GARTEUR GROUP FOR AERONAUTICAL RESEARCH AND TECHNOLOGY IN EUROPE

ORIGINAL: ENGLISH GARTEUR/TP-088-3

June 15, 1995

GARTEUR Open

# Robust Flight Control Design Challenge
# Problem Formulation and Manual:
# the Research Civil Aircraft Model (RCAM)

by

FM(AG08)

GARTEUR aims at stimulating and co-ordinating
co-operation between Research Establishments and Industry
in the areas of Aerodynamics, Flight Mechanics, Helicopters,
Structures & Materials and Propulsion Technology

GROUP FOR AERONAUTICAL RESEARCH AND TECHNOLOGY IN EUROPE

ORIGINAL: ENGLISH GARTEUR/TP-088-3

June 15, 1995

GARTEUR Open

# Robust Flight Control Design Challenge Problem Formulation and Manual: the Research Civil Aircraft Model (RCAM)

by

FM(AG08)

This report has been prepared under auspices of
the Responsables for Flight Mechanics, Systems
and Integration of the Group for Aeronautical
Research and Technology in EURope (GARTEUR)

Group of Resp. : FM-GoR
Report Resp. : P.F. Lambrechts/ 15-6-95
Project Man. : J.C. Terlouw/ 15-06-95
Monitoring Resp. : J.T.M. van Doorn/ 15-6-95

Action Group : FM(AG08)
Version : 1
Completed : June 15, 1995

## Distribution list

### FM-AG08 principal persons

| | | |
|---|---|---|
| Ahmed S (GB) | CCL | 1 copy |
| Ambrosino G (IT) | UN | 1 copy |
| Delgado I (ES) | INTA | 1 copy |
| Dormido S (ES) | UNED | 1 copy |
| Duranti P (IT) | ALN | 1 copy |
| Helmersson A (SE) | LiTH | 1 copy |
| Irving J (GB) | BAe (Warton) | 1 copy |
| Joos H D (DE) | DLR | 1 copy |
| Luckner R (DE) | DAA | 1 copy |
| Magni J F (FR) | CERT-ONERA | 1 copy |
| Muir E (GB) | DRA (Bedford) | 1 copy |
| Post H (NL) | FAC | 1 copy |
| Sheen P (GB) | AVRO Intl | 1 copy |
| Ståhl-Gunnarsson (SE) | SMA | 1 copy |
| Terlouw J C (NL) | NLR | 3 copies |
| Vaart J C van der (NL) | DUT | 1 copy |
| Verde L (IT) | CIRA | 1 copy |

### Members of the Flight Mechanics, Systems and Integration Group of Responsables

| | | |
|---|---|---|
| Brännströmm B (SE) | FMV-F-FL | 1 copy |
| Doorn J T M van (NL) | NLR | 1 copy |
| England P (GB) | DRA (Bedford) | 1 copy |
| Rodloff R (DE) | DLR | 1 copy |
| Verbrugge R A (FR) | ONERA-IMFL | 1 copy |

### Heads of National Delegates

| | | |
|---|---|---|
| Bouchet J (FR) | DGA/DPSA | 4 copies |
| Earwicker M J (GB) | DRA (Farnborough ) | 4 copies |
| Döllinger W (DE) | Bundesministerium für Forschung und Technologie | 4 copies |
| Houwelingen J van (NL) | NLR | 4 copies |
| Persson L B (SE) | FFA | 4 copies |

## Members of the Executive Committee

| | | |
|---|---|---|
| Abbink F (NL) | NLR | 1 copy |
| Duc J M (FR) | ONERA | 1 copy |
| Gustafsson A (SE) | FFA | 1 copy |
| Haupt R (DE) | DLR/PD-L | 1 copy |
| Coleman G (GB) | DRA (Farnborough) | 1 copy |

## Secretary GARTEUR

| | | |
|---|---|---|
| Sombroek L (NL) | NLR | 1 copy |

## Others

| | | |
|---|---|---|
| Ackermann J (DE) | DLR | 2 copies |
| Aranda J (ES) | UNED | 1 copy |
| Bennani S (NL) | DUT | 1 copy |
| Bernussou J (FR) | LAAS-CNRS | 2 copies |
| Boer W P de (NL) | NLR | 1 copy |
| Boumans L (NL) | NIVR | 1 copy |
| Ciniglio U (IT) | CIRA | 1 copy |
| Couwenberg M (NL) | NLR | 1 copy |
| Cruz M de la (ES) | UNED | 1 copy |
| Dam A A ten (NL) | NLR | 1 copy |
| Dang Vu B (FR) | ONERA (Salon) | 1 copy |
| Erkelens L (NL) | NLR | 1 copy |
| Game G (GB) | BAe (Filton) | 1 copy |
| Geest P van der (NL) | FAC | 1 copy |
| Gennuso D (IT) | ALN | 1 copy |
| Grübel G (DE) | DLR | 1 copy |
| Green M (GB) | AVRO Intl | 1 copy |
| Goverde R (NL) | NLR | 1 copy |
| Hulme K (GB) | BAe (Warton) | 1 copy |
| Huynh H T (FR) | ONERA (Salon) | 1 copy |
| Hyde R (GB) | CCL | 1 copy |
| Labarrère M (FR) | CERT-ONERA | 1 copy |
| Lambrechts P (NL) | NLR | 1 copy |
| Maciejowski J M (GB) | UC | 2 copies |
| Martinèz A (ES) | INTA | 1 copy |
| Menard P (FR) | AS | 1 copy |
| Moormann D (DE) | DLR | 1 copy |

| | | |
|---|---|---|
| Morales M (ES) | INTA | 1 copy |
| Mulder A (NL) | FAC | 1 copy |
| Rouwhorst W (NL) | NLR | 1 copy |
| Parra de la (ES) | INTA | 1 copy |
| Postlethwaite I (GB) | UL | 2 copies |
| Scala S (IT) | CIRA | 1 copy |
| Schuring J (NL) | NLR | 1 copy |
| Schuring-Coops M (NL) | NLR | 1 copy |
| Smith P (GB) | DRA (Bedford) | 1 copy |
| Spee J (NL) | NLR | 1 copy |
| Tonon A (IT) | ALN | 1 copy |
| Valk P (NL) | DUT | 1 copy |
| Weiden A van der (NL) | DUT | 1 copy |
| Weise K (DE) | DAA | 1 copy |

## Contents

## List of figures

## List of tables

## List of symbols and abbreviations

### Symbols

The used symbols are according to the nomenclature defined in the Communication Handbook [2].

### Abbreviations

| | |
|---|---|
| ALN | Alenia Un'Azienda FINMECCANICA S.P.A. |
| AS | Aérospatiale |
| AVRO Intl | AVRO International Aerospace |
| BAe | British Aerospace |
| CCL | Cambridge Control Ltd |
| CERT | Centre d'Etudes et de Recherces de Toulouse |
| CIRA | Centro Italiano Ricerche Aerospaziali S.p.A. |
| CoG | Centre of Gravity |
| DAA | Daimler-Benz Aerospace Airbus |
| DLR | Deutsche Forschungsanstalt für Luft- und Raumfahrt<br>(German Aerospace Research Establishment) |
| DRA | Defence Research Agency |
| DUT | Delft University of Technology |
| FAC | Fokker Aircraft B.V. |
| FFA | Flygtekniska Försöksanstalten<br>(The Aeronautical Research Institute of Sweden) |
| FMAG | Flight Mechanics Action Group |
| FMV-F-FL | Försvarets Materielverk<br>(Defense Material Administration) |
| INTA | Instituto Nacional de Técnica Aerospacial<br>(National Institute for Aerospace Technology) |
| LiTH | Linköping University |
| NIVR | Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart<br>(Netherlands Agency for Aerospace Programs) |
| NLR | Nationaal Lucht- en Ruimtevaartlaboratorium<br>(National Aerospace Laboratory, The Netherlands) |
| ONERA | Office National d'Etudes et de Recherches Aérospatiales<br>(National Institute for Aerospace Research and Studies) |
| RCAM | Research Civil Aircraft Model |
| SMA | Saab Scania AB, Military Aircraft |
| UC | University of Cambridge |
| UL | University of Leicester |

| | |
|---|---|
| UN | Universitá di Napoli "Fedirico II" |
| UNED | Universidad Nacional de Educación a Distancia |

# 1 Introduction

## 1.1 Objectives of GARTEUR Action Group FM-AG08

In this document a Robust Flight Control design benchmark problem is proposed. It has been prepared by GARTEUR Action Group FM-AG08 on "Robust Flight Control (RFC) in a Computational Aircraft Control Engineering Environment (CACEE)". The objectives and activities of this Action Group will be discussed in the following. More details can be found in the FM-AG08 Terms of Reference [1].

A theme of world-wide importance to aircraft manufacturing companies is the improvement of techniques for computer-aided aircraft design integration, which goes beyond mere functional integration of aircraft components and seeks to provide optimal performance for the vehicle as a whole. In [7] the following observation is made:

> The traditional process of systems integration is to make individually designed subsystems work together on an aircraft, that is, to ensure compatibility and minimise adverse interactions. The new goal is to carry out concurrent multi-disciplinary designs of the highly interactive systems in order to maximise aircraft performance, viewed in its broadest terms.

Achievement of this long term goal requires close collaboration between the major aeronautical disciplines: Aerodynamics; Structures; Propulsion; Guidance, Navigation and Control. Bearing this in mind, the Flight Control Engineering discipline should utilise and elaborate controller analysis and design methodology suitable for multi-disciplinary considerations. Robust control methodology has this potential and is therefore the main focus of FM-AG08.

A major problem facing designers of Flight Control Systems (FCS) is uncertainty in characterising not only the vehicle itself, but also the environment in which it must operate. Gain scheduling is often necessary because of the variation of characteristics for which the control laws must guarantee stability and performance. The design of gain scheduling is time consuming for two reasons: the control laws must be designed at each design point, and a great deal of assessment is required to ensure adequate stability and performance at off-design points.

Recent advances in control theory research has given rise to a number of novel Robust Control Techniques [5, 6] specifically developed for dealing with model uncertainties and parameter variations. These new techniques offer potential benefits to a control law designer for modern aircraft in the following ways:

- Multivariable systems can be handled in a concise methodological framework, thus removing the need for the sequentially loop closure approach, and reducing the design effort required.

- Robust control laws which cover larger regions of the flight envelope around a design point can be derived more efficiently. This offers the potential for reducing the number of design points required, simplifying the gain schedule, and reducing the amount of assessment required at off-design points.

The main consequence of these benefits is that a FCS design based on Robust Control Techniques yields a considerable reduction in the design effort required, and a potential reduction in the time-to-market and design costs. Subproject FM-AG08-3 (GARTEUR Robust Flight Control Design) aims at demonstrating these advantages to the European Aeronautical Industry.

### 1.2 Objectives of subproject FM-AG08-3

Robust control theory has been well assessed in the literature, where a great number of papers can be found dealing with the various aspects of robustness, parameter variations, modelling uncertainty, unmodelled dynamics, etc. At the same time a wide variety of algorithms implementing Robust Control Techniques can be found in many technical reports and general purpose software, such as Matlab/Simulink [14, 15] and MATRIX$_X$ [16].

However, Robust Control Techniques are seldom used by European Aircraft Manufacturers for the design of FCS. There are three main reasons for this:

- The application of robust control theory to the aircraft control law design problem has not been demonstrated. The techniques and algorithms associated with robust control theory are clearly expressed but do not, in their current form, lend themselves to direct FCS application.

- There are a limited number of dedicated robust control design tools, while most manufacturers have an extensive suite of classical control design tools that they have developped over a period of several years.

- There is no specific bibliographic source available on Robust Control Techniques. Consequently, a lot of time has to be spent in searching for appropriate references in a variety of widely distributed libraries, journals and general purpose data-bases.

Subproject FM-AG08-3 aims at removing these drawbacks and at demonstrating to European aircraft manufacturers that a significant improvement in the overall design process is possible by using Robust Control Techniques. In a greater detail, the aim is:

- To identify and apply existing and new controller design methods to robust control problems that are representative of operational industrial needs [4].

- To introduce robust controller design and analysis methods into the control law design cycle, in order to cope more efficiently with uncertainty in the models used and with operational changes that may occur.
- To identify tools which can be used in conjunction with multi-disciplinary design optimization to improve overall dynamic system performance.
- To develop robust controller design procedures that interface with industrial requirements.

To achieve these objectives, FM-AG08 has chosen for the following research approach. Two Robust Flight Control benchmark problems have been definied, which will be solved by design teams from the European aeronautical industry, research establishments and universities. A wide variety of modern and classical design methods will be applied. The controllers that are designed in response to these problems will be compared and evaluated. It is proposed that a Workshop wil be held at a suitable venue (e.g. a control conference) where the controllers and the results of the comparisions will be presented. However, it must be stated that the aims of these benchmark problems is not to produce an optimal control law, but to demonstrate how Robust Flight Control theory can be applied to realistic problems and also to demonstrate the limitations of such techniques. It is also intended that these problems will raise the awareness and confidence of the European aircraft industry in the use of RFC techniques.

