tactical decision making processes and anticipated operational conditions of flight. Various operational factors may be combined and their effects upon the six-degree-of-freedom controlled motion of an aircraft can be examined.

The concept of flight situation scenario in the form of a directed graph is proposed to formalize complex flight cases. It may be used to map the airworthiness requirements, pilot's manuals, test programs, flight recorder data, or other specifications of flight, including verbal descriptions, into compact input data structures for autonomous simulation. Both hypothetical and actual flight cases can be studied. An extensive library of flight scenarios can be constructed and retained in electronic format. Given new design or other inputs, this allows the VT&E process to be quickly repeated for the same or other vehicles.

However, a pre-requisite for successful application of the technique is the availability of a comprehensive mathematical model of vehicle's flight dynamics. Physics-based models of new technologies, which are employed in a new vehicle, are required as well. Input characteristics of the vehicle dynamic model must encapsulate the operational domain under study. A flight dynamics model and flight test data for a baseline vehicle are also desirable for validation purposes.

The autonomous situational model has demonstrated its performance as a practical, affordable tool for generating systematic knowledge about the behavior of the "pilot - vehicle - operational conditions" system in complex flight situations. Thus, this technique provides a research "short-cut" between the designer's solution (basic design variables, configurations, etc.) and its possible effects upon the system operational behavior.

Autonomous modeling and simulation is complementary to flight testing and manned flight simulation. By applying the VT&E technique, flight test programs can be better focused. As a result, the number of test and certification hours required for a new vehicle may be significantly saved with a simultaneous increase in the quality and amount of knowledge about complex operational domains of flight.

The autonomous situational model is also used in advanced research into automatic flight envelope protection, pilot-vehicle intelligent interface, and robotic flight [9].

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DEFINITIONS. ACRONYMS. ABBREVIATIONS.

α	Angle of attack
Π	Flight process
ω	Main rotor rotation speed, r.p.m.
φ	Mast angle
β	Sideslip angle
γ	Bank angle
ϑ	Pitch angle
τ	Delay
$\Omega(\Pi)$	United set of flight processes
$\Omega(\mathbf{E})$	Flight events calendar
δ_F	Flap setting
δ_{SP}	Spoiler deflection angle
$\mathbf{B}$	Onboard system function
C.G.	Center of gravity
$\mathbf{E}$	Flight event
$\mathbf{E}_*$	Source flight event
$\mathbf{E}^*$	Target flight event
$\mathbf{F}$	Onboard system failure
FLA	Future Large Aircraft [7]
H	Flight altitude
M	Mach number
m/s	Meters per second
$N(\Omega(\Pi))$	Total number of flight processes in $\Omega(\Pi)$
$N(\Omega(\mathbf{E}))$	Total number of flight events in $\Omega(\mathbf{E})$
n_z	Load factor
$\mathbf{O}$	State observer
$\mathbf{P}$	Control procedure
$\mathbf{R}$	"Rain"-type process
rpm	Revolutions per minute

S	Flight scenario
SCAS	Stability and control augmentation system
$SCAS_{roll}$	Ailerons deflection due to SCAS
$SCAS_{yaw}$	Rudder deflection due to SCAS
T	Piloting task
V1	Takeoff decision speed
V_{CAS}	Calibrated air speed
V_{east}	East speed (earth)
VEF	Engine failure speed
VOFF	Thrust reversers turn-off speed
V_{IAS}	Indicated air speed
V_z	Vertical speed (earth)
W	"Wind"-type process
W_{xg}	Horizontal component of wind speed (earth)
W_{zg}	Vertical component of wind speed (earth)
Y	"Runway surface condition"-type process
Δ	Ambient air density

APPENDIX 1. SPECIFICATION OF ABORTED TAKE-OFF AND ACCELERATE-STOP DISTANCE

According to FAR Part 25 "Airworthiness Standards: Transport Category Airplanes", Subpart B "Flight. Performance", Section 25.109 "Accelerate-stop Distance" [6], the accelerate-stop distance is defined as the greater of the outcomes of the following two cases:

CASE A. The sum of the distances needed to:

1. Accelerate the airplane from a standing start to VEF [engine failure speed] with all engines operating
2. Accelerate the airplane from VEF to V1 [decision speed] and continue the acceleration for 2.0 seconds after V1 is reached, assuming the critical engine fails at VEF; and
3. Come to a full stop from the point reached at the end of the acceleration period prescribed above, assuming that the pilot does not apply any means of retarding the airplane until that point is reached and the critical engine is still inoperative.

