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DISCRETE TIME MODELING OF HEAVY TRANSPORT PLANE PILOT BEHAVIOR

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1 - Introduction

The desire to improve flight safety leads to a classification of various flight troubles in three groups :

- troubles from sensitivity to flight disturbances,
- maneuverability troubles (whenever a correction maneuver induces an unexpected deviation on another parameter),
- pilot troubles (pilot overload when required attention is excessive or underload entailing a loss of vigilance).

Sensitivity to disturbances and maneuverability of a given aircraft may be evaluated from the early design stage. Evaluation of the pilot behavior, however, may be realized only in actual flight or with a flight simulator, that is quite late in the development period. For this reason, it is desirable to have available, at the design stage, a model of the pilot behavior to command the differential system describing the envisionned aircraft.

This aim implies two major requirements. First, the program must be compatible with a wide range of possible aircraft designs; ideally, the program should be self-learning. Second, mental load and overall pilot performance must be modeled.

Following J.C. Wanner [1] , a flight may be decomposed into a sequence of "phases", each having a long-term objective. Typical phases are ILS approach and landing. Each phase may be eventually divided in sub-phases with short-term objectives. For instance, the ILS approach phase may be broken into localizer beam engagement, glide beam engagement, push over and final descent.

The pilot's task (fig.1) may be defined by data describing.

- a flight sub-phase,
- the aircraft state,
- atmosphere conditions,
- the required control law to follow a nominal flight path during the sub-phase,
- secondary activities (e.g., radio communications, ...).

The objective of the pilot's task is the same as that of the corresponding sub-phase, namely to ensure a short-term safety, thus enabling to execute the next sub-phase with a reasonable chance of success. At the end of this sub-phase, the flight parameters must be within a given window of admissible deviations about the nominal values. Respect of immediate safety consists for the pilot on maintaining the actual flight path close to the nominal values.

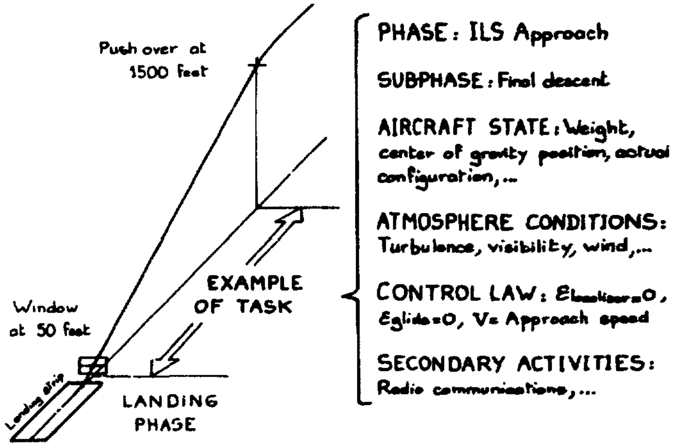

Figure 1 - Pilot's task

A second aspect of flight safety is relative to the pilot workload. This workload may be decreased by a better presentation of the necessary data. Therefore, it would be useful to determine which data are the most appropriate to supply to the pilot in order to reduce his workload and thus increase flights safety and regularity. For instance, data may be supplied by means of a head-up display [2] , but in the present study it is assumed that informations are provided <u>only</u> by a classical instrument panel and without external vision.

2 - Model of aircraft considered

We consider the model of a twin-engine heavy transport plane of Airbus A300B type. During the flight sub-phase considered in this study (final descent of ILS approach), the aircraft keeps a constant configuration (fully deflected flaps and landing gear down). The flight equations have been simplified and only the most relevant variables, including couplings, have been retained to describe the transport plane in its normal domain of flight. The only controls that the pilot (actually, the model) may use to achieve the required control law are :

δl = lateral control) on the stick
δm = longitudinal control) on the stick
δn = rudder control
δz = throttle lever .

to which elevator trim may be added.

3 - Assumptions

The conventional assumption of the pilot acting in a continuous manner and represented by transfer functions has not been retained here. Instead, another approach has been used in considering the pilot's behavior as a sequential process.