The two benchmarks cover respectively an automatic landing control problem and a high angle of attack enhanced manual control problem. This document is the manual for the first problem, which will be referred to as the RCAM (Research Civil Aircraft Model) benchmark.

Participants are asked to design an automatic pilot at landing for a fictitious aircraft (RCAM). The control law must be robust with respect to variation of the speed, weight, variation of the horizontal and vertical position of the center of gravity, time delays, nonlinearities and engine failure. Disturbance decoupling must also be performed so that tracking of the glideslope and localiser paths must be within certain tolerances.

### 1.3 Contents of this document

The structure of the document is as follows:

- In chapter 2 a description of the RCAM model is given, in which analytical expressions for all the variables of interest, states, inputs and outputs of the system, are derived. A detailed description of the components of the model (aircraft, sensors, actuators and engines, wind model) is included.

- In chapter 3 the design problem is formulated, and the criteria and procedure adopted for evaluation of the proposed design are described.
- In chapter 4 the standard layout of the document that will contain the design results is given, with a description of the items to be addressed in each design document.
- In appendix A an installation procedure and user reference for the RCAM software model in Matlab/Simulink is given, together with examples.
- In appendix B an installation procedure and user reference for the software for writing the design document is given.
- In appendix C an installation procedure and user reference for the automated evaluation software is given, by which an auto-evaluation of the designed control law is possible.

# 2 Description of the RCAM Model

## 2.1 Block Diagram of the System

A six degrees of freedom nonlinear model of the Research Civil Aircraft Model (RCAM) including nonlinearities of actuators (thresholds) and a model of disturbances has been proposed by Aérospatiale. A block diagram of the proposed model is given in Figure 2.1. Each box in this block diagram will be covered in more detail in following text. In section 2.3 an analytical description of the aircraft dynamics is given. In section 2.4 we explain why sensor modelling has not been deemed necessary. In section 2.5 the actuator dynamics and saturations are detailed. In section 2.6 the analytical models of wind disturbances are presented.

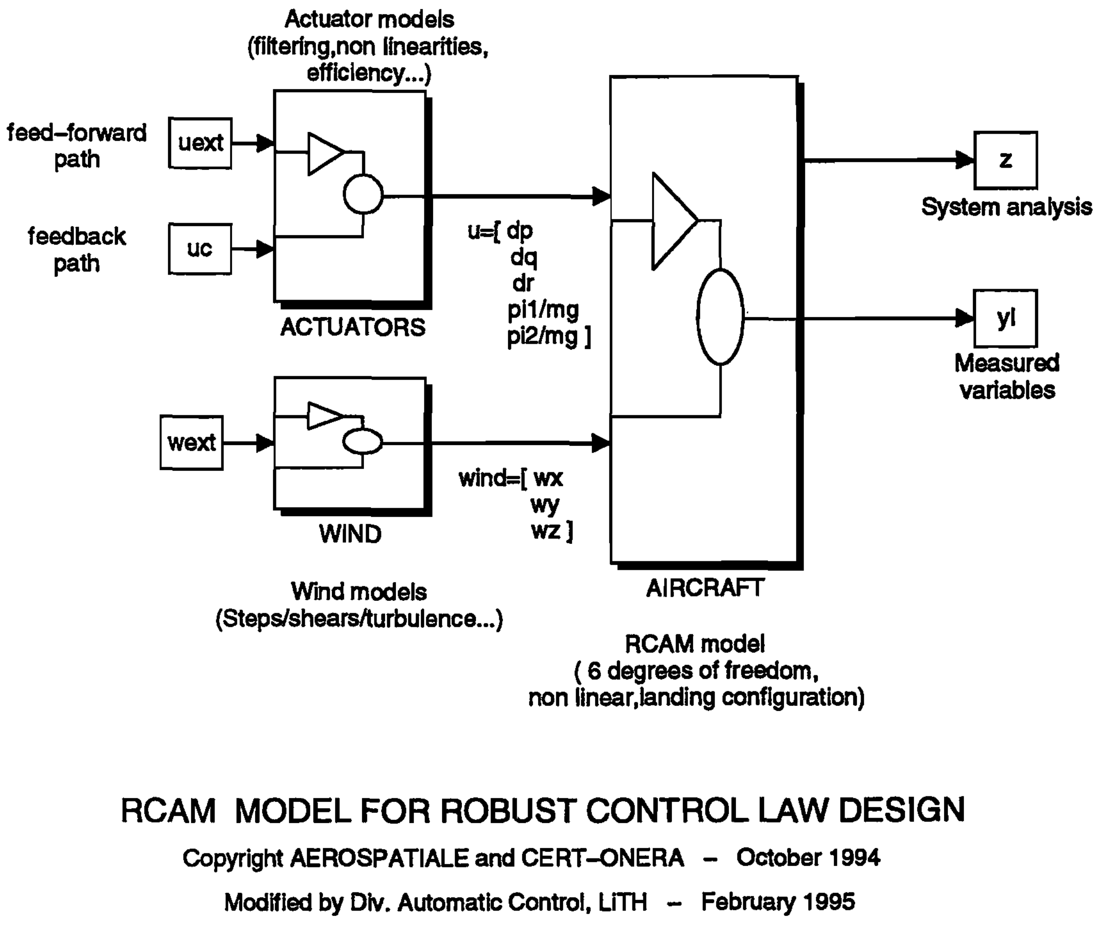

*Fig.2.1 Simulink diagram of the system*

## 2.2 Nomenclature: Inputs, States, Outputs, Parameters

The following tables summarise the adopted nomenclature used both for the formulation of the algorithms and the naming of variables in the software. Additional information can be found in Appendix A of this document.

The inputs are given in table 2.1. In this table, the index $E$ denotes that the wind is expressed in the earth-fixed reference frame, which is defined as follows.

| Symbol | Alphanumeric | | | Name | Unit |
|---|---|---|---|---|---|
| $\delta_A$ | DA | u(1) | = | aileron deflection | *rad* |
| $\delta_E$ | DE | u(2) | = | elevator deflection | *rad* |
| $\delta_R$ | DR | u(3) | = | rudder deflection | *rad* |
| $\delta_{TH_1}$ | THROTTLE1 | u(4) | = | throttle position of engine 1 | - |
| $\delta_{TH_2}$ | THROTTLE2 | u(5) | = | throttle position of engine 2 | - |
| $Wx_E$ | WXE | u(6) | = | longitudinal wind | $m/s$ |
| $Wy_E$ | WYE | u(7) | = | lateral wind | $m/s$ |
| $Wz_E$ | WZE | u(8) | = | vertical wind | $m/s$ |

*Table 2.1 Input definitions*

> The origin $O_E$ is located on the runway longitudinal axis at the threshold. $X_E$ is positive pointing along the runway in the landing direction. $Z_E$ is positive downward and $Y_E$ is in the appropiate direction for a right handed axis system.

The states used internally by the software are expressed in SI units and are defined in table 2.2. In this table, 'CoG' denotes 'Centre of Gravity', and the index $B$ stands for the body-fixed reference frame defined as follows.

> The origin $O_B$ is at the vehicle Centre of Gravity. $X_B$ is positive forward, $Z_B$ is positive downward and $Y_B$ is positive to the right.

Also the outputs are presented in SI units: they are defined in table 2.3. In this table, the index $V$ stands for vehicle-carried vertical frame. This frame is moving with the vehicle and is parallel to the earth-fixed frame. The origin $O_V$ is attached to the vehicle at the Centre of Gravity.

Used parameters are given in table 2.4. Finally, the uncertain parameters with their respective bounds are given in table 2.5:

| Symbol | Alphanumeric | | Name | Unit |
|---|---|---|---|---|
| $p$ | x(1) | = | roll rate | *rad/s* |
| $q$ | x(2) | = | pitch rate | *rad/s* |
| $r$ | x(3) | = | yaw rate | *rad/s* |
| $\phi$ | x(4) | = | roll angle | *rad* |
| $\theta$ | x(5) | = | pitch angle | *rad* |
| $\psi$ | x(6) | = | heading angle | *rad* |
| $u_B$ | x(7) | = | velocity in body-axis $x$ direction | *m/s* |
| $v_B$ | x(8) | = | velocity in body-axis $y$ direction | *m/s* |
| $w_B$ | x(9) | = | velocity in body-axis $z$ direction | *m/s* |
| $x$ | x(10) | = | $x$ position of CoG in earth-fixed frame | *m* |
| $y$ | x(11) | = | $y$ position of CoG in earth-fixed frame | *m* |
| $z$ | x(12) | = | $z$ position of CoG in earth-fixed frame | *m* |

*Table 2.2 States definitions*

| Symbol | Alphanumeric | | | Name | Unit |
|---|---|---|---|---|---|
| Measured | | | | | |
| $q$ | Q | y(1) | = | pitch rate = x(2) | $rad/s$ |
| $n_x$ | NX | y(2) | = | horizontal load factor = $\frac{F_x}{mg}$ | - |
| $n_z$ | NZ | y(3) | = | vertical load factor = $\frac{-F_z}{mg}$ | - |
| $w_V$ | WV | y(4) | = | velocity in vehicle-carried system along $z$ direction = $(R_{VB}V_B)(3)$ | $m/s$ |
| $z$ | Z | y(5) | = | height = −x(12) | $m$ |
| $V_c$ | VCAS | y(6) | = | (calibrated) air speed | $m/s$ |
| $V$ | V | y(7) | = | total velocity = $\parallel \vec{V}_B \parallel$ | $m/s$ |
| $\beta$ | BETA | y(8) | = | angle of sideslip = $asin(\frac{v_a}{V})$ | $rad$ |
| $p$ | P | y(9) | = | roll rate = x(1) | $rad/s$ |
| $r$ | R | y(10) | = | yaw rate = x(3) | $rad/s$ |
| $\phi$ | PHI | y(11) | = | roll angle = x(4) | $rad$ |
| $u_V$ | UV | y(12) | = | velocity in vehicle-carried system along $x$ direction = $(R_{VB}V_B)(1)$ | $m/s$ |
| $v_V$ | VV | y(13) | = | velocity in vehicle-carried system along $y$ direction = $(R_{VB}V_B)(2)$ | $m/s$ |
| $y$ | Y | y(14) | = | $y$ position in earth fixed frame = x(11) | $m$ |
| $\chi$ | CHI | y(15) | = | flight path heading angle | $rad$ |
| Simulation | | | | | |
| $\psi$ | PSI | y(16) | = | heading angle = x(6) | $rad$ |
| $\theta$ | THETA | y(17) | = | pitch angle = x(5) | $rad$ |
| $\alpha$ | ALPHA | y(18) | = | angle of attack = $atan(\frac{w_a}{u_a})$ | $rad$ |
| $\gamma$ | GAMMA | y(19) | = | flight path angle = $asin(\frac{-y(4)}{V})$ | $rad$ |
| $x$ | X | y(20) | = | $x$ position in earth fixed frame = x(10) | $m$ |
| $n_y$ | NY | y(21) | = | lateral load factor = $\frac{F_y}{mg}$ | - |

*Table 2.3 Outputs definitions*

| Symbol | Alphanumeric | | | Name | Default | Unit |
|---|---|---|---|---|---|---|
| Mass Parameters | | | | | | |
| $m$ | MASS | p(1) | = | aircraft total mass | 120000 | $kg$ |
| Engine Parameters | | | | | | |
| $X_{APT1}$ | XAPT1 | p(2) | = | $x$ pos. of application point of thrust of engine 1 in body axes w.r.t. CoG | 0.0 | $m$ |
| $Y_{APT1}$ | YAPT1 | p(3) | = | $y$ pos. of application point of thrust of engine 1 in body axes w.r.t. CoG | 7.94 | $m$ |
| $Z_{APT1}$ | ZAPT1 | p(4) | = | $z$ pos. of application point of thrust of engine 1 in body axes w.r.t. CoG | 1.9 | $m$ |
| $X_{APT2}$ | XAPT2 | p(5) | = | $x$ pos. of application point of thrust of engine 2 in body axes w.r.t. CoG | 0.0 | $m$ |
| $Y_{APT2}$ | YAPT2 | p(6) | = | $y$ pos. of application point of thrust of engine 2 in body axes w.r.t. CoG | -7.94 | $m$ |
| $Z_{APT2}$ | ZAPT2 | p(7) | = | $z$ pos. of application point of thrust of engine 2 in body axes w.r.t. CoG | 1.9 | $m$ |
| Aerodynamic Parameters | | | | | | |
| $l$ | L | p(8) | = | generalised length | 6.6 | $m$ |
| $l_t$ | LT | p(9) | = | distance between CoG and the aerodynamic centre of the tail unit | 24.8 | $m$ |
| $S$ | S | p(10) | = | Wing planform area | 260.0 | $m^2$ |
| $S_t$ | ST | p(11) | = | Tail unit planform area | 64.0 | $m^2$ |
| $\Delta x$ | DELX | p(12) | = | Displacement of aerodynamic centre from CoG along $x$-body axis | – | $m$ |
| $\Delta y$ | DELY | p(13) | = | Displacement of aerodynamic centre from CoG along $y$-body axis | – | $m$ |
| $\Delta z$ | DELZ | p(14) | = | Displacement of aerodynamic centre from CoG along $z$-body axis | – | $m$ |

*Table 2.4 Parameter definitions*

| Parameter | | | Bounds | | | | |
|---|---|---|---|---|---|---|---|
| $m$ | p(1) | : | 100000 $kg$ | < | $m$ | < | 150000 $kg$ |
| $\Delta x$ | p(12) | : | 0.2 $m$ | < | $\Delta x$ | < | 1.25 $m$ |
| $\Delta y$ | p(13) | : | -0.2 $m$ | < | $\Delta y$ | < | 0.2 $m$ |
| $\Delta z$ | p(14) | : | 0 $m$ | < | $\Delta z$ | < | 1.38 $m$ |

*Table 2.5 Parameter uncertainty definitions*

### 2.3 Aircraft Dynamics Model

This section describes the RCAM dynamics model corresponding to the `AIRCRAFT` block in Figure 2.1. The dynamic objects are depicted in Figure 2.2.

