ROBUST FLIGHT CONTROL: A REAL-TIME SIMULATION INVESTIGATION

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Abstract

There exist many robust flight control techniques. Some of them require complicated control structures, which lead to a high level of computing complexity. Further, aircraft systems consist of multiple subsystems and components that interact with each other. Therefore, real-time simulation for distributed systems become a critical stage in order to bring design to reality. However, investigation in this field is rarely reported. This paper presents the research work of real-time implementation and simulation for a distributed aircraft model with one robust flight controller. Further, a comparative analysis between off-line and real-time simulation is provided, to highlight several design considerations during the real-time implementation.

1 Introduction

Modern aircraft include a variety of automatic control systems that aid the flight in navigation, flight management, and augmenting the stability characteristics of the airplane. The robustness problem, involved with the design of these flight control systems, is intended to deal with system uncertainties. These system uncertainties in flight may come from either parameter variations, unstructured models inaccuracies, or external disturbance, such as turbulence and wind gust. Further, large envelope flight operation requires the flight control system to be robust; aircraft agility requires attention of the robustness aspect when the aerodynamic control is lost; and even in hypersonic flight, high speed requires stability robustness as well.

There exist many robust flight control techniques. Some of them require complicated control structures, which lead to a high level of computing complexity. Further, aircraft systems consist of multiple subsystems and components that interact with each other. Therefore, real-time simulation for distributed systems become a critical stage in order to bring design to reality. However, investigation in this field is rarely reported. This paper presents the research work of implementing distributed aircraft models for real-time simulation.

The remainder of this paper is organized as follows. First, a distributed benchmark aircraft model and its robust control system are introduced. The real-time computing facility is then presented where our research work of real-time modeling and control is conducted. In the following section, the test procedure of flight simulation is introduced to evaluate the designed robust control technique. Afterwards, real-time simulation results are presented. Further, a comparative analysis between off-line (non real-time) and real-time simulation results is provided, to highlight several design considerations during the real-time implementation. Finally, the concluding remarks and future development work are offered.

2 The Benchmark System Development

In 1995, the Group for Aeronautical Research and Technology in Europe (GARTEUR) issued a design challenge geared towards the improvement and optimization of computer aided aircraft design integration [3]. The focus of this study was on the flight control discipline and making the controller analysis and design methodology suitable for muli-disciplinary considerations. It was determined that robust control methodology had the potential to satisfy these criteria.

A fictitious commercial aircraft model (named RCAM) was developed, using Matlab/Simulink, and supplied to a number of research teams in the European aerospace community. The goal was for each team to design an autopilot for the final segments of a landing approach. Each team centralized around a different robust technique and the result was a collection of technical papers comparing each of the methods benefits and drawbacks [6].

This model was deemed ideal for our investigation of remodeling and implementation for real-time simulation, since its structure allows for easy replacement and distribution of subsystems. As well, its development and offline results are well documented.

The software platform for real-time development is RT-LAB, developed by OPAL-RT Technologies [7]. The original RCAM model was re-grouped into subsystems as illustrated in Figure 1.

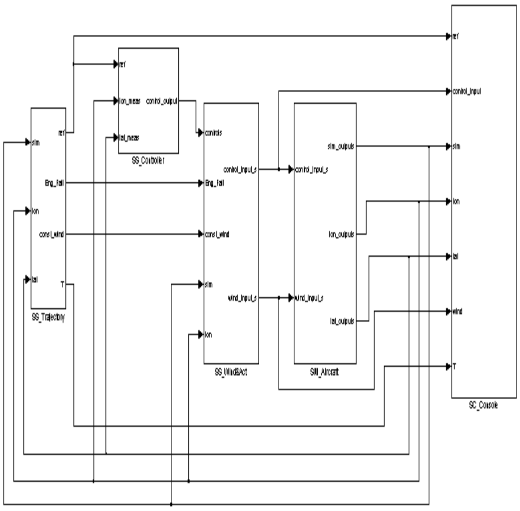

Fig. 1 RCAM Block Diagram

The model was grouped into the depicted subsystems in a manner that best resembled a real aircraft, for the purposes of running distributed simulations. The sub-systems are described as follows: 1) The trajectory generator outputs a set of reference signals that the virtual aircraft model is to follow; 2) The wind inputs and aircraft actuators are grouped into a separate subsystem. All system actuators are assumed to have first order system dynamics with rate limits and saturations; 3) The nonlinear aircraft model is a Matlab S-function and represents the aircraft's dynamic behavior; 4) The separation of the controller from the rest of the model allows the incorporation of different robust controllers to be quite easy; 5) The final subsystem is known as the console. It consists of all the outputs from the nonlinear aircraft model subsystem as well as the simulation clock. This subsystem is necessary for user interface when implementing the model into RT-LAB and simulating in real-time.

Further, we adopted a specific robust flight controller which is designed by the eigenstructure assignment [1]. Consider the linear control system:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \\ u &= -Kx \end{aligned}$$

The principal concept of eigenstructure assignment is that the desirable pole and zero locations, represented by eigenvectors v_i, are given based on flight performance, if we can find a vector u_i such that

$$\begin{bmatrix} \lambda_i I - A & B \end{bmatrix} \begin{bmatrix} v_i \\ u_i \end{bmatrix} = 0$$

then one can choose the feedback gain K to satisfy $Kv_i = u_i$, and finally we obtain

$$0 = [\lambda_i I - (A - BK)]v_i$$

3 Real-Time Computing Facility

Presently, at the University of Toronto Institute for Aerospace Studies, we are developing a real-time systems simulator (RTSS). The core computing facility of RTSS consist of a networked cluster of high-end commercial off-the-shelf (COTS) real-time computers, and has been installed in our laboratory. The current system setup is depicted in Figure 2.