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3.1 - Assumptions on the pilot's behavior

We have made the same assumptions that in the previous study [3] and these assumptions have been confirmed by experimentation. The pilot's behavior has been investigated for the case of the "final descent" sub-phase, on a static simulator cockpit. An electro-oculometer equipment (EOM) has been used, thus allowing continuous determination of the pilot's line of sight.

Due to these experimental conditions, the pilot's control activity is being considered here only as a monitoring and control activity of the data as displayed on the instrument panel. "Secondary activities", such as communication with air traffic control and other crew members, have not been taken into account. Moreover , any "involuntary" information perceived by the pilot has been neglected, for instance peripheral sight of the instrument panel and of outside environment, acceleration effects on the inner ear, noise, etc. It may be noted that, in IFR conditions, an important part of the pilot's training consists on neglecting the involuntaryly perceived information (especially accelerations).

We shall then consider :

1) that, at a given time, the pilot can either make a decision or take one of the three following elementary actions :

- act on one control
- read an information on the instrument panel,
- monitor a given parameter reading on a dial;

2) that the strategy used by the pilot, that is the whole of the heuristic rules he is using, is a function of the flight situation defined [1] by the aircraft type and state, the type of flight sub-phase and the atmosphere environmental conditions (turbulence, visibility, wind, etc);

3) that, it is a priori important to take into account the sequential character of the pilot's decision making, as opposed to the conventional view taken in automatic control on this same problem.

3.2 - Mechanism of the pilot's actions (Fig.2)

It is assumed that the pilot's memory contains :

1) a catalog of "actions". The pilot selects one action out of the catalog as a function of the differences between the image of the actual situation he has in memory and the image of the typical situation in which the implementation of each of these actions is proposed.

2) an operating insight, that is an internal model of the aircraft allowing him to foresee the aircraft reactions, therefore to evaluate the situation while taking into account the previous actions taken; this evaluation is, of course, re-actualized after each reading.

The model of pilot including this evaluation of the actual situation, called "memorized situation", can calculate, while using his operating insight, foreseensituations and select the action to be taken as a function of these foreseen situations and of their subjectively-appreciated seriousness.

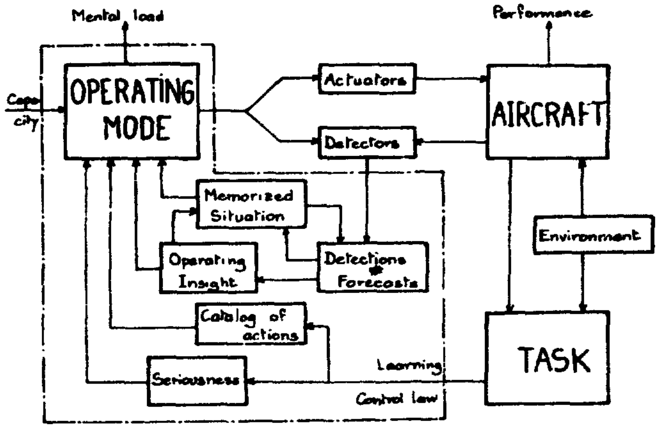


Figure 2 - Mechanism of the pilot's actions

4 - Experimentation

The dynamical flight equations of the heavy transport plane previously described (§2) were wired on a hybrid computer connected to a static simulator cockpit.

4.1 - Experimental conditions

The requirement of knowing which information is read at a given time by the pilot leads to a particular type of instrument panel. Several informations usually gathered within a single given instrument have been separated in order to associate a single information to a given line of sight (for instance, the ILS whose two informationswere separated). For the final descent sub-phase, the following nine instruments were used :

- two instruments resulting from the ILS split, i.e. localizer deviation indicator ε_{loc}, glide path deviation indicator ε_{glide}.
- roll indicator ϕ , pitch indicator θ , yaw indicator ψ .
- vertical speed indicator $\dot{z}$, an altimeter z.
- thrust indicator F, airspeed indicator V.

The cockpit includes also the five controls described in §2 : lateral control δ_l, longitudinal control δ_m, rudder control δ_n, throttle lever δ_z and an elevator trim.

Eye motion can be determined through an EOM equipment (Fig.3). Potential differences depending on the relative position of the eyes with respect to the skull were measured by electrodes applicated on the pilot's face. Assuming that the pilot's head remains fixed, the dial observed by the pilot at any given time can be determined from the amplified and filtered EOM signals.