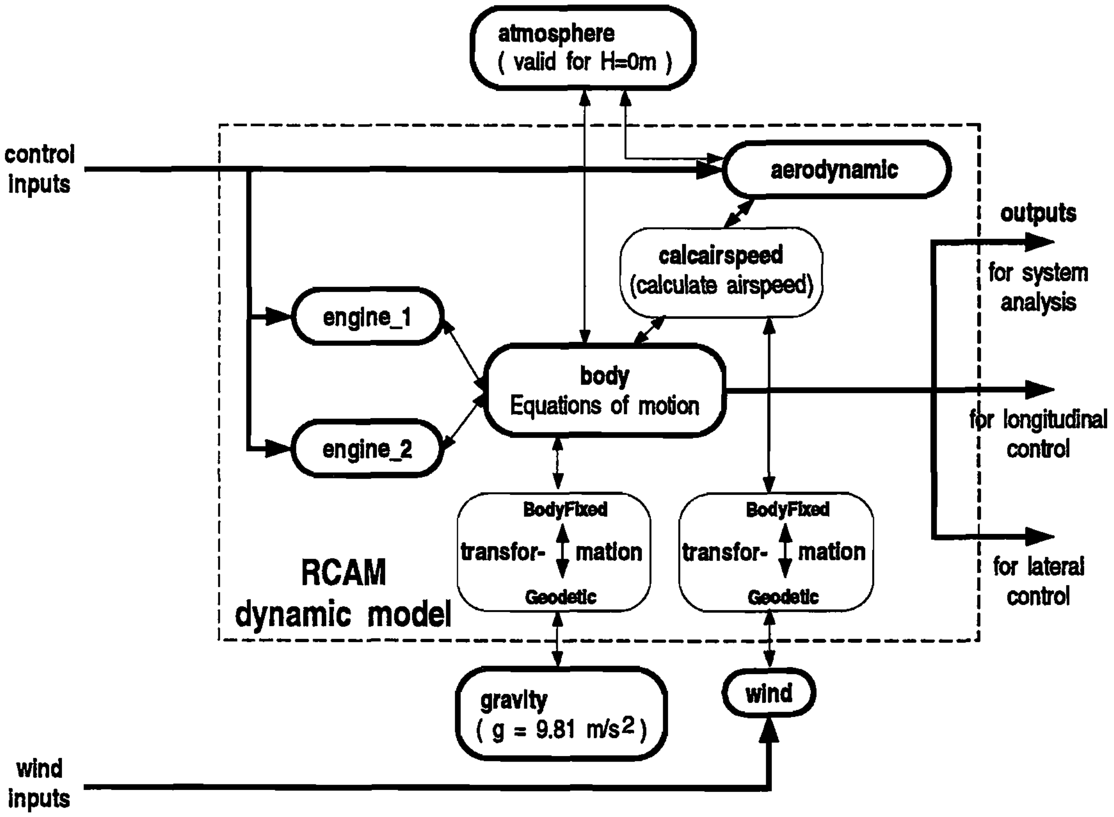

*Fig.2.2 Dynamic objects of RCAM aircraft model inside the* `AIRCRAFT` *block of Figure 2.1. Connection arrows between objects characterise physical interactions*

These objects are:

- **body** describes the body differential equations of motion (see subsection 2.3.1);
- two **transformation** objects describe the coordinate transformation between the body-fixed coordinates of the body object and the geodetic coordinates of the gravity object, and between the body-fixed coordinates of body and the geodetic coordinates of wind, respectively (see subsection 2.3.2);
- **calcairspeed** describes the relationship between the inertial movement, the wind, and the movement relative to the air (see subsection 2.3.3);
- **engine$_1$** and **engine$_2$** describe the relevant engine behaviour (see subsection 2.3.5);

- **atmosphere** describes the atmosphere model (see subsection 2.3.6);
- **aerodynamic** describes the aerodynamic forces and moments (see subsection 2.3.4);
- **gravity** describes the gravitational influence (see subsection 2.3.7).

### 2.3.1 Body equations of motion

#### 2.3.1.1 Translational motion

The equations for the translational movement in body-fixed coordinates are derived from the force equation,

$$F = m\,(\,a_B + \omega \times V_B\,) \tag{2.1}$$

F is the sum of forces due to the engine, the aerodynamics and gravity, $m$ is the mass of the aircraft, $V$ is the airspeed and $\omega$ is the rotational velocity expressed in body-fixed coordinates. The acceleration (in body-fixed system) is the time derivative of velocity:

$$a_B = \frac{d\,V_B}{dt} = \frac{d}{dt}\begin{bmatrix} u_B \\ v_B \\ w_B \end{bmatrix} \tag{2.2}$$

and the velocity is the time derivative of the position vector expressed in the vehicle-carried vertical frame:

$$V_V = \frac{d\,X_V}{dt} = \frac{d}{dt}\begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{2.3}$$

Additionally, the aircraft specific quantities are defined:

$$n_z = \frac{a_{nz}}{g} \tag{2.4}$$

where $a_{nz}$ is the z-body axis accelerometer output at Centre of Gravity.

The height h, which is the negative z coordinate in the vehicle carried system.

$$h = -z \tag{2.5}$$

the flight path angle $\gamma$

$$\tan\gamma = \frac{-w_V}{\sqrt{{u_V}^2 + {v_V}^2}} \tag{2.6}$$

is given as a function of the speed components in vehicle-carried coordinates.

The track angle $\chi$

$$\tan\chi = \frac{-v_V}{u_V} \tag{2.7}$$

### 2.3.1.2 Rotational motion

The equations for the rotational movement in body-fixed coordinates are derived from the moments equation,

$$M = I\,\dot{\omega} + \omega \times I\,\omega \tag{2.8}$$

M is the sum of moments w.r.t. the Centre of Gravity due to the engine and the aerodynamics, $\omega$ is the rotational velocity, and $\dot{\omega}$ is the rotational acceleration in body-fixed system.

$$\dot{\omega} = \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{2.9}$$

The relation between the rotational velocities and the Euler Angles is,

$$\frac{d\Phi}{dt} = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{2.10}$$

The aircraft inertia tensor I defined in the body frame is,

$$I = \begin{bmatrix} I_x & 0 & -I_{xz} \\ 0 & I_y & 0 \\ -I_{xz} & 0 & I_z \end{bmatrix} = m\begin{bmatrix} 40.07 & 0 & 2.098 \\ 0 & 64 & 0 \\ 2.098 & 0 & 99.92 \end{bmatrix} \tag{2.11}$$

where all numbers are expressed in $m^2$.

### 2.3.2 Coordinate transformation (Body-Fixed ⇔ Vehicle-Carried)

The rotations between the body-fixed and the vehicle-carried coordinate system are depicted in figure 2.3.

To describe the position of the aircraft, a transformation using the three Euler angles $\phi$, $\theta$, and $\psi$ becomes necessary. For the transformation the vehicle-carried system is rotated about the $z$-axis by the heading angle $\psi$. The next rotation is done by the pitch angle $\theta$ about $k2$ and finally by the roll angle $\phi$ about the $x_f$-axis.

The transformation matrix between body-fixed and vehicle-carried axis system results in,

$$R_{BV} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}\begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}\begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.12}$$

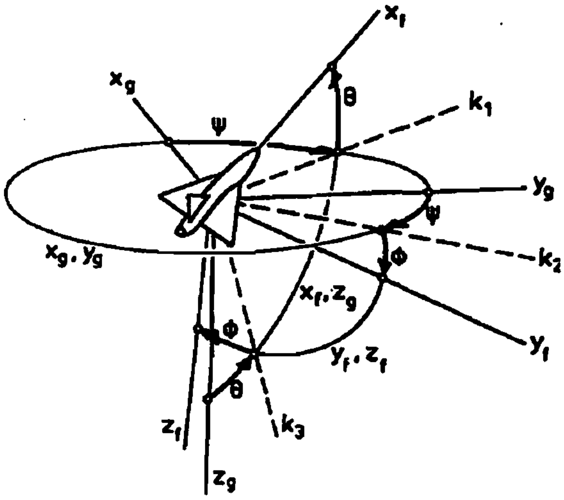

*Fig.2.3 Coordinate transformation body-fixed ⇔ vehicle-carried*

Note that $R_{BV} = R_{VB}^T$.
Multiplying the three matrices yields,

$$R_{BV} = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \cos\theta\sin\phi \\ \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi & \sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{2.13}$$

For example, the transformation of velocities between vehicle-carried (index V) and body-fixed (index B) coordinates is,

$$V_B = R_{BV}\, V_V \tag{2.14}$$

with

$$V_B = \begin{bmatrix} u_B \\ v_B \\ w_B \end{bmatrix} \quad \text{and} \quad V_V = \begin{bmatrix} u_V \\ v_V \\ w_V \end{bmatrix} \tag{2.15}$$

Similarly, the accelerations, rotational velocities, positions, forces and moments can be transformed between the coordinate systems.

### 2.3.3 Calculate Airspeed

The vector airspeed $V_a$ (expressed in body axes) is the difference between the inertial velocity of the aircraft $V_B$, and the wind velocity $W_B$ expressed in body-fixed coordinates:

$$V_a = V_B - W_B \tag{2.16}$$

with

$$V_a = \begin{bmatrix} u_a \\ v_a \\ w_a \end{bmatrix} \tag{2.17}$$

and $V$ is the total velocity.

$$V = \sqrt{(u_a{}^2 + v_a{}^2 + w_a{}^2)} \tag{2.18}$$

The angle of attack $\alpha$ and the angle of sideslip $\beta$ are defined as,

$$\tan\alpha = \frac{w_a}{u_a} \tag{2.19}$$

$$\sin\beta = \frac{v_a}{V} \tag{2.20}$$

The derivatives of $\alpha$ and $\beta$ with respect to time are,

$$\dot{\alpha} = \frac{a_{a_z}\ u_a\ -\ a_{a_x}\ w_a}{u_a{}^2 + w_a{}^2} \tag{2.21}$$

$$\dot{\beta} = \frac{a_{a_y}\ (\ u_a{}^2\ +\ w_a{}^2\ )\ - v_a\ (\ a_{a_x}\ u_a\ +\ a_{a_z}\ w_a\ )}{(\ u_a{}^2 + v_a{}^2 + w_a{}^2\ )\ \sqrt{u_a{}^2 + w_a{}^2}} \tag{2.22}$$

where $a_{a_x}$, $a_{a_y}$, and $a_{a_z}$ are the x,y,z-time derivatives of the airspeed in body-fixed coordinates. (i.e. $a_{a_x} = \frac{du_a}{dt}$)

### 2.3.4 Aerodynamics

The aerodynamic forces and moments are given in wind axes as a function of the aerodynamic factors ($\bar{q}S$), aerodynamic coefficients ($C_D$, $C_Y$, $C_L$), the angle of attack ($\alpha$) and the sideslip angle ($\beta$).

The dynamic pressure $\bar{q}$ is,

$$\bar{q} = \frac{1}{2}\ \rho\ V^2 \tag{2.23}$$

with $V$ as the total airspeed.

The aerodynamic lift coefficient $C_L$ is defined as (see Figure 2.4),

$$C_L = C_{L_{wb}} + C_{L_t} \tag{2.24}$$

$C_{L_{wb}}$ is the lift coefficient of the wing/body alone, and is given by,

$$C_{L_{wb}} = 5.5\ (\alpha - \alpha_0) \tag{2.25}$$

$$\alpha_0 = \frac{11.5}{180/\pi} \tag{2.26}$$

$\alpha_0$ is the angle of attack at which the lift becomes zero.