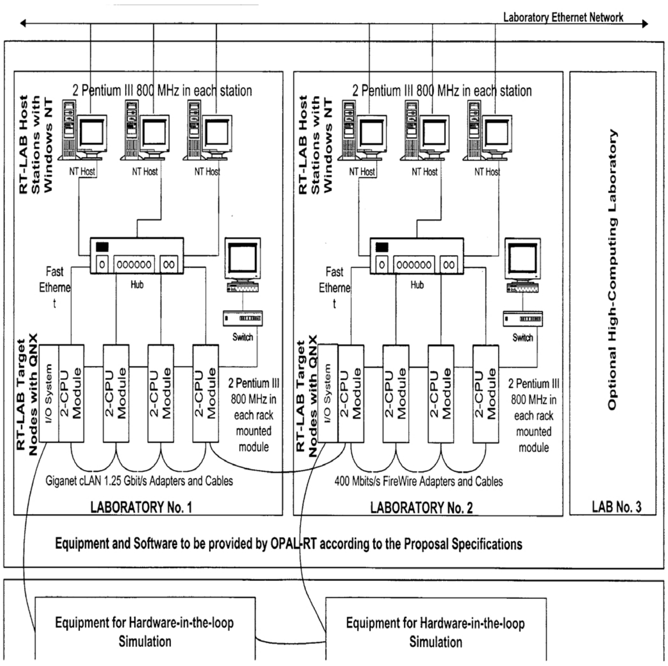

Fig. 2 UTIAS RTSS Facility

The main components of the facility include [5]:

- Three host computers each having dual-Pentium-processors running Windows 2000 operating system.

- Four real-time computers each having dual-Pentium-processors running Neutrino (QNX6) real-time operating system.
- The real-time nodes are directly connected by 400Mbit/sec FireWire and communicate with the hosts over a dedicated 100Mbit/s Ethernet network.
- The system consists of 108 multiple channel IO system for hardware-in-the-loop simulation.
- RTSS is also connected through a 1.25 Gbit/s Giganet to a similar facility to share data and resources.

This real-time computing facility is suitable for our proposed distributed real-time simulation of the benchmark aircraft model. The RT-LAB software groups models into three different categories: slave blocks (denoted by SS_), a console block (denoted by SC_), and a master block (denoted by SM_). The master block is responsible for the model's real time calculations and synchronization of the network. In the RT-LAB interface, only one master block is permitted per model. In the RCAM model, the master block is selected as the aircraft dynamics model. The slave blocks are used for performing additional calculations in the model. They are driven by the master block and are only limited by the amount of CPUs available for computation. When models are run on the RT-LAB real time system different subsystems can be loaded and run on different computer nodes. The purpose for having slave blocks is to speed up the simulation time by having them run on different nodes than the master block (ultimately lightening up the Master's computation load). For the RCAM model, slave blocks have been created for the: trajectory generator, the controller, and the wind and actuator models. The console block is where the user interacts with the model. It is run on a separate machine (Windows NT station) than the other blocks, which are run on the real-time machines. Any Simulink blocks related to the acquisition or visualization of data are included in this subsystem. For the purposes of the RCAM model, the console block acquires the following data and stores it in the Matlab workspace: simulation time, reference signals, control inputs, model outputs, wind inputs, time delays and the simulation clock. Some modifications had to be made to the original RCAM model in order for it to be used in the RT-LAB real-time environment [4].

4 Test Procedure

In the GARTUER project, a uniform test procedure is set up to evaluate all kinds of different control design methods [3]. In this paper, we follow the same procedure to investigate the real-time implementation of the eigenstructure assignment designed controller.

The testing flight mission consists of manoeuvres of a typical landing approach scenario, as shown in Figure 3.

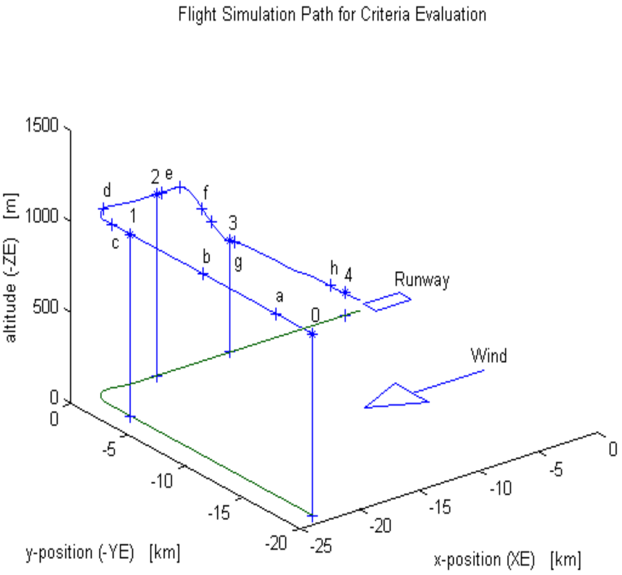

Fig. 3 Testing Flight Mission: a Landing Approach

This flight path is divided into four segments.