Figure 3 - Electro-oculameter (EOM) equipment

4.2 - Remarks and results

In a first experimental phase, the simulated aircraft was "flown" by five professional pilots. When pilots are asked about the simulated aircraft and its dynamics, they express their operating insight in terms of relations between the parameters and between the parameters and controls. This insight conforms with the linearized equations of the aircraft flight dynamics with respect to the lateral control, but seems much more complex with respect to the longitudinal mode (Ɛglide-airspeed coupling) (Fig.4).

The pilot model incorporates this operating insight as illustrated by a state vector representing the memorized situation of the aircraft and a set of equations describing the flight dynamics used mentally by the pilot to take his forecasts.

In a second phase, the results of all flight phases simulated by human pilots have been analyzed while distinguishing three levels of activity in the pilot's operating mode [3] (Fig.5). This classification is only a working assumption which seems close to the observed reality.

Short term safety is the objective of the strategy. Immediate safety is a constraint that can be satisfied only with a correction procedure that keeps the actual flight path close to the nominal path.

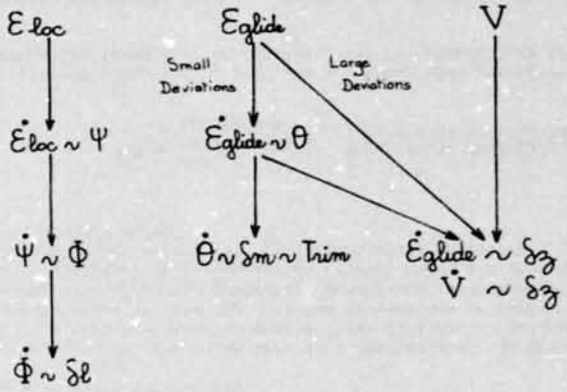


Figure 4 - Operating insight

LEVEL	DEFINITION	OBJECTIVE	COST
STRATEGY	Choice of Correction Procedures	Short-term Safety	Mental Load (Decision)
CORRECTION PROCEDURE	Algorithmic sequence of elementary actions	Immediate Safety	Mental Load (Memorization)
ELEMENTARY ACTION	• Read indicator • Act on one control • Monitor one dial		Physical Load

Figure 5 - Levels in operating mode

The recorded phases are further divided in correction procedures or in monitoring of the instrument dials. Various quantities are determined such as mean reading time, monitoring frequency for each parameter, action laws on controls, sequence of monitored dials, etc. On example of correction procedure for localizer deviation is given on figure 6.

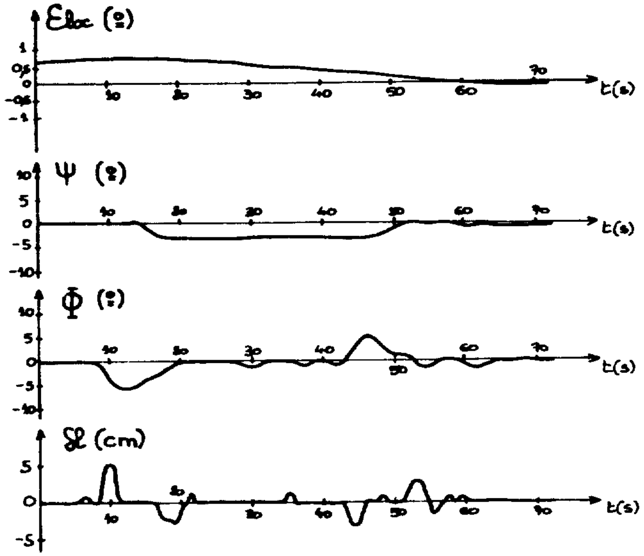


Figure 6 - Localizer correction procedure effectued by a human pilot.

5 - Digital model

5.1 - Program description

The flow chart is given on figure 7.

After initializations, the pilot's model selects the correction procedure to be used as a function of the strategy followed. This correction procedure is then further divided in a sequence of elementary actions (instrument reading, monitoring of a parameter, action on a control) which are successively taken.

As a matter of fact, while a parameter is being monitored, the model can select and undertake the execution of another correction procedure which acquires a higher priority. The abandoned correction procedure is then resumed.