The lift coefficient of the tail unit $C_{L_t}$ is,

$$C_{L_t} = \frac{S_t}{S}\, 3.1\, \alpha_t \tag{2.27}$$

where $\alpha_t$ denotes the angle of attack of the tail unit

$$\alpha_t = \alpha - \varepsilon + \delta_E + 1.3\, \frac{q\, l_t}{V} \tag{2.28}$$

$$\varepsilon = \frac{d\epsilon}{d\alpha} * (\alpha - \alpha_0) \tag{2.29}$$

$$\frac{d\epsilon}{d\alpha} = 0.25 \tag{2.30}$$

with $\varepsilon$ the downwash angle, $\delta_E$ the elevator deflection, $q$ the pitch rate, and $l_t$ the longitudinal distance between aerodynamic centre of the tail unit and the Centre of Gravity of the aircraft. (See Figure 2.4).

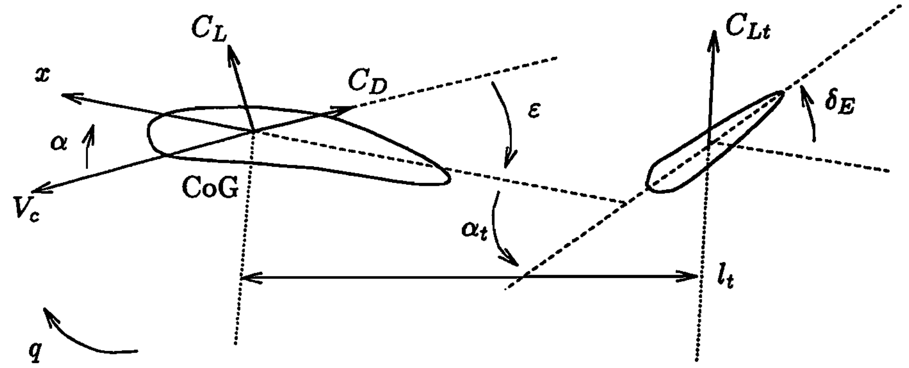

*Fig.2.4 Illustration of aerodynamic forces*

The aerodynamic drag coefficient $C_D$ is given as function of the aerodynamic lift coefficient of the wing/body $C_{L_{wb}}$ without the tail.

$$C_D = 0.13 + 0.07\, (C_{L_{wb}} - 0.45)^2 \tag{2.31}$$

The aerodynamic sideforce coefficient $C_Y$ can be written as follows,

$$C_Y = -1.6\, \beta + 0.24\, \delta_R \tag{2.32}$$

with $\beta$ as the angle of sideslip and $\delta_R$ as the rudder deflection.

The equations for the moment coefficients $C_l, C_m, C_n$ expressed in body axes are given by:

$$\begin{bmatrix} C_l \\ C_m \\ C_n \end{bmatrix} = \begin{bmatrix} -1.4\,\beta \\ -0.59 - 3.1\frac{S_t l_t}{S l}(\alpha - \epsilon) \\ (1 - \alpha\frac{180}{15\pi})\beta \end{bmatrix} + \begin{bmatrix} -11 & 0 & 5 \\ 0 & -4.03\frac{S_t\, l_t^2}{S\, l^2} & 0 \\ 1.7 & 0 & -11.5 \end{bmatrix} \frac{l}{V} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$
$$+ \begin{bmatrix} -0.6 & 0 & 0.22 \\ 0 & -3.1\frac{S_t\, l_t}{S\, l} & 0 \\ 0 & 0 & -0.63 \end{bmatrix} \begin{bmatrix} \delta_A \\ \delta_E \\ \delta_R \end{bmatrix} \tag{2.33}$$

$\alpha$: angle of attack
$\beta$: angle of sideslip
$S$: wing planform area
$S_t$: tail unit planform area
$l$: generalised length
$l_t$: distance between the CoG and the aerodynamic centre of the tail
$V$: total airspeed
$p$, $q$,and $r$: rotational rates (body axes)
$\delta_A, \delta_E$, and $\delta_R$: deflections of aileron, elevator and rudder

In order to calculate dimensional forces and moments the following expressions must be applied,

- Aerodynamic force along the X wind axis

  $D = C_D\, \frac{1}{2}\, \rho\, V^2\, S$

- Aerodynamic force along the Y wind axis

  $Y = C_Y\, \frac{1}{2}\, \rho\, V^2\, S$

- Aerodynamic force along the Z wind axis

  $L = C_L\, \frac{1}{2}\, \rho\, V^2\, S$

- Rolling moment in body axes

  $\mathcal{L} = C_l\, \frac{1}{2}\, \rho\, V^2\, S\, b$

- Pitching moment in body axes

  $\mathcal{M} = C_m\, \frac{1}{2}\, \rho\, V^2\, S\, \bar{c}$

- Yawing moment in body axes

$$\mathcal{N} = C_n \, \tfrac{1}{2} \, \rho \, V^2 \, S \, b$$

$L$ = Lift
$D$ = Drag
$b$ = wingspan = 44.8 $m$
$\bar{c}$ = mean aerodynamic chord = 6.6 $m$

In order to transform the aerodynamic forces from wind axes $(D, Y, L)$ into the body-axes frame $(F_{xA}, F_{yA}, F_{zA})$ the following expressions are used,

$$\begin{aligned}
F_{xA} &= L \sin\alpha - D\cos\alpha\cos\beta - Y\cos\alpha\sin\beta \\
F_{yA} &= -D\sin\beta + Y\cos\beta \\
F_{zA} &= -L\cos\alpha - D\sin\alpha\cos\beta - Y\sin\alpha\sin\beta
\end{aligned}$$

### 2.3.5 RCAM Engine Model

The thrust $F$ provided by each of the two engines $(\pi_1,\pi_2)$ is described by:

$$F = \delta_{THi} \, m \, g \tag{2.34}$$

where $\delta_{TH} = 0$ means zero thrust and $\delta_{TH} = 1$ means a thrust equal to the gravity force $(m\,g)$, acting at the aircraft. The engines thrust vector is aligned along the x-body axis pointing forward.

$$F_{xT} = F \tag{2.35}$$

$$F_{yT} = F_{zT} = 0 \tag{2.36}$$

The moments from engine about the Centre of Gravity $T_E$ are,

$$T_{Ei} = \begin{bmatrix} X_{APTi} \\ Y_{APTi} \\ Z_{APTi} \end{bmatrix} \times (F, 0, 0)' \quad (i = 1, 2) \tag{2.37}$$

These are due to the distance of the engines from the Centre of Gravity. $P_1$ and $P_2$ are the points where the thrust is applied. See Figure 2.5 with body-fixed axes centred at the aerodynamic centre of the wing/body.

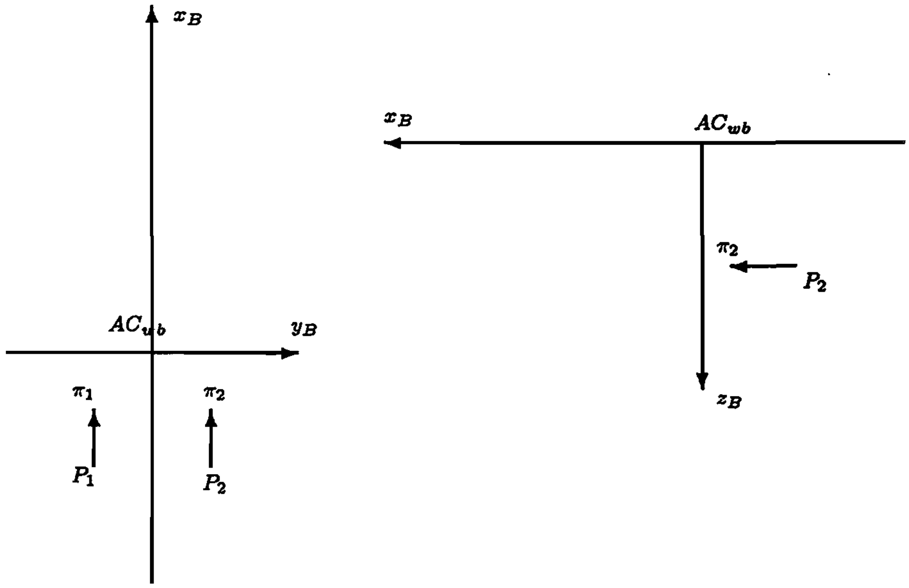

*Fig.2.5 Application points of thrusts.*

### 2.3.6 Atmosphere

The atmosphere is considered to be constant irrespective of height and position:

$$\rho = 1.225 \frac{kg}{m^3} \tag{2.38}$$

$$P = 101325.0 \frac{N}{m^2} \tag{2.39}$$

$$T = 288.15K \tag{2.40}$$

with $\rho$ as the density of air, $P$ the static pressure, and $T$ the absolute temperature.

### 2.3.7 Gravity Model

Gravity is not considered to be a function of altitude in this model:

$$W = mg \tag{2.41}$$

The acceleration due to gravity near the surface of the earth is taken to be a constant, $g = 9.81\ m/s^2$.

## 2.4 Sensor model

Sensor models are not provided because sensors are assumed to be sufficiently perfect.

### 2.5 Actuator models and engine dynamics

The Simulink diagram given in Figure 2.6 is self explanatory.

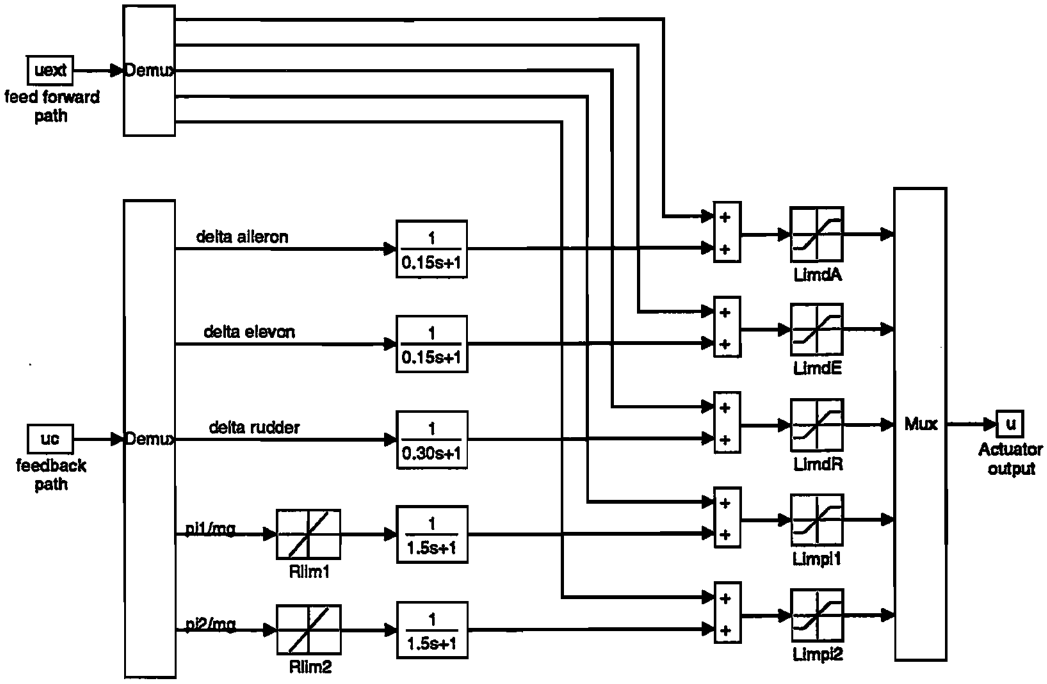

*Fig.2.6 Actuator models*

Numerical values

- Rate limits for thrust: rising slew rates = +1.6, falling slew rates = −1.6
- Thrust limits (saturations): $+0.5 \leq \delta_{TH} \leq 1$ (for $\delta_{TH} = 1$ the thrust over weight ratio is about 0.35)

In case of engine failure we can assume that the thrust reduces to $\delta_{TH} = +0.5$ with a first order system dynamics of transfer function $1/(1 + 3.3s)$.