- **Segment I (point 0 to 1).** Starting at an altitude of 1000 m, a level flight is to be maintained with a constant airspeed of 80 m/s. During this level flight, an engine failure occurs at point a and the engine restarts at point b.
- **Segment II (point 1 to 2).** This segment consists of a commanded coordinated turn from point c to d, to maintain the constant speed and the lateral acceleration close to zero.
- **Segment III (point 2 to 3).** The descent phase starts with $\gamma = -6$ *deg* approach at point e, and descent with $\gamma = -3$ *deg* at point f.
- **Segment IV (point 3 to 4).** The glide slope of $\gamma = -3$ *deg* is to be maintained during a wind shear between points g and h.

The designed controller is to be evaluated by the following criteria to "obtain an objective comparison between completely different controllers" at each phase:

- performance;
- quality;
- safety;

- control; and
- robustness

Further, four test cases are conducted:

1. nominal case;
2. CG fwd case where the horizontal center of gravity has been shifted to the most forward position;
3. CG aft case where the CG is shifted to the most afterward position; and
4. time delay case where the flight is executed with a nominal center of gravity and a time delay of 100 ms.

In the next section of this paper, we will present our real-time experimental results using the eigenstructure assignment designed controller [1].

5 Real-Time Simulation Results

5.1 Nominal Test Case at RT = 0.01 seconds

5.1.1 *Segment I*

The performance criterion of Segment I defines the lateral deviation boundary of $20m$ to account for the effect of turbulence, and the boundary of $100m$ during engine failure:

$$P_1 = \frac{1}{2}\left(\max_{t_0\le t\le t_1}\frac{|e_{yb}(t)|}{100}+\frac{|e_{yb}(t_1)|}{20}\right) \tag{1}$$

where $e_{yb}(t)$ denotes the lateral deviation in body coordinates.

The quality criterion considers the maximum lateral acceleration of $0.2g$:

$$Q_1 = \max_{t_0\le t\le t_1}\left(\frac{|n_y(t)|}{0.2}\right) \tag{2}$$

The safety criterion sets the limit of the maximum angle of attack α of 12 deg:

$$S_1 = \max_{t_0\le t\le t_1}\left(\frac{|\alpha(t)|}{12}\right)^3 \tag{3}$$

The control criterion concerns the rudder actuator effort to stabilize the aircraft after engine failure is recovered:

$$C_1 = \int_{t_b}^{t_1}\delta_R^2\,dt \tag{4}$$

The maximum difference between the lateral deviation of the trajectories with nominal and perturbed center of gravity (CG forward, CG backward) and with the time delay is defined as:

$$\Delta_{eyb}(t) = \max\Big(|e_{yb_{\max}}(t)-e_{yb}(t)|,|e_{yb_{\min}}(t)-e_{yb}(t)|\Big) \tag{5}$$

and the robustness criterion sets the limit of maximal allowable deviations and the limit at the end of this segment:

$$R_1 = \frac{1}{2}\max_{t_0\le t\le t_1}\left(\frac{|\Delta_{eyb}(t)|}{10}+\frac{|\Delta_{eyb}(t_1)|}{2}\right) \tag{6}$$

The real-time simulation results, using sampling time (step size) of 10ms, of Segment I are shown in Figure 4.

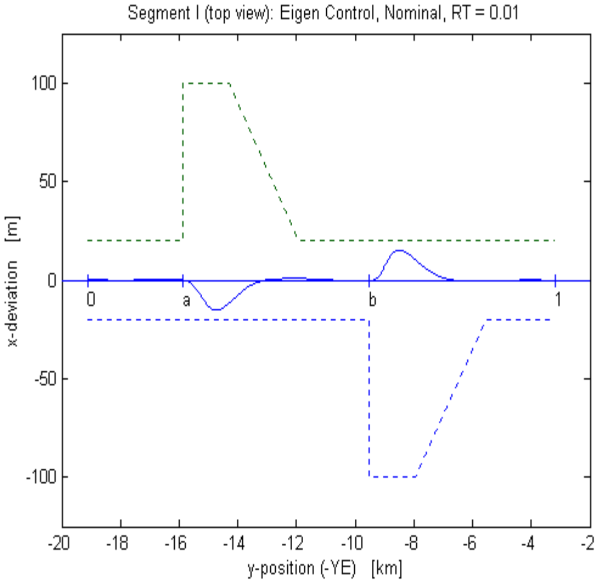

Fig. 4 Segment I Real-Time Simulation Results, RT = 0.01 seconds

It is shown that the lateral deviation is less than 20m that complies with the corresponding specifications.

5.1.2 *Segment II*

The performance criterion defines the maximum lateral deviation of $200m$ due to the turn and the lateral deviation of $20m$ at the end of the segment:

$$P_2 = \frac{1}{2}\left(\max_{t_1\le t\le t_2}\frac{|e_{yb}(t)|}{200}+\frac{e_{yb}(t_2)}{20}\right) \tag{7}$$

The quality criterion considers the maximum lateral acceleration of $0.02g$:

$$Q_2 = \max_{t_1\le t\le t_2}\left(\frac{|n_y(t)|}{0.02}\right) \tag{8}$$

The safety criterion sets the limit of the maximum angle of attack α of 12 deg:

$$S_2 = \max_{t_1\le t\le t_2}\left(\frac{|\alpha(t)|}{12}\right)^3 \tag{9}$$

The control criterion concerns the rudder and aileron actuator effort:

$$C_2 = \int_{t_1}^{t_2} \left(\delta_R^2 + \delta_A^2\right) dt \tag{10}$$

The robustness sets the limit of maximal allowable lateral deviations with perturbed center of gravity and time delays:

$$R_2 = \frac{1}{2} \max_{t_1 \le t \le t_2} \left(\frac{|\Delta_{eyb}(t)|}{20} + \frac{|\Delta_{eyb}(t_2)|}{2} \right) \tag{11}$$

The real-time simulation results, using sampling time (step size) of 10ms, of Segment II are shown in Figures 5 and 6.