During an elementary action, the time increment dT controls on the one hand, the integration of the flight path according to the equations of motion and, on the other hand, the integration of the situation as memorized by the model.

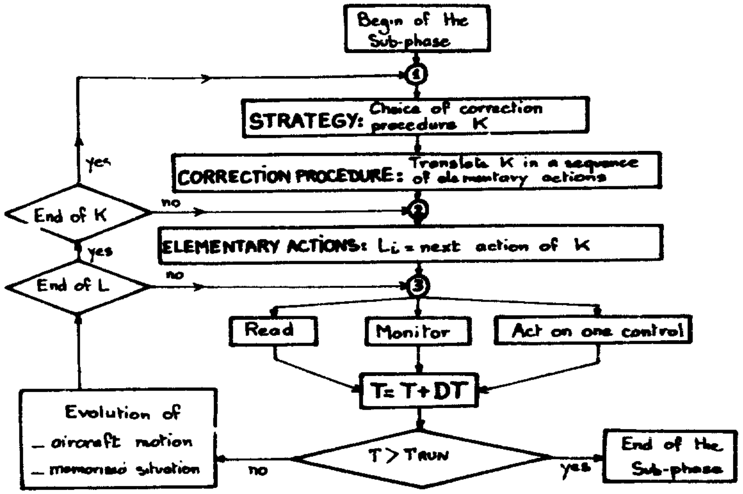


Figure 7 - Program description

5.2 - Model of strategy used

Strategy is the most elaborate level of the pilot's behavior. In the digital program, the strategy allows the pilot's model, at a given time, to select which correction procedure or dial monitoring he will take. This choice is made while complying with short-term safety.

The strategy model described here is a synthesis of two previously used model [3] . Care has been exercised to make a clear distinction between the choice of dials monitoring (a strategy with Markov readings of random nature is used) and the manner to select the parameter corrections (a heuristic strategy using short-term evaluation). Differenciation between these two strategies is based on the concept of seriousness of the instantaneous situation as perceived by the pilot's model defined by

$$G = \underset{\substack{\text{on the main}\\ \text{parameters}}}{\text{Max}} \left| \frac{\text{estimated deviation}}{\text{permissible deviation}} \right|$$

This is the maximum ratio, over the sub-phase main parameters, between the estimated deviation (memorized or foreseen) and the permissible deviation on a parameter.

The permissible deviations were determined experimentally.

5.2.1 - Strategy for dials monitoring

For this strategy, reading of instruments depends upon two random processes as far as digital simulation is concerned. The sequence of looked up dials is regarded as a Markov chain and the sequence of reading times as a Poisson process.

The sequence of looked dials is governed by a matrix of conditional probability to read one instrument after another. This matrix is called here switching matrix. After every instrument reading, the value of a random variable determines, taking into account the switching matrix, which dial will be read next.

Reading of the dials is made at a variable rhythm and the mean time between switchings is denoted by MTBS. This time interval is the time necessary for the simulated pilot to acquire one datum.

The random character of the sequence of observed dials is eliminated if one or more parameters exceed or have exceed at the time t a certain level preset for each parameter. Then, the process becomes deterministic.

If only one parameter exceeds its threshold. It is the instrument corresponding to this parameter which is read. If at the reading time, several parameters have exceeded the preset threshold, it is the instrument with the greatest probability according to the switching matrix which will be read.

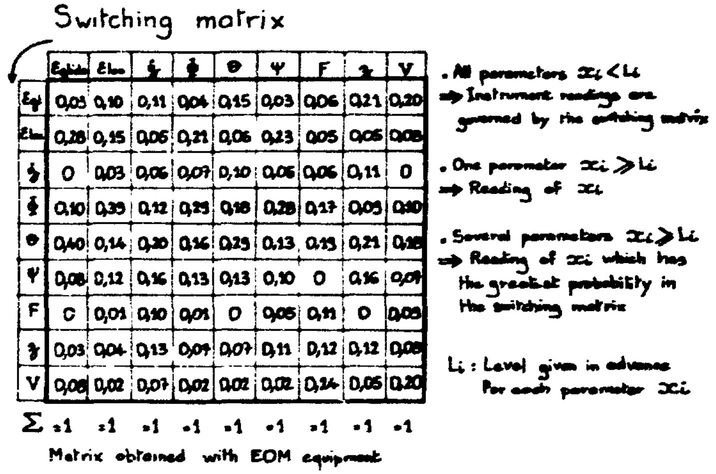
The phenomenon can be seen experimentally : if an instrument diverges, the pilot's line of sight is generally directed at the corresponding instrument because his peripheral sight allows him to detect any significant deviation on one of the dials. If several parameters diverge, the pilot is busy with the parameter which has higher priority in his opinion and temporily neglects other parameters which keep diverging.