- Saturations of $\delta_A$ (aileron deflection): $-25 \leq \delta_A \leq 25$ *deg.*
- Saturations of $\delta_E$ (elevator deflection): $-25 \leq \delta_E \leq 10$ *deg.*
- Saturations of $\delta_R$ (rudder deflection): $-30 \leq \delta_R \leq 30$ *deg.*

### 2.6 Wind turbulence model

Turbulence is a stochastic process that can be defined by velocity spectra. A commonly used velocity spectra for turbulence modelling is the Dryden spectra, which has the following form:

$$\Phi_{x_g}(\omega) = \sigma_x^2 \frac{2L_x}{\pi} \frac{1}{(1+(L_x\omega)^2)} \tag{2.42}$$

$$\Phi_{y_g}(\omega) = \sigma_y^2 \frac{L_y}{\pi} \frac{1+3(L_y\omega)^2}{(1+(L_y\omega)^2)^2} \tag{2.43}$$

$$\Phi_{z_g}(\omega) = \sigma_z^2 \frac{L_z}{\pi} \frac{1+3(L_z\omega)^2}{(1+(L_z\omega)^2)^2} \tag{2.44}$$

The values of $L_x$, $L_y$, $L_z$ ('turbulence scale lengths') and $\sigma_x$, $\sigma_y$, $\sigma_z$ ('turbulence amplitudes') are given by the following procedure:

Select $W_{20} = 15.4\ m/s$ (30 *kts*) for 'moderate' conditions ($W_{20}$ is wind speed at 20 *ft* above the ground). When $W_{20}$ is chosen, calculate the 'turbulence amplitudes' $\sigma_x$, $\sigma_y$, $\sigma_z$ using the following equation:

$$\sigma_z = 0.1W_{20} \tag{2.45}$$

$\sigma_x$ and $\sigma_y$ are functions of $\sigma_z$ and the altitude $h$. For $h < 305\ m$ (1000 *ft*):

$$\sigma_x = \sigma_y = \frac{\sigma_z}{(0.177+0.0027h)^{0.4}} \tag{2.46}$$

and for $h > 305\ m$ (1000 *ft*):

$$\sigma_x = \sigma_y = \sigma_z \tag{2.47}$$

As for $L_x$, $L_y$ and $L_z$, we shall use for $3 < h < 305\ m$:

$$L_x = L_y = \frac{h}{(0.177+0.0027h)^{1.2}} \tag{2.48}$$

$$L_z = h \tag{2.49}$$

and for $h > 305\ m$ we take:

$$L_x = L_y = L_z = 305\ m \tag{2.50}$$

# 3 Design problem formulation and evaluation criteria

## 3.1 Motivation design and evaluation criteria

Within the aerospace industry there is a large amount of experience in the flight control system design area . For this reason, the main objective of the control problem stated here is not so much to obtain a satisfactory controller, but more specifically to exhibit approaches which might reduce the complexity of control laws and the overall control system design cycle.

Some of the main features addressed by modern control design techniques provide the possiblity to take into account:

- the multivariable nature of the control problem
- the non linear behaviour of the plant
- the time-varying nature of the plant
- robustness to parameter changes and uncertainties
- simultaneous performance and robustness specifications.

From the consideration of these features it is expected that improvements could be made in areas such as:

- control system architecture development
- control law design cycle
- control design solution
- control system implementation

The RCAM design challenge consists of the synthesis of a control law capable of fulfilling an approach to landing under various external conditions eg. turbulence and windshear, while being robust to parameter changes. Furthermore, the aircraft guidance must not degrade under engine failure. Details on the design objectives are given in section 3.2.

For the uniform comparison of all design entries from the design challenge participants, a set of evaluation criteria is formulated in section 3.3. To evaluate proper control system logic and to make the challenge more realistic, an evaluation trajectory has been designed to reflect typical phases during approach to landing. The evaluation criteria given in this section are based on sets of signals from which certain characteristics will be calculated. All designs should be able to track the given trajectory within the specified bounds. Note that the choice of a trajectory as an evaluation criterion is independent of the control law and control design methodology.

An important subject considered in this chapter is the translation of design objectives into evaluation criteria: the evaluation criteria should be sufficiently representative for the considered design objectives, but will not be able to cover all aspects. It is asked that the benchmark problem participants consider the design objectives given in section 3.2 and for them to use their own methods to illustrate to what extent these are met by their controller design. For instance, we give robustness specifications in terms of real parameter variations, although they are often also considered in the frequency domain or in terms of gain and phase margins. The evaluation procedure is only aimed at obtaining an objective measure for comparison with other designs.

## 3.2 Design criteria

### 3.2.1 Introduction

The controller design problem for the RCAM model is characterised by a number of fundamental trade-offs between conflicting design specifications. For typical aircraft autopilot systems we recognise five classes of criteria:

- performance criteria: these reflect tracking error and disturbance rejection characteristics of certain signals;
- robustness criteria: these reflect the stability bounds with respect to parameter variations;
- passenger comfort criteria: these reflect the ride quality in the form of bounds on certain maximum allowable accelerations and minimum damping levels;
- safety criteria: these reflect envelope safeguards;
- power consumption criteria: these are a measure of the power consumed by the controls and also give an indication of fatigue effects.

### 3.2.2 Performance criteria

The performance of the controlled system can be specified in terms of command response characeristics to normalised reference signals, tracking error and disturbance rejection features (see [12]). The command response charateristics are defined in terms of rise time $t_r$, settling time $t_s$ and overshoot $M_p$. Rise time is defined here as the time the unit step response $y(t)$ takes from $y = .10$ to $y = .90$ eg. $t_r = t(y_{90\%}) - t(y_{10\%})$. Settling time is here defined as the time for $y(t)$ to achieve 99 percent of its final value. Finally, overshoot is defined as the relative peak of $y(t)$ eg., $M_p = (y_{peak} - y(\infty)) \times 100\%$ (see [11]).

- **Lateral deviation:** The controlled aircraft's lateral deviation $e_{yb}(t)$ defined as the difference between the actual and commanded lateral aircraft position $y(t) - y_c(t)$, should be reduced to 10 percent within 10 seconds.

There should be no overshoot in the step response to lateral command signals at altitudes above 300 *m* (1000 *ft*) eg. $M_p < 5\%$. At lower altitudes $M_p$ may increase to 30% in order to obtain higher tracking performance. There should be no steady state error due to constant lateral wind disturbances. In the final phase of flight (landing approach glide path) the lateral deviation from the desired flight path should not exceed that given in figure 3.1

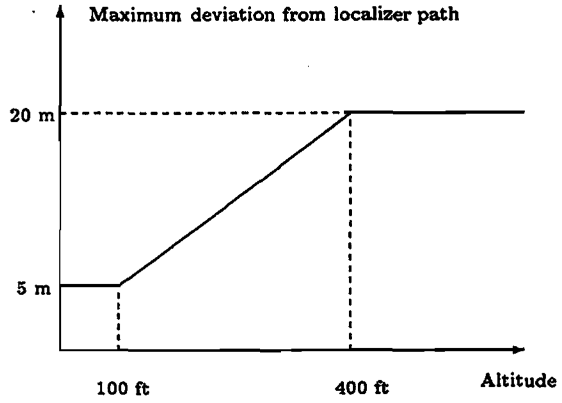

*Fig.3.1 Maximum lateral deviation*

- **Altitude response.** The controlled system should be able to track altitude commands $h_c$ with rise time $t_r < 12$ sec and settling time $t_s < 45$ sec. There should be no overshoot in the step response to altitude commands at altitudes above 300 *m* (1000 *ft*) eg. $M_p < 5\%$. At lower altitudes $M_p$ may increase to 30% in order to obtain higher tracking performance. In the final phase of flight (landing approach glide path) the vertical deviation from the desired flight path should not exceed that given in figure 3.2

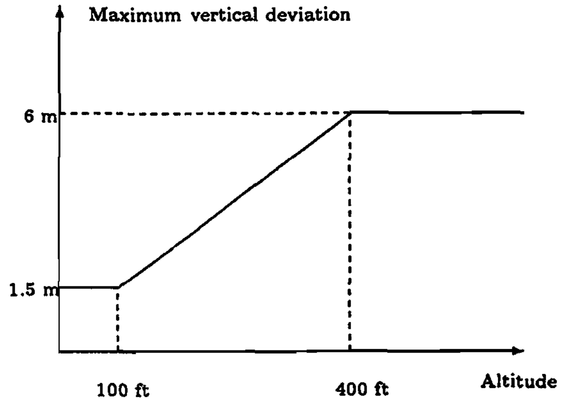

*Fig.3.2 Maximum vertical deviation*

- **Heading angle response:** The commanded heading angle $\psi_c$ should be tracked by the actual flight path angle $\psi$ with a rise time $t_r < 15$ sec and and settling time $t_s < 55$ sec . There should be no overshoot in the step response to heading commands at altitudes above 300 *m* (1000 *ft*) eg. $M_p < 5\%$. At lower altitudes $M_p$ may increase to 30% in order to obtain higher tracking performance. For unit RMS intensity lateral Dryden gust there should be at least 30 % heading angle disturbance rejection when compared to the open loop response.

- **Flight path angle response:** The commanded flight path angle $\gamma_c$ should be tracked by the actual flight path angle $\gamma$ with a rise time $t_r < 12$ sec and settling time $t_s < 45$ sec. There should be no overshoot in the step response to flight path commands at altitudes above 300 *m* (1000 *ft*) eg. $M_p < 5\%$. At lower altitudes $M_p$ may increase to 30% in order to obtain higher tracking performance.

- **Roll angle response:** In case of engine failure and external disturbances, the actual roll angle $\phi$ should not exceed 5 *deg* from trim. The maximum steady state deviation of the roll angle to these disturbances should not exceed 1 *deg*. An initial condition specification on the roll angle to characterise engine reconfiguration from 1 to 2 engines active is given by the following: given an initial roll angle due to 1 engine failure, the time-domain response of the roll angle to engine reactivation must be such that 0 *deg* steady state roll angle is achieved with less than 50 % overshoot.

- **Airspeed response:** The controlled system's air speed $V_{air}$ should be able to track speed commands $V_c$ with a rise time $t_r < 12$ sec and settling time $t_s < 45$ sec. There should be no overshoot in the step response to speed commands at altitudes above 300 *m* (1000 *ft*) eg. $M_p < 5\%$. At lower altitudes $M_p$ may increase to 30% in order to obtain higher tracking performance. In the presence of a wind step with an amplitude of 13 *m/s* (25 *kts*) there should be no deviation in the airspeed larger than 2.6 *m/s* (5 *kts*) for more than 5 *sec*. There should be no steady state error due to constant wind disturbances.

- **Heading rate:**

  In case of engine failure, the maximum heading rate $\dot{\Psi}$ should be less than 3 *deg/sec*.

- **Cross coupling between $V_{air}$ and $\gamma$:**

  For a step deviation in $\gamma$ of 3 *deg*, the peak value of the transient of the absolute error between $V_{air}$ and $V_c$ ($V_c$ demanded airspeed) should be smaller than 1 *m/s* (2 *kts*). Conversely, for a step deviation in $V_{air}$ of $-13$ *m/s* ($-25$ *kts*), the peak value of the transient of the absolute error between $\gamma$ and $\gamma_c$ ($\gamma_c$ demanded flight path angle) should be smaller than 0.5 *deg*.

- **Cross-coupling between $\beta$ and $\phi$:** Cross-coupling between $\beta$ and $\phi$ should be minimised. For a deviation in $\beta$ of 2 *deg*, the peak transient value of $\phi$ should be less than 1 *deg*. For a deviation in $\phi$ of 20 *deg*, the peak transient value of $\beta$ should be less than 1 *deg*.

### 3.2.3 Robustness criteria

- **Centre of Gravity variation:** Stability and sufficient performance should be maintained for horizontal and vertical Centre of Gravity variations, respectively between 15 and 31 % and between 0 and 21 % of the mean aerodynamic chord.
- **Mass variations:** Stability and sufficient performance should be maintained for aircraft mass variations between 100000 to 150000 *kg*.
- **Time Delay:** Stability and sufficient performance should be maintained for transport delays from 50 to 200 *ms*.

### 3.2.4 Ride Quality Criteria

Ride quality criteria should ensure sufficient passenger and pilot comfort. The following specifications are designed to obtain an acceptable level.

- **Maximum vertical acceleration:** Under normal conditions the vertical acceleration should be minimised and at least limited to ± 0.05 $g$ [*].
- **Maximum lateral acceleration:** Under normal conditions the lateral acceleration should be minimised and at least limited to ± 0.02 $g$.
- **Damping:** Unless stated differently, there should be no overshoot in any step response of any controlled variable at altitudes above 300 *ft* (1000 *ft*). Below that altitude overshoot may increase to 30 % in order to obtain higher tracking performance.

### 3.2.5 Power consumption criteria

- **Actuator effort minimization:** RMS norm of actuator signals should be minimised.
- **Engine effort minimization:** RMS norm of thrust should be minimised.

### 3.2.6 Safety criteria

- **Angle of attack :** The maximum angle of attack $\alpha_{\text{stall}}$ should be limited to 18 *deg*.

---

[*] The data given here are used in industry during the design phase, in fact the vertical and lateral acceleration limits depend on frequency. They are even lower at 2 $Hz$.

- **Airspeed** : The minimum airspeed should be larger than 1.05 × $V_{\text{stall}}$. $V_{\text{stall}}$ corresponds to an angle of attack equal to $\alpha_{\text{stall}}$ defined above :

  $$m\,g = \frac{1}{2}\rho S V_{air}^2 C_z \tag{3.1}$$

  With the approximation ($C_z$ replaced by $C_{L_{wb}}$, see 2.24)):

  $$m\,g = \frac{1}{2}\rho S V_{\text{stall}}^2 5.5 \frac{\alpha_{\text{stall}} + 11.5}{57.3} \tag{3.2}$$

  Numerical values: $\rho = 1.225\ kg/m^3$, $S = 260\ m^2$, for example, if the mass is equal to 120000, $V_{\text{stall}} = 51.1\ m/s$[†].