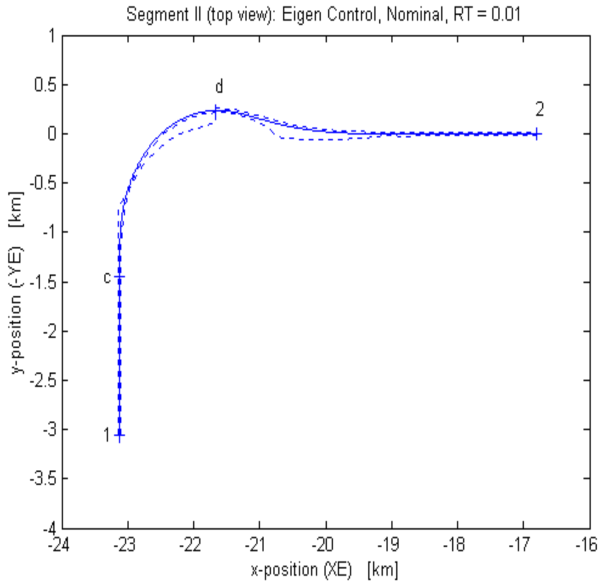

Fig. 5 Segment II Real-Time Simulation Results, RT = 0.01 seconds

The objectives are to maintain a constant speed of 80 m/s, to keep the lateral acceleration close to zero, to restrict the bank angle to $\phi = 30\ deg$ with consistent rudder/aileron deflections, not to exceed a lateral deviation of 200 m during the entire segment, and not to exceed a lateral deviation of 20 m at the end of Segment II. It is shown that the trajectory of the model surpasses the bounds but the lateral deviation never exceeds the maximum value of 200 m and at the end the lateral deviation is close to zero.

5.1.3 Segment III

The performance criterion considers the maximum vertical deviation during the capture of the -6 degree glide slope and the vertical deviation at the end of this segment. Further, speed variations should be kept small in spite of the change in required angle of attack:

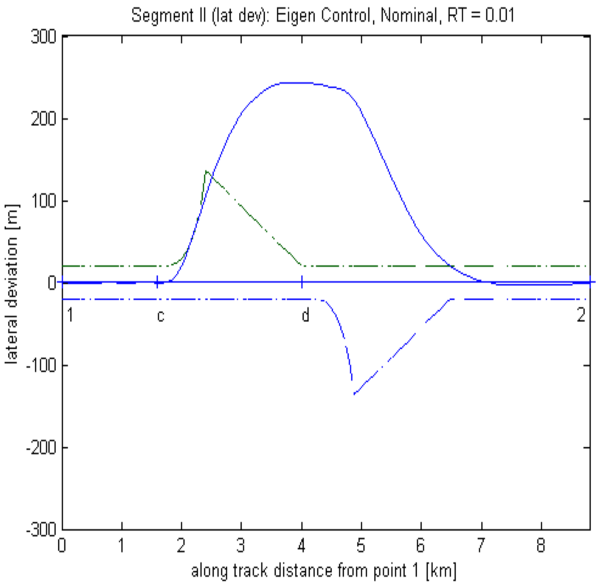

Fig. 6 Segment II Real-Time Simulation Results, RT = 0.01 seconds

$$\begin{aligned} P_3 \;&=\; \frac{1}{3}\Big(\max_{t_2 \le t \le t_3} \frac{|e_{zb}(t)|}{20} + \frac{|e_{zb}(t_3)|}{6} \\ &\quad + \max_{t_2 \le t \le t_3} \frac{|V - V_{command}|}{4} \Big) \end{aligned} \tag{12}$$

The quality criterion considers the maximum vertical acceleration:

$$Q_3 = \max_{t_2 \le t \le t_3} \left(\frac{|n_z(t)|}{0.05} \right) \tag{13}$$

The safety criterion sets the limit of the maximum angle of attack α of 12 deg:

$$S_3 = \max_{t_2 \le t \le t_3} \left(\frac{|\alpha(t)|}{12} \right)^3 \tag{14}$$

The control criterion concerns the tailplane actuator effort:

$$C_3 = \int_{t_2}^{t_3} \delta_T^2 \, dt \tag{15}$$

The robustness sets the limit of maximal allowable vertical deviations with perturbed center of gravity and time delays:

$$R_3 = \frac{1}{2} \max_{t_2 \le t \le t_3} \left(\frac{|\Delta_{ezb}(t)|}{2} + \frac{|\Delta_{ezb}(t_3)|}{0.6} \right) \tag{16}$$

The real-time simulation results, using sampling time (step size) of 10ms, of Segment III are shown in Figures 7 and 8.