A switching matrix determined experimentally by using the simulator cockpit and the electro-oculometer equipment in the case of the final descent is given on figure 8.

5.2.2 - Strategy for correction procedures

This strategy is based on the fact that the pilot makes decisions depending on the short-term predicted evolution of the situation, while taking into account intended actions.

The model has not access to the equations governing the aircraft dynamics. Its operating insight conforms with that determined at the beginning of the experimental phase. Its task consists in correcting the detected deviation in order to maintain the difference between the read-out values and the nominal values of the main parameters of the sub-phase within a certain tolerance on each of them.


Switching matrix

	Eglide	Eloc	ζ	φ	θ	ψ	F	γ	V
Egl	0,03	0,10	0,11	0,04	0,15	0,03	0,06	0,21	0,20
Elo	0,28	0,15	0,06	0,21	0,06	0,23	0,05	0,05	0,08
ζ	0	0,03	0,06	0,07	0,10	0,06	0,06	0,11	0
φ	0,10	0,39	0,12	0,25	0,18	0,28	0,17	0,05	0,10
θ	0,40	0,14	0,20	0,16	0,25	0,13	0,15	0,21	0,18
ψ	0,08	0,12	0,16	0,13	0,13	0,10	0	0,16	0,07
F	0	0,01	0,10	0,01	0	0,05	0,11	0	0,05
γ	0,03	0,04	0,13	0,07	0,07	0,11	0,12	0,12	0,08
V	0,08	0,02	0,07	0,02	0,02	0,02	0,14	0,05	0,20
Σ	=1	=1	=1	=1	=1	=1	=1	=1	=1

Matrix obtained with EOM equipment

- All parameters $x_i < L_i$
  $\Rightarrow$ Instrument readings are governed by the switching matrix
- One parameter $x_i \gg L_i$
  $\Rightarrow$ Reading of x_i
- Several parameters $x_i \gg L_i$
  $\Rightarrow$ Reading of x_i which has the greatest probability in the switching matrix

L_i : Level given in advance for each parameter x_i

Figure 8 - Strategy for dials monitoring

Let So be the memorized situation at time t_0, the model may use its operating insight to compute the predicted situation S_1 at $t_1 = t_0 + \Delta t_1$ if it does not intervene. It may also imagine that, during the time Δt_1, it will implement the K_1 correction procedure on the P_1 parameter. The predicted situation S'_1 will then be similar to S_1 to the difference that P_1 will be corrected and that the dials whose reading are necessary to carry out K_1 will have been read out.

This prediction capacity is applied by the model to select whenever necessary, the "best correction procedure" to carry out to comply with the short term safety. This choice is made by unfolding a logical tree (Fig.9) for which

- the root is the memorized situation,
- branches are correction procedures whose implementation is considered,
- nodes other than the root are situations predicted from the root by means of the operating insight while taking into account the intended correction procedures.

The instantaneous seriousness $G(K)$ is computed at each node K. Considering that it remains constant during the time Δt_1 elapsed from the previous node to the node I, the model computes a short term mean seriousness $\mathcal{G}(I)$ on each path leading to a terminal node. To that end, the instantaneous seriousness is weighted by the time elapsed on each branch and the result is divided by the total time elapsed on the path. The short-term mean seriousness of a path (I,J) is then denoted by :

$$\mathcal{G}([I,J]) = \frac{1}{t_J - t_I} \sum_{K = I \rightarrow J} G(K). \Delta t_K$$