- **Roll angle** : The maximum roll angle $\phi$ should be limited to 30 *deg.*

- **Sideslip angle response:** At all times, sideslip angle $\beta$ should be minimised. For unit RMS intensity lateral Dryden gust there should be at least 30 % sideslip angle disturbance rejection when compared to the open loop response.

### 3.3 Evaluation procedure: RCAM mission and scenario

To be able to evaluate all kinds of different control design procedures and resulting controllers it is necessary to find a uniform evaluation procedure, independent of the design method. An established procedure to do this is to define a mission and a typical landing approach scenario (see [8, 3, 9]). This mission consists of manoeuvres that can be evaluated by means of nonlinear simulations. The performance of the control law depends on the mission phase, within which hard criteria or bounds on certain signals should be met and/or error signals must be minimised.

The mission and scenario to be 'flown' by the RCAM model consists of a landing approach divided into the following segments (see Figure 3.3)

- **Segment I (0 to 1)**
  Starting with an altitude of 1000 $m$ and a heading of $\psi = 90$ *deg*, level flight is to be maintained with a constant speed of $V_0 = 80\ m/s$. During this segment, we shall check proper lateral autopilot features by means of simulation of an engine failure occuring at point **a**, and an engine restart at point **b** in Figure 3.3. During this phase a constant lateral wind $w_{wind} = 10\ m/s$ and a moderate Dryden gust field with scale length $L = 305\,m$ and amplitude $\sigma = 1.5\ m/s$ are active. We will consider both transient and steady state behaviour.

- **Segment II (1 to 2)**
  This segment consists of a commanded coordinated turn from points **c** to **d** in

---

[†] Note that the nominal air speed during the landing phase depends on the mass, it is equal to 1.23 times $V_{\text{stall}}$.

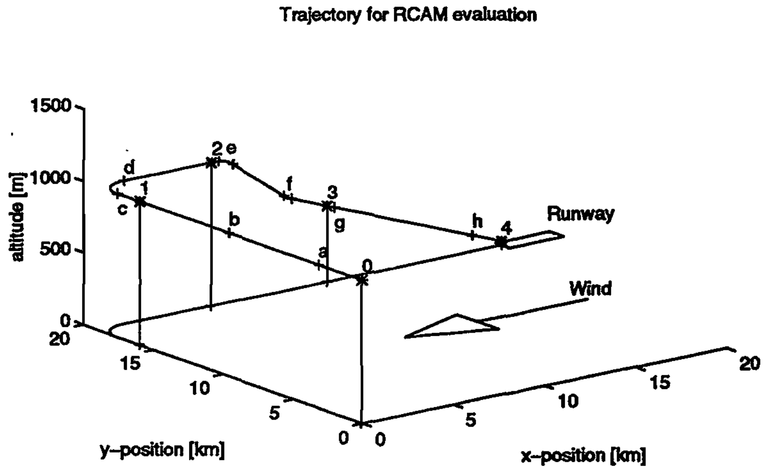

*Fig.3.3 the landing approach for RCAM*

Figure 3.3 with heading rate of $\dot{\psi} = 3$ *deg/sec.* The objectives are to maintain a constant speed $V_0$, to keep the lateral acceleration close to zero, and to restrict the bank angle to $\phi = 30$ *deg* with consistent rudder/aileron deflections.

- **Segment III (2 to 3)**
  The descent phase will be started according to the so-called *Frankfurt* descent procedure (see [10]), which has been proposed for reasons of environmental noise reduction. This descent procedure is engaged later and is steeper than the classical descent that has a constant glide slope angle of $\gamma = -3$ *deg*. The starting altitude is $h = 1000$ *m*; the localiser heading has to be stabilised first. Then, the flight path angle is set to $\gamma = -6$ *deg* (points e to f in Figure 3.3). Although this angle is usually maintained for a longer period, it will be set to $\gamma = -3$ *deg* after 30 seconds (points **f** to **g** in Figure 3.3). Stabilization of the aircraft on the final flight path angle must again be achieved within 30 seconds. In this phase of the flight constant headwind is turned off leaving only Dryden gust acting as a perturbation on the system.

- **Segment IV (3 to 4)**
  The glide slope of $\gamma = -3$ *deg* is to be maintained. In this phase, the effect of wind shear (g to **h** in Figure 3.3) will be analysed: the aircraft has to maintain safe flight during a simulated wind shear. We adopted a two dimensional wind shear model derived from [13].

To check robustness properties the entire approach will be flown with a most forward, a nominal and a most aft horizontal Centre of Gravity location. Furthermore, one flight will be executed with a nominal Centre of Gravity location and a time delay of 200 *ms*.

### 3.4 Translation of design criteria into evaluation criteria

It should be noted that it is not possible to check all desired autopilot features by flying a single landing approach trajectory. Furthermore, the evaluation procedure should be relatively simple and straightforward: we want to be able to apply it to a great variety of controllers. Hence, the evaluation criteria should be independent of the type of controller used: they should consist of calculable indicators that enable us to obtain an objective comparison between completely different controllers.

For these evaluation criteria we will use the same classification as was given in the definition of the design criteria.

- performance
- robustness
- passenger comfort
- safety
- control activity

For each of these items and for each of the four trajectory segments a single number will be calculated. This number should not be considered to be the final word on overall autopilot performance: it is merely an indicator for one or two important aspects. In most cases it is chosen such that a value of smaller than one is acceptable.

To further evaluate the dynamic behaviour of the autopilot, we will consider several plots of key variables during each of the segments. We will compare the shape of the actual trajectory with the demanded trajectory and provide bounds that should be respected for good performance. Similarly, we will plot the most important deviations from the desired trajectory.

#### 3.4.1 Segment I

For segment I we will plot a plan view of the trajectory and then superimpose the bounds given in Figure 3.4. The points a and b correspond to the beginning and end of the engine failure segment. The initial bound of 20 $m$ is given to account for the effect of lateral wind. During engine failure, we allow a maximum lateral deviation of 100 $m$ that, again, should be quickly reduced to less than 20 $m$ at the end of the segment (when the aircraft should be stabilised again). With $e_{yb}$ denoting the lateral deviation in body coordinates for the trajectory with nominal Centre of Gravity we will use

$$\left(\max_t \frac{|e_{yb}(t)|}{100} + \frac{|e_{yb}(t_1)|}{20}\right)/2 \tag{3.3}$$

as a measure that should be smaller than one for sufficient performance. Note that we allow a maximum deviation of 100 $m$ and a final deviation of 20 $m$. Further $t_1$ corresponds to

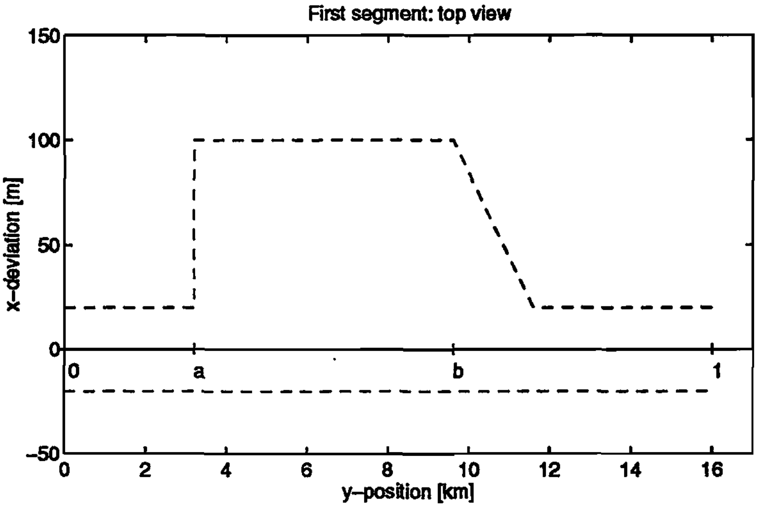

*Fig.3.4 Segment I: the effect of engine failure with bounds*

the time in point 1 at the end of segment I). For robustness we will consider the maximum difference between the lateral deviation of the trajectory with nominal and perturbed Centre of Gravity, aircraft weight and time delays:

$$\Delta_{eyb}(t) := \max\left(|e_{ybmax}(t) - e_{yb}(t)|, |e_{ybmin}(t) - e_{yb}(t)|\right) \tag{3.4}$$

We will allow differences of 10% of the maximal allowable lateral deviations:

$$\left(\max_t \frac{\Delta_{eyb}(t)}{10} + \frac{\Delta_{eyb}(t_1)}{2}\right)/2 \tag{3.5}$$

should be smaller than one. For passenger comfort we use the maximum lateral acceleration $n_y$: we will consider:

$$\frac{|n_y|}{0.2} < 1 \tag{3.6}$$

i.e. $|n_y|$ should be smaller than $0.2g$: under normal flight conditions this value should much lower ($0.02g$, see section 3.2.4), but engine failure is an emergency situation such that an unusually large lateral accelaration is acceptable. For safety we will look at the maximum angle of attack $\alpha$ during the segment:

$$\max_t \left(\frac{|\alpha(t)|}{12}\right)^3 < 1 \tag{3.7}$$

This implies we accept $\alpha = 12$ *deg*; the power is taken to stress the fact that $\alpha > 12$ *deg* quickly becomes unacceptable (stall situation). Finally, for control activity we will consider the rudder actuator effort needed to stabilise the aircraft after engine failure is lifted: this is calculated as:

$$\int_{t_b}^{t_1} \delta_r^2 dt \tag{3.8}$$

with $t_{11}$ denoting the end of engine failure (corresponds to point b in Figure 3.4). This value is not 'normalised to one' as it is not clear what bounds can be obtained: it will act as a value for relative comparison of controllers.

### 3.4.2 Segment II

For segment II we will plot a plan view of the trajectories for the three possible Centre of Gravity locations and time delay, and then superimpose the bounds given in Figure 3.5. To obtain a better insight in the results, we will also plot lateral deviations with bounds as given in Figure 3.6. For performance we will look at the maximum lateral deviation (due to the turn) and the lateral deviation at the end of the segment (when the aircraft should be stabilised again). We will use

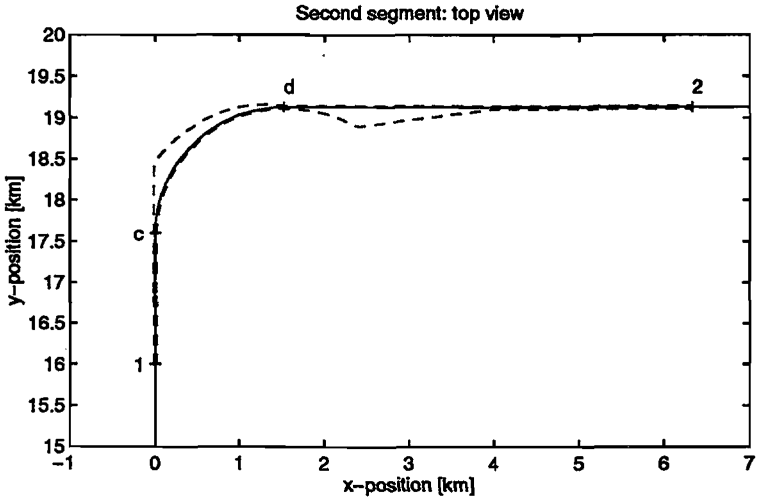

*Fig.3.5 Segment II: plan view of the 90 degrees turn with bounds*

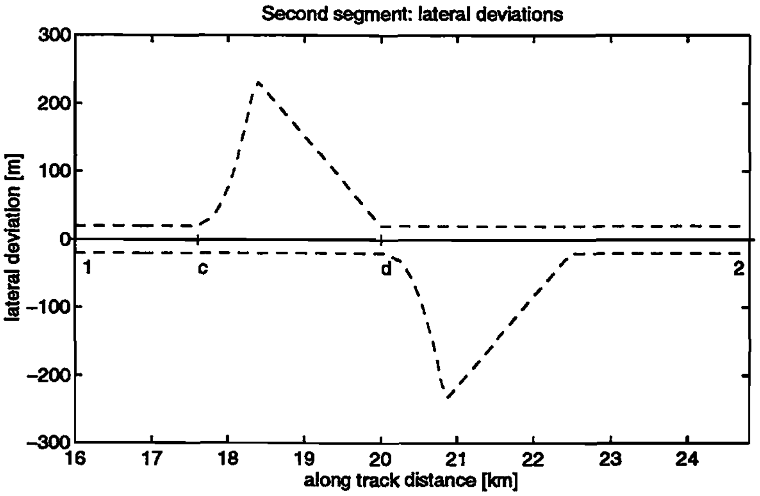

*Fig.3.6 Segment II: lateral deviations during the 90 degrees turn with bounds*

$$\left(\max_t \frac{|e_{yb}(t)|}{200} + \frac{|e_{yb}(t_2)|}{20}\right)/2 < 1 \tag{3.9}$$

for sufficient performance. Note that we allow a maximum deviation of 200 $m$ and a final deviation of 20 $m$. In Figure 3.6 points **1** and **2** correspond to the beginning and end of segment II. Furthermore, $t_1$ and $t_2$ are the times at points **1** and **2**. The command actions for the turn initiation and end are labeled with the points **c** and **d**. For robustness we will again consider the maximum difference between the lateral deviation of the trajectory with nominal and perturbed Centre of Gravity locations and time delays. We will allow differences of 10% of the maximal allowable lateral deviations:

$$\left(\max_t \frac{\Delta_{eyb}(t)}{20} + \frac{\Delta_{eyb}(t_2)}{2}\right)/2 < 1 \tag{3.10}$$

For passenger comfort we use the maximum lateral acceleration $n_y$: we will consider:

$$\frac{|n_y|}{0.02} < 1 \tag{3.11}$$

i.e. $|n_y|$ should be smaller than 0.02 $g$. For safety we will again look at the maximum angle of attack during the segment:

$$\max_t \left(\frac{|\alpha(t)|}{12}\right)^3 < 1 \tag{3.12}$$

Finally, for control activity we will consider the rudder and aileron actuator effort: this is calculated as:

$$\int_{t_1}^{t_2} \left(\delta_r^2 + \delta_a^2\right) dt \tag{3.13}$$

This value is not 'normalised to one' as it is not clear what bounds can be obtained: it will act as a value for relative comparison of controllers.