Both figures represent the behaviour of the model in the descent phase. It is shown that the trajectories

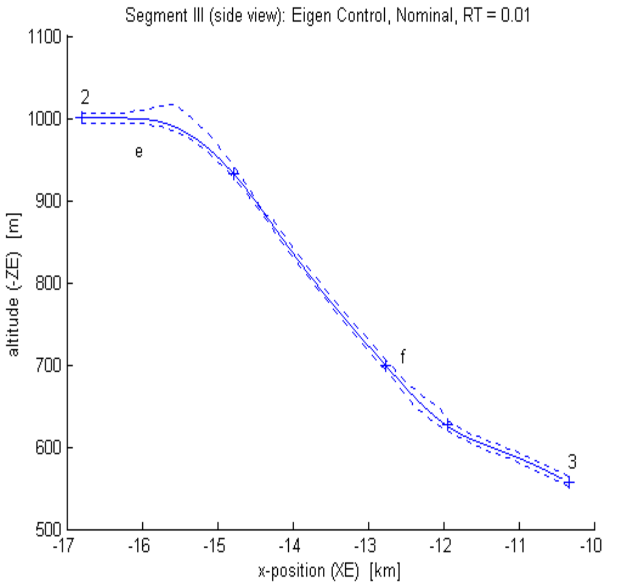

Fig. 7 Segment III Real-Time Simulation Results, RT = 0.01 seconds

of the model surpass the bounds although the vertical deviation never exceeds the maximum value of 20 m and at the end of Segment III the deviation is close to zero.

5.1.4 Segment IV

The performance criterion considers the maximum vertical deviation due to the wind shear and the vertical deviation at the end of this segment:

$$P_4 = \frac{1}{2}\left(\max_{t_3\leq t\leq t_4}\frac{|e_{zb}(t)|}{20}+\frac{|e_{zb}(t_4)|}{1.5}\right) \tag{17}$$

The quality criterion considers the maximum vertical acceleration:

$$Q_4 = \max_{t_3\leq t\leq t_4}\left(\frac{|n_z(t)|}{0.2}\right) \tag{18}$$

The safety criterion considers whether the aircraft is within the decision window at the end of the segment:

$$S_4 = \sqrt{\frac{1}{3}\left[(\frac{e_{yb}}{5})^2+(\frac{e_{ab}}{1.5})^2+(\frac{V-V_{command}}{3})^2\right]} \tag{19}$$

The control criterion considers the tailplane and throttle actuator effort:

$$C_4 = \int_{t_3}^{t_4}\left[\delta_T^2+(\delta_{T_{H1}}+\delta_{T_{H2}})^2\right]dt \tag{20}$$

The robustness sets the limit of maximal allowable vertical deviations with perturbed center of gravity and time delays:

$$R_4 = \frac{1}{2}\max_{t_c\leq t\leq t_d}\left(\frac{|\Delta_{ezb}(t)|}{2}+\frac{|\Delta_{ezb}(t_d)|}{0.15}\right) \tag{21}$$

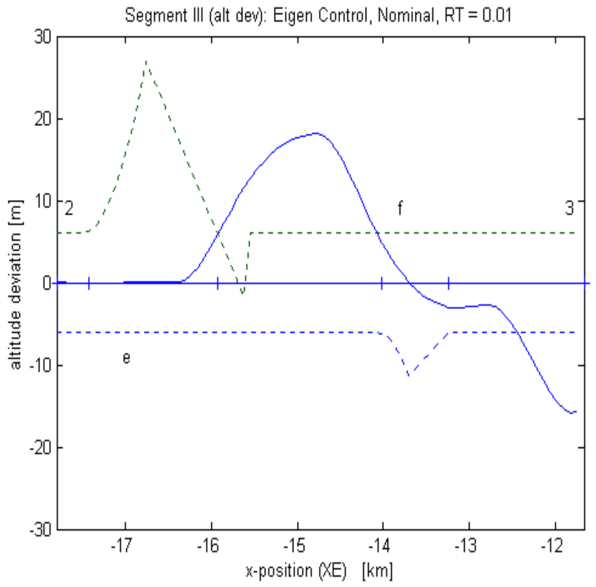

Fig. 8 Segment III Real-Time Simulation Results, RT = 0.01 seconds

The real-time simulation results, using sampling time (step size) of 10ms, of Segment IV are shown in Figures 9 and 10.

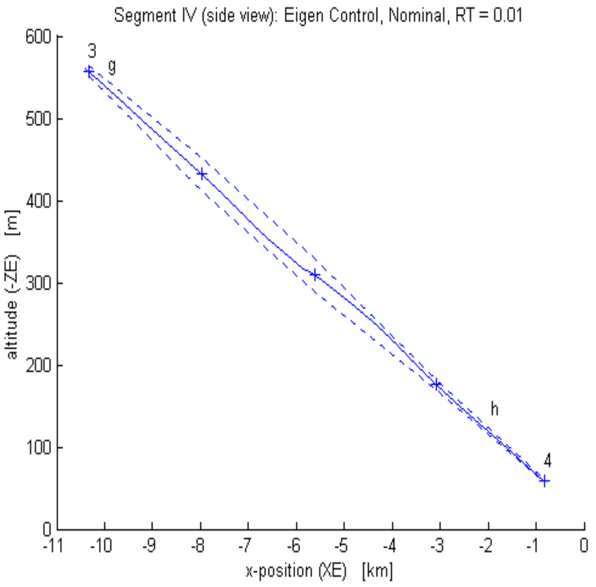

Fig. 9 Segment IV Real-Time Simulation Results, RT = 0.01 seconds

During this final approach, a maximum deviation of 20 m should not be exceeded, and at its end a maximum deviation of 1.5 m is taken into account. It can be seen that the trajectories of the model fall inside the bounds during the entire segment. The rest