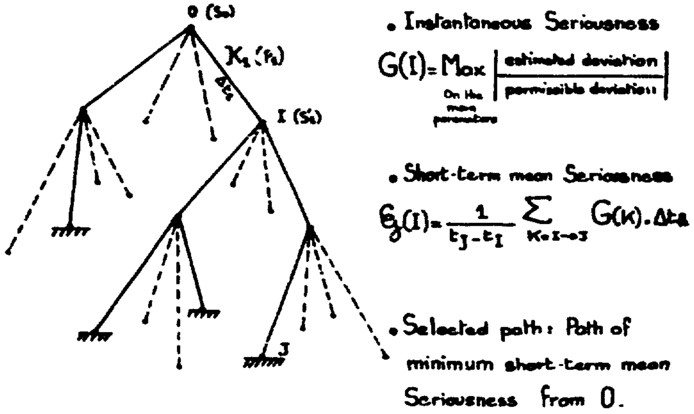


Figure 9 - Strategy for correction procedures

The mean seriousness of the best path $\mathcal{G}_J([I,J])$ chosen in I is noted $\mathcal{G}_J(I)$. This choice is made simply by taking, among all possible paths from I, the one which has the minimum mean seriousness.

The path from the root with the minimum mean seriousness is then selected and the implementation of the correction procedure corresponding to its first branch may begin.

5.2.3 - Overall strategy used

It is assumed that a correction procedure has just been completed. It may be the first part of a correction procedure (and there is then a dial monitoring phase usable in the framework of the strategy), or the second part of this correction (a fully completed correction procedure).

The model returns to the strategy (Fig.10) and begins with the evaluation of the instantaneous seriousness $G(0)$ at the root of the tree. This evaluation is restricted to the main parameters present in the memory and those read too far in the past are omitted (the omission phenomenon changes the seriousness of the situation as perceived by the pilot and makes his behavior more realistic).

After the evaluation of $G(0)$, the model asks itself the following question : is the situation serious ? (is $G(0)$ over a certain level of minimum seriousness ?).

- If the answer is "no", the model monitor dials while using the strategy with Markov readings and begins again the evaluation of the instantaneous seriousness $G(0)$.
- If the answer is "yes" the model asks itself whether the situation is well recognized.

If the situation is not recognized, the model makes all necessary readings in a deterministic manner, thus allowing full knowledge of this situation.

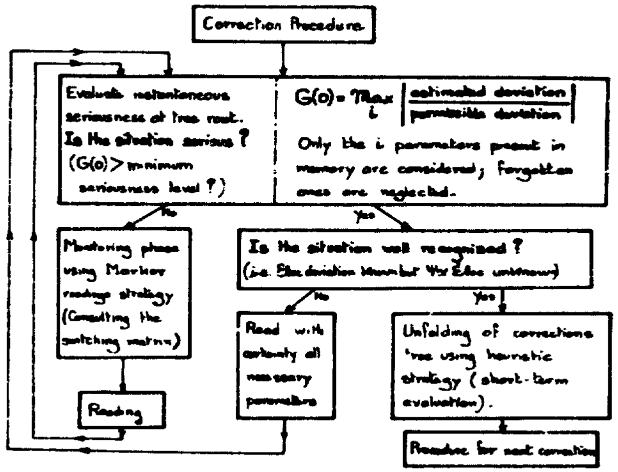


Figure 10 - Overall strategy

If the situation is serious and well recognized, the model unfolds the tree of the all possible corrections and makes a choice between them while evaluating the short-term situation.

6 - Results

Final descent sub-phases have been made by the model with conventional instrument without external vision (IFR conditions). These sub-phases have been displayed on the scope of a Cathode Ray Tube display with superposition of the head-up information (Fig.11) only for illustration of the results.

It has been shown in the introduction that a better display of information could decrease the pilot's workload and therefore improve flight safety. Information display by a head-up display is one of the solution that could be considered.

If a program with self-learning features is used, such a display mode of information will sensibly change the strategy and the correction procedures with beneficial effects on the overall system performance and the pilot's workload.

The various returns to the strategy during a final descent sub-phase are indicated on Fig. 12 for the case of initial airspeed (+8 kts), glide (+0,2°) and localizer (+0,5°) deviations. One can see on the same figure the unfolding of the first tree (with a single branch) and the various seriousness associated with each branch; the latter led to the choice of the correction on the parameter with the branch of minimum seriousness.