CASE B. The sum of the distanced needed to:

1. Accelerate the airplane from a standing start to V1 and continue the acceleration for 2.0 seconds after V1 is reached with all engines operating; and
2. Come to a full stop from the point reached at the end of the acceleration period prescribed above, assuming that the pilot does not apply any means of retarding the airplane until that point is reached and that all engines are still operating.

SPECIAL REQUIREMENTS. In both cases, in determining this distance:

- any safe, reliable stopping means other than wheel brakes may be used
- the landing gear must remain extended while this distance is being determined
- if this distance covers surfaces of varying roughness (i.e., other that a smooth, hard runways surface), correlation factors must be applied to correct for the effects of the various surfaces on the distance.

APPENDIX 2. SIMULATION RESULTS

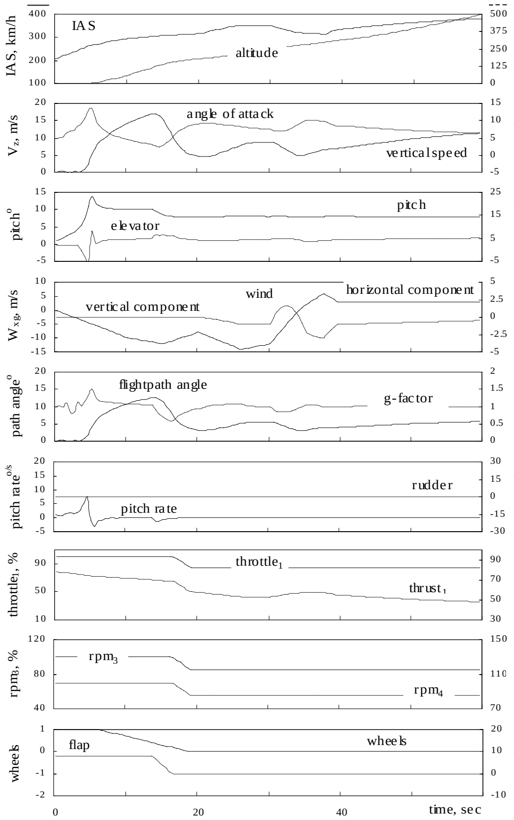

Figure 14: Take-off under strong wind shear and heavy rain conditions (FLA, scenario $\mathbf{S}_4$)