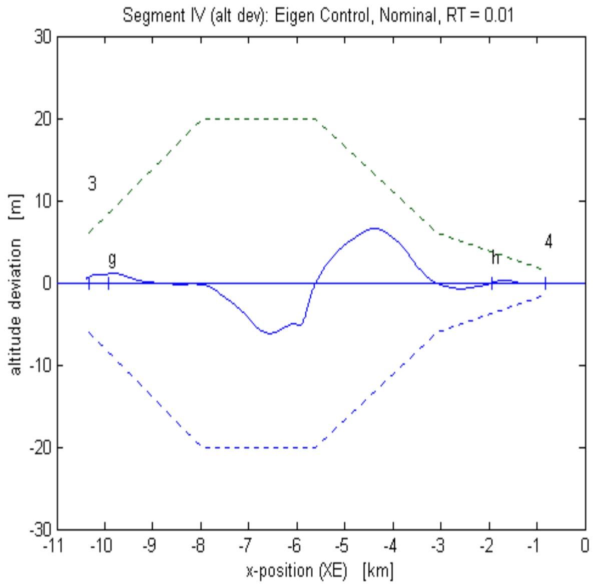

Fig. 10 Segment IV Real-Time Simulation Results, RT = 0.01 seconds

of specifications are also fulfilled.

The numerical measures of evaluation of all 4 segments are listed in Table 1.

Table 1 Numerical results of the real-time simulation

	P	Q	S	C	R
Seg I	0.0766	0.5488	0.0041	0.0031	0.0320
Seg II	0.6096	0.7109	0.0304	0.0024	0.0149
Seg III	0.3481	1.1903	0.0079	0.0160	0.5036
Seg IV	0.1967	0.6119	0.0374	0.0319	0.1705
Total	0.3078	0.7655	0.0199	0.0134	0.1803

6 Real-Time Comparison Analysis

Before we conducted the real-time implementation, the off-line simulation work has been investigated. The results were reported in [4]. Several conclusions were drawn from this work. First of all, we have created a new, upgraded benchmark model based on a distributed real-time computing platform. We concluded that this upgraded RCAM model matched the simulation results of the original RCAM model [2]. Secondly, the comparison between the CMEX-file and M-file RCAM simulation models brought to light the realization that the former runs approximately 20 times faster, in terms of clock time. It is obvious that the CMEX-file RCAM model is the superior choice for simulation. Thirdly, off-line simulation results have been analyzed extensively, especially in comparison with published results in the GARTEUR project. The simulation results verified our re-engineered model and validated the simulation approaches that we took.

The next step, which is the topic of this paper, is to implement RCAM model and the controller into the real time environment. To avoid the evaluation errors due to possible configuration setup differences between our RCAM model and GARTEUR reported results, which has been addressed in our off-line simulation analysis, we will compare our real-time simulation results with off-line results, instead of aforementioned published results.

6.1 Segment I Comparison

The comparison of off-line simulation results (NRT) and real-time (RT) simulation results, using RT = 0.01 seconds, are shown in Figure 11 and Table 2.

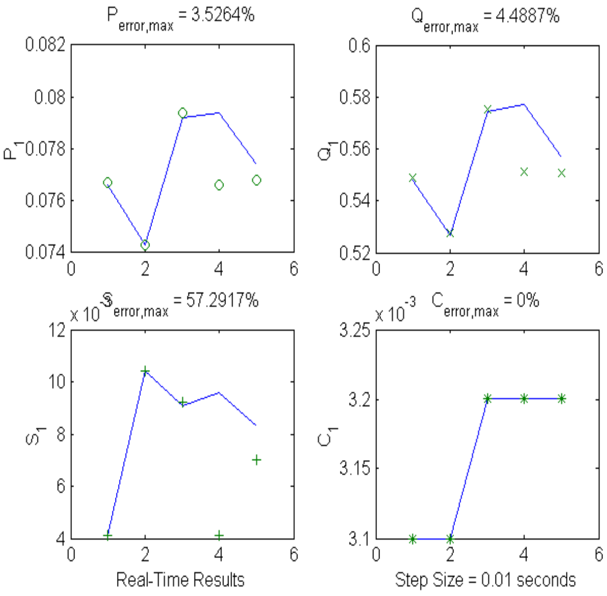

Fig. 11 Segment I Criteria Evaluation: Case (1) - nominal, (2) - CG fwd, (3) - CG aft, (4) - delay, (5) - average

6.2 Segment II Comparison

The comparison of off-line simulation results (NRT) and real-time (RT) simulation results, using RT = 0.01 seconds, are shown in Figure 12 and Table 3.