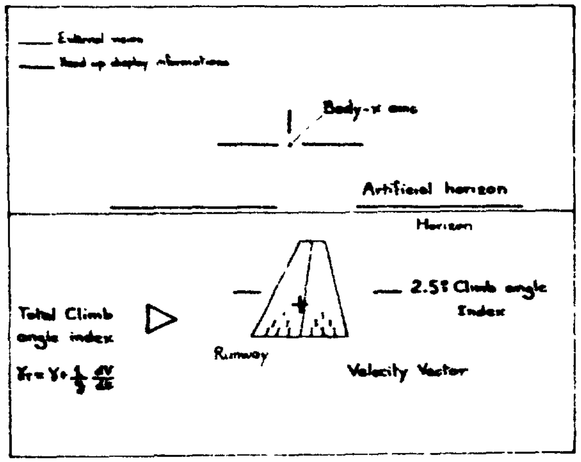


Figure 11 - Head-up display information

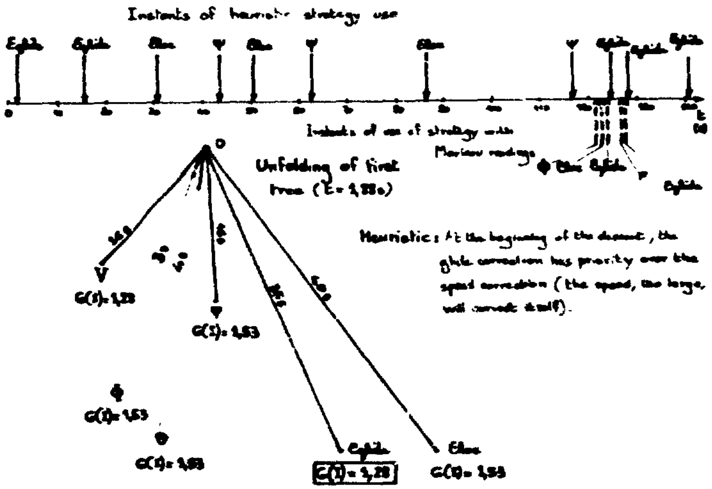


Figure 12 - Example of strategy use

The digital model responses have been compared, in the case of the final descent considered above, with the responses of a human pilot on our static simulation cockpit. The correction procedure coefficients (parameter of the magnitude laws) of the digital model have been adjusted in order to obtain approximate coincidence between the two types of responses (Fig.13). A good coincidence is achieved during the first correction procedure; responses, then, become oscillatory with small amplitude about nominal values.

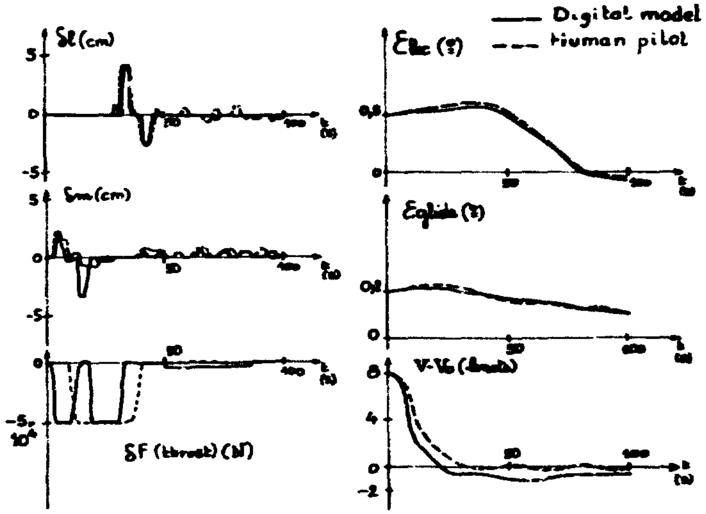


Figure 13 - Responses comparison

7 - Conclusion

A digital program simulating the behavior of the pilot of a transport plane (of Airbus A300B type) is now operating for one flight sub-phase (final descent of the ILS approach).

Future investigations will be concerned with the introduction of the self-learning capability, that is the auto-adaptation of the pilot's model to any type of new aircraft and also the analysis of the influence of information display on the pilot's behavior and workload. These investigations will be implemented using a moving flight simulator at the Istres Flight Test Center.

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