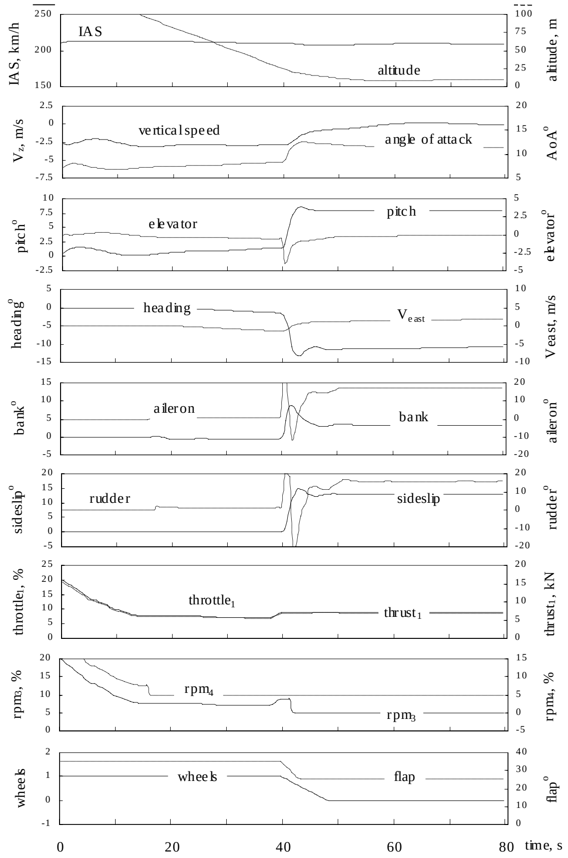

Figure 15: Go-around with two right-hand engines out (FLA, scenario $\mathbf{S}_6$)

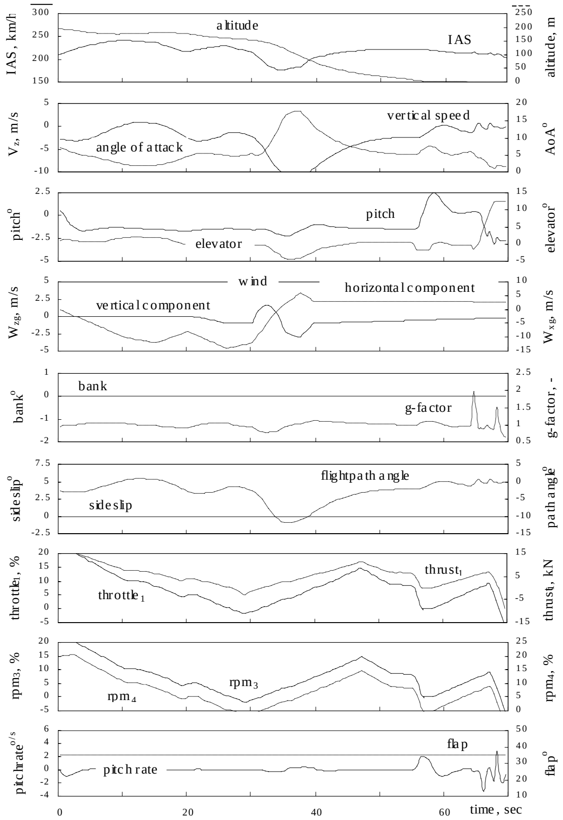

Figure 16: "Rough landing in strong windshear and heavy rain conditions (FLA, scenario $\mathbf{S}_5$)

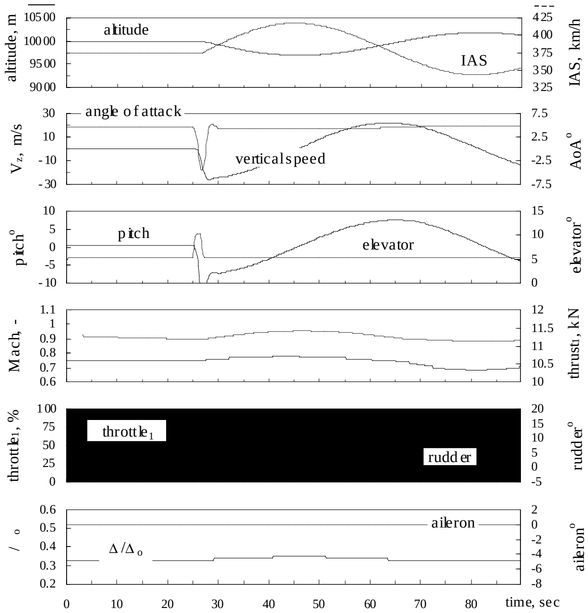

Figure 18: Elevator pulse input in cruise flight configuration (FLA, scenario $\mathbf{S}_7$)