6.3 Segment III Comparison

The comparison of off-line simulation results (NRT) and real-time (RT) simulation results, using RT = 0.01

Table 2 Segment I Real-Time (RT) and Non Real-Time (NRT) Measurement Comparison

Segment I			
P_1	**NRT**	**RT**	**Error (%)**
Nominal	0.0766	0.0767	0.1305
CG fwd	0.0743	0.0743	0.0000
CG aft	0.0792	0.0794	0.2525
Time Delay	0.0794	0.0766	3.5264
Average	0.0774	0.0768	0.7752
Q_1	**NRT**	**RT**	**Error (%)**
Nominal	0.5482	0.5488	0.1094
CG fwd	0.5269	0.5275	0.1139
CG aft	0.5744	0.5751	0.1219
Time Delay	0.5770	0.5511	4.4887
Average	0.5566	0.5506	1.0780
S_1	**NRT**	**RT**	**Error (%)**
Nominal	0.0041	0.0041	0.0000
CG fwd	0.0104	0.0104	0.0000
CG aft	0.0091	0.0092	1.0989
Time Delay	0.0096	0.0041	57.2917
Average	0.0083	0.0070	15.6627
C_1	**NRT**	**RT**	**Error (%)**
Nominal	0.0031	0.0031	0.0000
CG fwd	0.0031	0.0031	0.0000
CG aft	0.0032	0.0032	0.0000
Time Delay	0.0032	0.0032	0.0000
Average	0.0032	0.0032	0.0000
R_1	**NRT**	**RT**	**Error (%)**
Average	0.0347	0.0320	7.7810

seconds, are shown in Figure 13 and Table 4.

6.4 Segment IV Comparison

The comparison of off-line simulation results (NRT) and real-time (RT) simulation results, using RT = 0.01 seconds, are shown in Figure 14 and Table ??.

The comparative study has shown that the most significant impact of real-time implementation is the test case with time delay, where the maximum error occurs.

7 Conclusions

We use the GARTEUR project RCAM aircraft model as our benchmark aircraft system, since its structure allows for easy replacement and distribution of subsystems. The remodelling of the model is carried out for real-time investigation, under the RT-LAB software platform. An eigenstructure assignment designed robust controller is selected for evaluation.

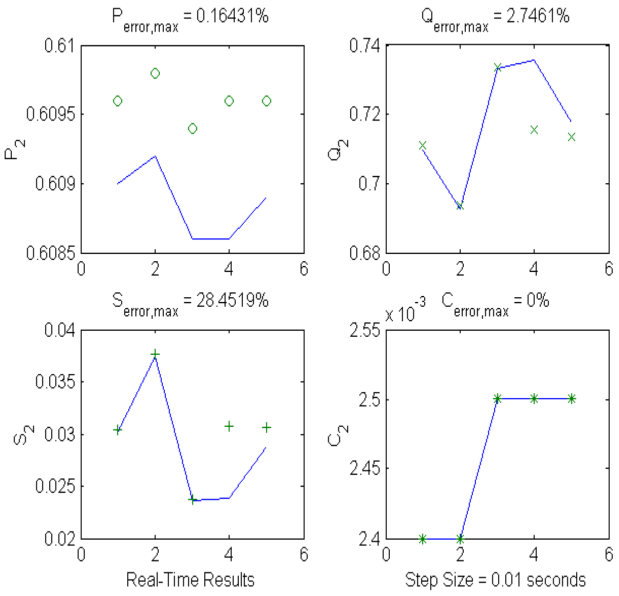

Fig. 12 Segment II Criteria Evaluation: Case (1) - nominal, (2) - CG fwd, (3) - CG aft, (4) - delay, (5) - average

The test procedure consists of 4 identified segments in a landing approach. At each segment, 4 measures of criteria are used to evaluate the design. Our real-time simulation results verified the effectiveness of the original design. Further, the comparative study is conducted between off-line simulation and real-time simulation results. We note that the time delay test case was affected by the real-time implementation.

Our next step is to evaluate the impact of sampling rate to the time delay test case, which is currently under investigation.

Acknowledgement

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Table 3 Segment II Real-Time (RT) and Non Real-Time (NRT) Measurement Comparison

Segment II			
P_2	**NRT**	**RT**	**Error (%)**
Nominal	0.6090	0.6096	0.0985
CG fwd	0.6092	0.6098	0.0985
CG aft	0.6086	0.6094	0.1314
Time Delay	0.6086	0.6096	0.1643
Average	0.6089	0.6096	0.1150
Q_2	**NRT**	**RT**	**Error (%)**
Nominal	0.7095	0.7109	0.1973
CG fwd	0.6925	0.6938	0.1877
CG aft	0.7332	0.7335	0.0409
Time Delay	0.7356	0.7154	2.7461
Average	0.7177	0.7134	0.5991
S_2	**NRT**	**RT**	**Error (%)**
Nominal	0.0302	0.0304	0.6623
CG fwd	0.0374	0.0376	0.5348
CG aft	0.0236	0.0237	0.4237
Time Delay	0.0239	0.0307	28.4519
Average	0.0288	0.0306	6.2500
C_2	**NRT**	**RT**	**Error (%)**
Nominal	0.0024	0.0024	0.0000
CG fwd	0.0024	0.0024	0.0000
CG aft	0.0025	0.0025	0.0000
Time Delay	0.0025	0.0025	0.0000
Average	0.0025	0.0025	0.0000
R_2	**NRT**	**RT**	**Error (%)**
Average	0.0156	0.0149	4.4872