### 3.4.3 Segment III

For segment III we will plot a side view of the trajectory to see the shapes of the actual trajectories (for nominal and perturbed Centre of Gravity locations and time delay). The start and end points of segment III are labeled with **2** and **3**, the command actions with **e** and **f** and the bounds considered are given in Figure 3.7.

We will also plot the vertical deviation of the trajectories and overlay the bounds shown in Figure 3.8. The performance assessment will be based upon the maximum vertical deviation during the capture of the -6 degrees glideslope and the vertical deviation at the end of the segment (when the aircraft should be stabilised again). Furthermore, we will consider speed variations, that should be kept small in spite of the change in required angle of attack. With $e_{zb}$ denoting the vertical deviation in body coordinates for the trajectory with nominal Centre of Gravity, we will use

$$\left(\max_t \frac{|e_{zb}(t)|}{100} + \frac{|e_{zb}(t_3)|}{6} + \frac{|V - V_c|}{4}\right)/3 < 1 \tag{3.14}$$

for sufficient performance (note that we allow a maximum deviation of 100 $m$, a final deviation of 6 $m$ and speed variations of 4 $m/s$, i.e. 5% of $V_c = 80$ $m/s$). For robustness

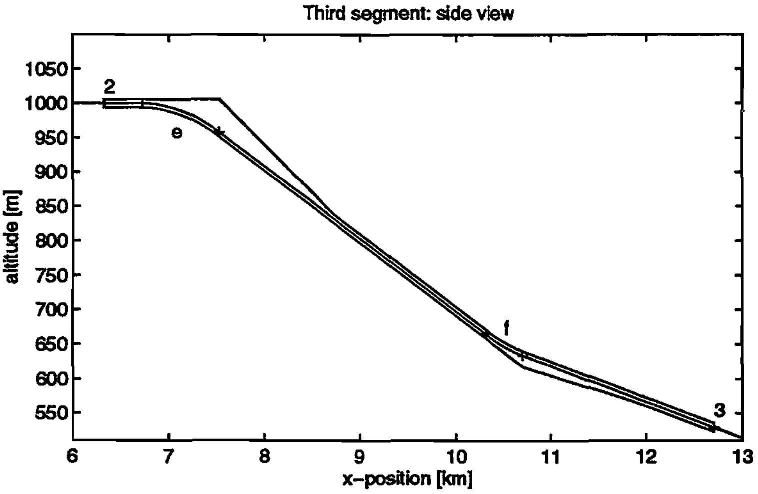

*Fig.3.7 Segment III: side view of the -6 and -3 degrees glideslope captures with bounds*

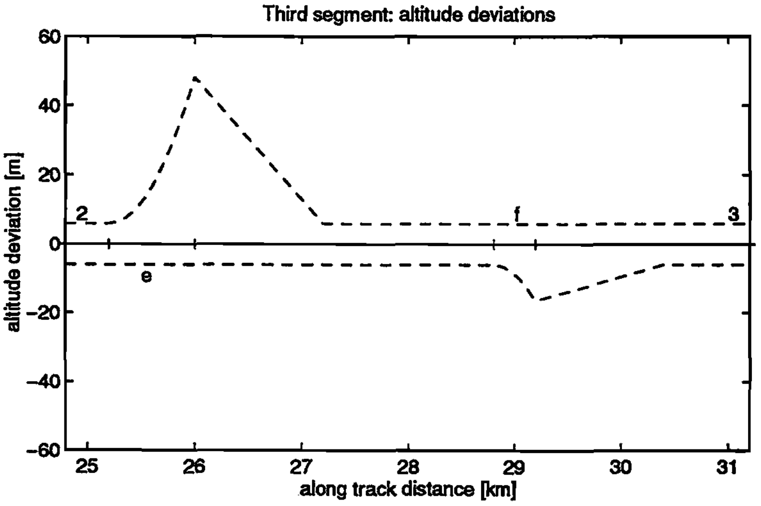

*Fig.3.8 Segment III: vertical deviations during the -6 and -3 degrees glideslope captures with bounds*

we will consider the maximum difference between the vertical deviation of the trajectory for the nominal and perturbed Centre of Gravity location and time delay:

$$\Delta_{ezb}(t) := \max\left(|e_{zbmax}(t) - e_{zb}(t)|, |e_{zbmin}(t) - e_{zb}(t)|\right) \tag{3.15}$$

We will allow differences of 10% of the maximal allowable vertical deviations:

$$\left(\max_t \frac{\Delta_{ezb}(t)}{10} + \frac{\Delta_{ezb}(t_3)}{0.6}\right)/2 < 1 \tag{3.16}$$

For passenger comfort we use the maximum vertical acceleration $n_z$: we will consider:

$$\frac{|n_z|}{0.1} < 1 \tag{3.17}$$

i.e. $|n_z|$ should be smaller than 0.1 $g$. For safety we will again look at the maximum angle of attack during the segment:

$$\max_t \left(\frac{|\alpha(t)|}{12}\right)^3 < 1 \tag{3.18}$$

Finally, for control activity we will consider the elevator actuator effort: this is calculated as:

$$\int_{t_2}^{t_3} \delta_e^2 dt \tag{3.19}$$

This value is not 'normalised to one' as it is not clear what bounds can be obtained: it will act as a value for relative comparison of controllers.

### 3.4.4 Segment IV

For segment IV we will plot a side view of the trajectory to see the shapes of the actual trajectories (for nominal and perturbed Centre of Gravity locations and time delay). The considered bounds are given in Figure 3.9. We will also plot longitudinal deviations with bounds as given in Figure 3.10. For performance we will look at the maximum longitudinal deviation (due to the wind shear) and the longitudinal deviation at the end of the segment (when the aircraft should be within the decision window). We will use

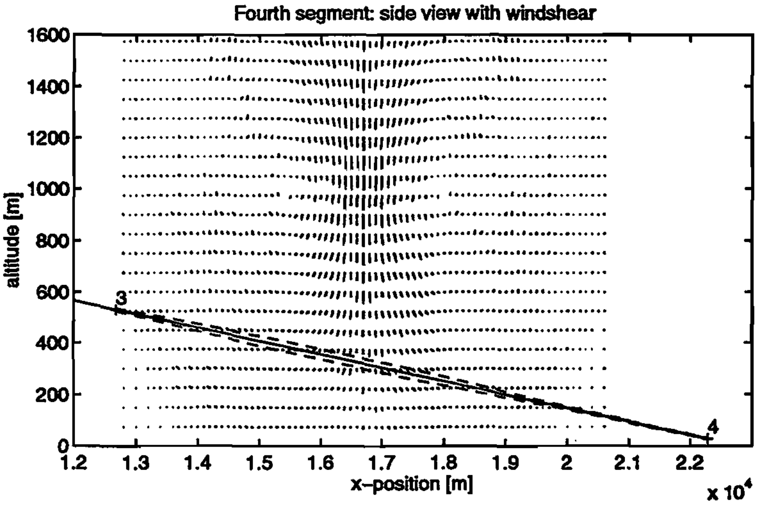

*Fig.3.9 Segment IV: side view of the final approach with wind shear and bounds*

$$\left(\max_t \frac{|e_{zb}(t)|}{100} + \frac{|e_{zb}(t_4)|}{1.5}\right)/2 < 1 \tag{3.20}$$

for sufficient performance (note that we allow a maximum deviation of 100 $m$ and a final deviation of 1.5 $m$). For robustness we will again consider the maximum difference between the vertical deviation of the trajectory with nominal Centre of Gravity and either the maximum or minimum value. We will allow differences of 10% of the maximal allowable vertical deviations:

$$\left(\max_t \frac{\Delta_{ezb}(t)}{10} + \frac{\Delta_{ezb}(t_4)}{0.15}\right)/2 < 1 \tag{3.21}$$

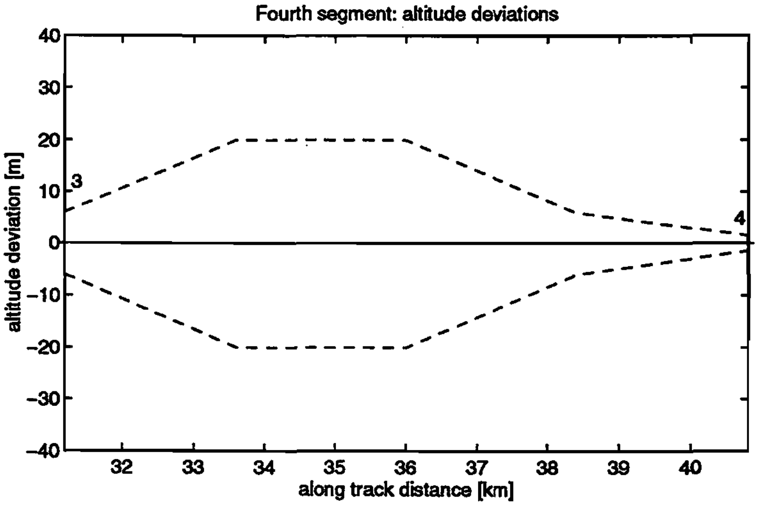

*Fig.3.10 Segment IV: vertical deviations during the final approach with bounds*

For passenger comfort we use the maximum vertical acceleration $n_z$: we will consider:

$$\frac{|n_z|}{0.2} < 1 \tag{3.22}$$

i.e. $|n_z|$ should be smaller than $0.2g$ (usually this value is lower, but wind shear is an emergency situation). For safety we will consider whether the aircraft is within the decision window at the end of the segment: we will restrict lateral, vertical and speed variations to 5 $m$, 1.5 $m$ and 3 $m/s$ respectively as follows:

$$\sqrt{\frac{1}{3}\left((\frac{e_{yb}}{5})^2 + (\frac{e_{zb}}{1.5})^2 + (\frac{(V - V_c)}{3})^2\right)} < 1 \tag{3.23}$$

Finally, for control activity we will consider the elevator and throttle actuator effort: this is calculated as

$$\int_{t_3}^{t_4} \left(\delta_e^2 + \delta_{th}^2\right) dt \tag{3.24}$$

This value is not 'normalised to one' as it is not clear what bounds can be obtained: it will act as a value for relative comparison of controllers.

# 4 Design entry document layout

## 4.1 Introduction

The objective of this chapter is to provide guidelines to the participants on how to present their results to the Action Group. It is intended that this will result in a uniform presentation of the results from each of the participants despite the use of a wide variety of methodologies and will hence make comparisons much easier. The main aim of the design challenge is not just to obtain 'good' or even 'excellent' controllers: as mentioned before, the given design problem has already been solved for many similar aircraft. The purpose of the design challenge is to obtain insight into the relative merits of several design methodologies. Therefore, it is stressed that the contributions should be tutorial in nature: this implies that it must be possible to retrace the applied procedure and independently redesign the resulting controller(s). Furthermore, it is considered of great importance that all necessary assumptions and design objectives are well motivated and related to the general design specifications given in section 3.2. The suggested layout and structure of the standard presentation format is intended to filter out the specific design aspects relevant for each method, such that a clear idea about the performance of each design method is obtained. The performance of a method will be assessed in terms of flexibility, applicability, generality, and effectiveness, thereby providing economic guidelines for the industry and research institutes.

The automated evaluation procedure for the resulting controller as described in section 3.3 is only a part of the final evaluation of the reported design methodology. More specifically, the following aspects should be considered, with approximately equal weight to each of the main items:

- the tutorial value of the entry;
    - the general description of the method,
    - the set up of a controller architecture,
    - the motivation of assumptions made,
    - the motivation for the use of method specific design objectives,
    - the translation of general design specifications into method specific design objectives,
    - the selection of weight functions and trade-off parameters,
    - the execution of the design cycle,
    - the method dependent analysis of results,
- the (estimated) effort necessary for application of the methodology;
    - the complexity of the method,

  - the effort related to the setting up of the design cycle (modelling, controller architecture, weight functions)
  - the effort related to the execution of the design cycle (numerical effort, degree of automation)
  - the effort of performing a redesign after a major aircraft design change,
- the complexity of the control solution;
  - the controller architecture (required measurement signals, reference signals, modes, actuators and filters),
  - non-linearity of the controller (adaptive, gain scheduling),
  - (linear) order of the controller,
  - ease of implementation,
- the behaviour of the controller as found by the automated evaluation procedure of section 3.3.