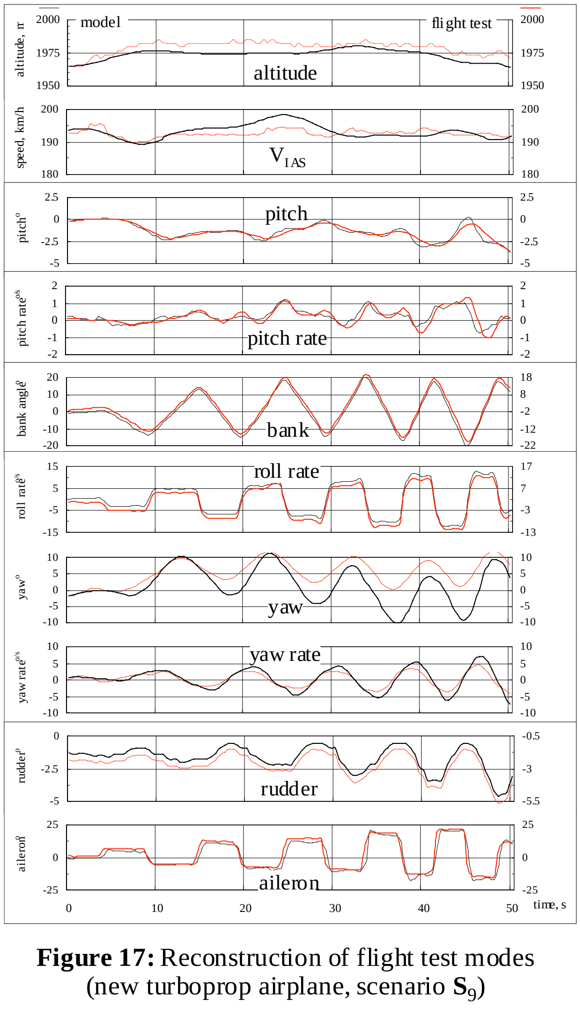

Figure 17: Reconstruction of flight test modes (new turboprop airplane, scenario $\mathbf{S}_9$)

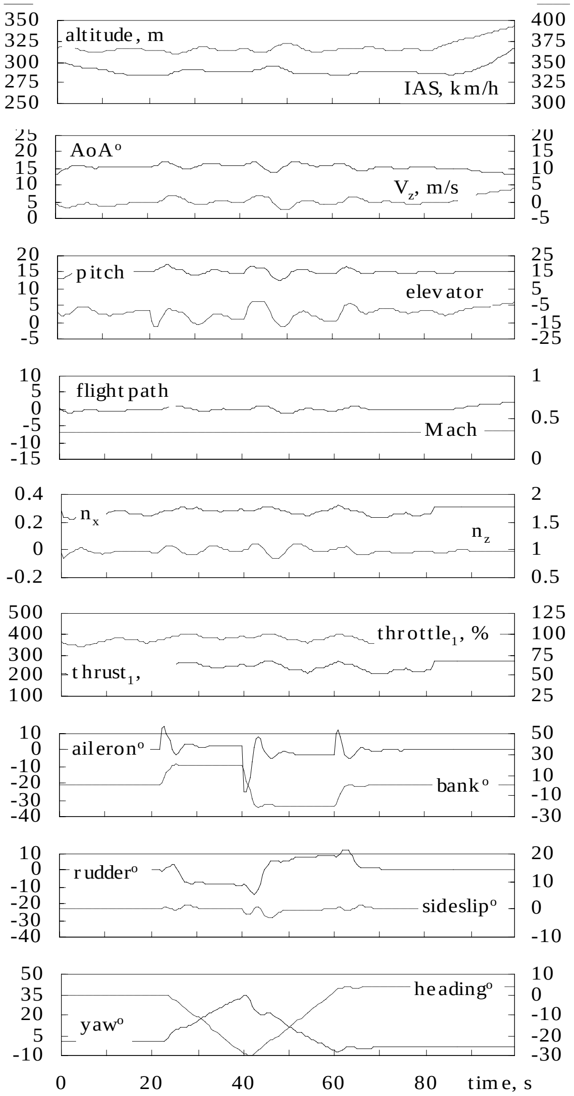

Figure 19: Aileron/elevator pulse inputs and airspeed control (HSCT, scenario $\mathbf{S}_8$)