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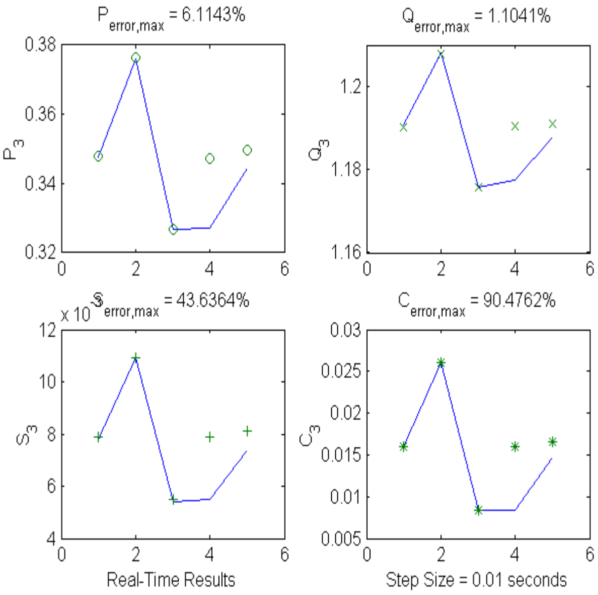

Fig. 13 Segment III Criteria Evaluation: Case (1) - nominal, (2) - CG fwd, (3) - CG aft, (4) - delay, (5) - average

Table 4 Segment III Real-Time (RT) and Non Real-Time (NRT) Measurement Comparison

Segment III			
P_3	**NRT**	**RT**	**Error (%)**
Nominal	0.3475	0.3479	0.1151
CG fwd	0.3759	0.3762	0.0798
CG aft	0.3268	0.3266	0.0612
Time Delay	0.3271	0.3471	6.1143
Average	0.3443	0.3495	1.5103
Q_3	**NRT**	**RT**	**Error (%)**
Nominal	1.1907	1.1903	0.0336
CG fwd	1.2080	1.2077	0.0248
CG aft	1.1757	1.1757	0.0000
Time Delay	1.1774	1.1904	1.1041
Average	1.1880	1.1910	0.2525
S_3	**NRT**	**RT**	**Error (%)**
Nominal	0.0078	0.0079	1.2821
CG fwd	0.0109	0.0109	0.0000
CG aft	0.0054	0.0055	1.8519
Time Delay	0.0055	0.0079	43.6364
Average	0.0074	0.0081	9.4595
C_3	**NRT**	**RT**	**Error (%)**
Nominal	0.0160	0.0160	0.0000
CG fwd	0.0261	0.0261	0.0000
CG aft	0.0084	0.0084	0.0000
Time Delay	0.0084	0.0160	90.4762
Average	0.0147	0.0166	12.9252
R_3	**NRT**	**RT**	**Error (%)**
Average	0.5034	0.5036	0.0397

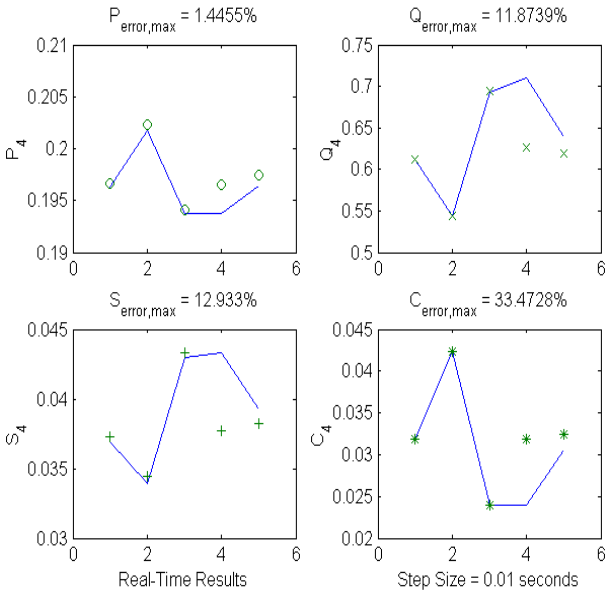

Fig. 14 Segment IV Criteria Evaluation: Case (1) - nominal, (2) - CG fwd, (3) - CG aft, (4) - delay, (5) - average

Table 5 Segment IV Real-Time (RT) and Non Real-Time (NRT) Measurement Comparison

Segment IV			
P_4	**NRT**	**RT**	**Error (%)**
Nominal	0.1963	0.1967	0.2038
CG fwd	0.2017	0.2023	0.2975
CG aft	0.1938	0.1941	0.1548
Time Delay	0.1937	0.1965	1.4455
Average	0.1964	0.1974	1.5103
Q_4	**NRT**	**RT**	**Error (%)**
Nominal	0.6115	0.6119	0.0654
CG fwd	0.5445	0.5436	0.1653
CG aft	0.6929	0.6946	0.2453
Time Delay	0.7108	0.6264	11.8739
Average	0.6399	0.6191	3.2505
S_4	**NRT**	**RT**	**Error (%)**
Nominal	0.0369	0.0373	1.0840
CG fwd	0.0339	0.0344	1.4749
CG aft	0.0430	0.0433	0.6977
Time Delay	0.0433	0.0377	12.9330
Average	0.0393	0.0382	2.7990
C_4	**NRT**	**RT**	**Error (%)**
Nominal	0.0319	0.0319	0.0000
CG fwd	0.0424	0.0424	0.0000
CG aft	0.0239	0.0239	0.0000
Time Delay	0.0239	0.0319	33.4728
Average	0.0305	0.0325	6.5574
R_4	**NRT**	**RT**	**Error (%)**
Average	0.2047	0.1705	16.7074