This implies for instance that information on duration of each design iteration and the motivation for each relevant design action have to be reported. Furthermore, specific problems should be pointed out and discussed.

The structure proposed for the standard document to be prepared by each design challenge contestant is aimed at accommodating all these aspects. The next section will give a short overview of this structure, after which each element will be discussed in more detail. Framework documents that accommodate this structure are available in LaTeX and WordPerfect: if necessary, the correct use of these documents is indicated.

### 4.2 Standard presentation format layout

In short, the standard presentation format will consist of a document with the following structure:

- title, table of contents, list of figures, list of tables, list of symbols and abbreviations,
- summary,
- introduction,
- a tutorial review of the applied control design methodology,
  - introduction,
  - typical applications,
  - plant model requirements,
  - controller structure,

  - possible design objectives,
  - design cycle description,
  - a simple design example (optional),

- the selection of the controller architecture for the RCAM problem,
  - required measurement signals,
  - required actuator signals (control effectors),
  - required filters, (reference) models,
  - required reference signals,

- the translation of RCAM design criteria into method dependent objectives, for instance (if applicable):
  - time domain criteria into frequency domain criteria,
  - time domain criteria into pole-zero criteria,
  - the definition of cost functions,
  - the setting up of an interconnection structure,
  - graphical methods,
  - non-linear specifications into linear specifications,
  - etc.

- the description of the design cycle,
  - required numerical tools for controller synthesis/analysis,
  - intermediate analysis,
  - design parameter adjustment strategy,

- analysis of the resulting controller in terms of the applied methodology, for instance (if applicable):
  - closed loop frequency domain analysis,
  - open loop frequency domain analysis at actuators and sensors: gain and phase margins, roll off actuator loop,
  - singular value or structured singular value analysis,
  - covariance response or RMS response of states and control signals to disturbances and gusts,
  - robust performance assessement,
  - time domain simulations: linear and non-linear,

- results of the automated evaluation procedure,

- general conclusions,
- references,
- appendices, etc. (if applicable).

In general, each of the aforementioned main items will give rise to a separate chapter: in the following sections the possible contents of these chapters will be discussed.

### 4.3 Title page and preamble

The available standard documents are self explanatory with respect to generation of title page and preamble.

### 4.4 Summary and introduction contents

The summary should provide a short description of the applied methodology, the obtained controller and some general comments on the achieved results.
The introduction is mostly standard for all design challenge entries, it describes the framework in which the design challenge was set up (i.e. GARTEUR action group FM-AG08) as well as its overall objectives. The problem formulation should be adjusted to match the presented design methodology; furthermore,it may be necessary to adjust the description of the document's contents.

### 4.5 A tutorial review of the applied control design methodology

Explain the aim of your chosen method and its potentials; formulate objectives. You might use a combination of methods for each specific objective, if so, explain why and how. Does the method have some particular features, such as special analysis and synthesis features. Does the method a priori take into account performance and robustness specifications, does it need gain scheduling and can it decouple interaction in loops and, finally, can it handle feedforward or do you require to consider regulation and a feedforward loop separately. Is the controller robust in a linear sense, or in a non-linear sense. Can you guarantee stability, think of non-linear controllers or adaptive controllers.

### 4.6 The selection of the controller architecture for the RCAM problem

Define the control system architecture for the overall system. This means that a description has to be given of the subcomponents in your control system and that the arrangement has to be reasoned. You might choose a uniform and reduced set of variables to command inner loop variables for any selected mode. All this boils down to a functional description of the control system.

Describe the controller structure you have adopted for the design task. For instance, this could be a feedback controller in combination with a feedforward controller for which the design could consist of either separate or simultaneous design of feedforward and feedback loops. Important information on the feedback design is the choice of regulated variables, the use of additional integrators, the use of full or partial state estimation, etc. When considering feedforward design, subjects like performance features, ideal model response, decoupling features and coordination can be discussed.

### 4.7 The translation of the RCAM design criteria into method dependent objectives

The RCAM design criteria are set up in method independent terms in section 3.2. This chapter should consider these requirements and provide a motivated procedure to approximate them by means of objectives that are of significance for the proposed design methodology. A discussion may be given with respect to the specific properties of the possible design method dependent objectives and their potential to reflect the given requirements: it is to be expected that some requirements allow a good representation, while others are much harder to incorporate. Indicate your opinion on the application area of the method.

### 4.8 The description of the design cycle

This chapter should consider the numerical tools and methods necessary to perform the actual design cycle. A description should be given of the necessary actions that are to be taken for each iteration. An important aspect is, for instance, whether it is possible to automate the procedure and to what extent expert knowledge of the designer is required for intermediate decisions. This implies a extensive description of weight function selection criteria, design parameters and search strategies as well as a discussion on the convergence of the iteration procedure.

### 4.9 Analysis of the resulting controller in terms of the applied methodology

The analysis of the resulting design will be dependent on the applied methodology. It should be made clear to what extent the controller satisfies the design objectives formulated in section 4.7. Again, it is necessary to consider the relation between the design objectives and the original design requirements formulated in section 3.2. Methods and indicators that may be of interest for a specific design method could be:

- eigenvalues, minimum damping,
- broken loop frequency analysis at actuators and sensors, gain margins and phase margins, actuator loop roll off,

## References

[1] GARTEUR Exploratory Group FM-EG12, *Terms of Reference for GARTEUR Flight Mechanics Action Group (FM-AG08): Robust Flight Control in a Computational Aircraft Control Egineering Environment*, National Aerospace Laboratory (NLR), Amsterdam, Jan. 1995.

[2] GARTEUR Action Group FM-AG08, *Communication Handbook*, GARTEUR/TP-088-5, June 1995.

[3] Brumbaugh R. W., 'Aircraft Model for the AIAA Controls Design Challenge', *Journal of Guidance, Control and Dynamics*, Vol.17, No.4, 1994.

[4] Favre C., 'Fly-by-wire for commercial aircraft: the Airbus experience', *Int. J. Control, Special Issue on Aircraft Flight Control*, Vol.59, No.1, pp.139-158, 1994.

[5] Dorato P. (ed.), *Robust Control*, IEEE Press, 1987.

[6] Dorato P. and Yedavalli R.K. (eds.), *Recent Advances in Robust Control*, IEEE Press, 1990.

[7] McRuer, D., 'Interdisciplinary interactions and dynamic systems integration', *Int. J. Control, Special Issue on Aircraft Flight Control*, Vol.59 No.1, Jan. 1994.

[8] Wise, K. et al., 'Linear and Nonlinear Aircraft Flight Control for the AIAA Controls Design Challenge', *Proceedings AIAA Guidance, Navigation and Control Conference*, 1992.

[9] Ying-Jyi P.W., 'Intelligent Control Law Tuning for AIAA Controls Design Challenge', *Journal of Guidance, Control and Dynamics*, Vol.17, No.4, 1994.

[10] Brockhaus R., *Flugregelung*, Springer Verlag, Berlin, 1994.

[11] Franklin G.F., Powell J.D. and Emami-Naeni A., *Feedback Control of Dynamic Systems*, Addison-Wesley 1986.

[12] Kaminer I., Benson R.A., Coleman E.E. and Ebrahimi Y.S., 'Design of Integrated Pitch Axis for Autopilot/Autothrottle and Integrated Lateral Axis for Autopilot/Yaw Damper for NASA TSRV Airplane Using Integral LQG Methodology', *NASA CR-4268*, Jan. 1990.

[13] Robinson P.A., 'The Modelling of Turbulence and Downbursts for Flight Simulators', *UTIAS report No.339*, University of Toronto, 1991.

[14] *Matlab User's Guide*, The MathWorks Inc., 24 Prime Park Way, Natick, Mass. 01760, USA, July 1993.

[15] *Simulink User's Guide*, The MathWorks Inc., 24 Prime Park Way, Natick, Mass. 01760, USA, April 1993.

[16] *MATRIX$_X$/SystemBuild V.2.4, User's Guide*, Integrated Systems Inc., Santa Clara, CA, USA, 1991.

# A The RCAM model and design environment software description

In this chapter the software of the six-degree-of-freedom RCAM model, as detailed in chapter 2, is described. The software code is automatically generated by Dymola, where the objects, given in Figure 2.2, are coded in form of equations. The connections between those objects represent their physical interaction.

From the physical description set up in Dymola, a consistent symbolical mathematical model is built automatically by the Dymola symbolic equations handler, and from that an efficient simulation code for different simulation environments is generated.

For the Matlab/Simulink simulation environment, code can be generated in the form of a Matlab m-file and of mex-files for Fortran or C. Also Fortran or C-code according to the neutral DSblock format may be generated, which can be directly used within the ANDECS simulation environment.

The RCAM software supplied with this manual uses the C-code version of the RCAM model: it is relatively easy to use and much faster than the m-file version. Hence, we assume that you have a C-compiler that can be used in combination with `cmex` (see section A.1).

If you are interested in other versions of the RCAM software model, see section A.2.

## A.1 RCAM model in Matlab/Simulink

We assume that you have a correctly installed version of Matlab/Simulink (Matlab version 4.2 or higher, Simulink version 1.3c or higher) on a workstation or a, preferrably fast, PC. As mentioned before, you also need a C-compiler that can be used in combination with `cmex`.

### A.1.1 Installation

All files, which are required for the design of the controller should be arranged in a single directory, for instance:

```
....\GARTEUR\RCAM\RCAM-DES
```

You can obtain these files on floppy disk (supplied with this manual) or from anonymous ftp.

#### A.1.1.1 From floppy disk

The following procedure should be executed for installation from floppy disk onto an IBM compatible PC:

- insert floppy disk into drive A: (or B:),

- create on your harddisk a new directory to work in and make this your current directory,
- enter the command:
  `copy A:\RCAM\RCAM-DES\*.*`
- compile the cmex-file `RCAMEX.C` by entering the command:
  `cmex rcamex.c`

### A.1.1.2 From anonymous ftp

The following procedure should be executed for installation from anonymous ftp:

- create on your harddisk a new directory to work in and make this your current directory (e.g. `./garteur`),
- start ftp; check whether your current local directory is still your intended work directory,
- from the ftp> prompt: enter open `ftp.nlr.nl`, enter username `anonymous` and supply you e-mail address as password,
- change remote directory by entering the command: `cd transit`
- do not be alarmed when the `ls` command reports that no files are available: this is done for security reasons,
- make sure that the file transfer mode is set to binary by entering the command: `bin`,
- now get the file `rcam3721.uue` by entering the command: `get rcam3721.uue`,
- leave ftp and check whether your current directory is still your intended work directory,
- decode, uncompress and untar the file `rcam3721.uue`:

  ```
  uudecode rcam3721.uue
  uncompress -f rcam.tar.Z
  tar xvfo rcam.tar,
  ```

- go to directory: `./rcam/rcam-des`
  then compile the cmex-file `rcamex.c` by entering the command:
  `cmex rcamex.c`,

#### A.1.1.3 Installed files

You should now have at least the following files:

```
trimrcam.m   rcam9.m
rcam_des.m
control.m    control.mat
rcamex.c
dryden.m
init.mat
```

The routine `trimrcam.m` is used together with `rcam9.m` to set the initial conditions of the model. `rcam_des.m` is the Simulink Design model including a controller example `control.m` and its corresponding data `control.mat`, the actuator model and the S-function of the RCAM dynamics in C: `rcamex.c`. The file `dryden.m` contains the Dryden velocity spectra for turbulence modelling (see chapter 2). Finally, the file `init.mat` contains all variables (controller, parameters, etc.) necessary for simulation (this file is automatically generated if you use `trimrcam`).

### A.1.2 Use

Before you start simulations within Simulink the RCAM model has to be trimmed. This is done by setting the initial trim conditions in `trimrcam.m`. This trim routine may serve as an example, how a gamma-trim of the RCAM model can be performed. Some of the parameter and initial conditions definitions given in `trimrcam.m` are:

```
v0     =       80 ;          % m/s
gamma0 =        0 ;          % rad
pos    = [ 0 0 -1000]';      % [m m m]
p      = [120000 0.3 0 0]';  % [kg m m m]
alpha0 =        0 ;          % rad
beta0  =        0 ;          % rad
phi0   =        0 ;          % rad
theta0 = alpha0 + gamma0;
%
...
```

The airspeed `v0` is set to 80 m/s (155.52 kts), the flight path angle `gamma0` is set to zero (level flight) and the starting position `pos` in the earth fixed coordinate system is set to an altitude of 1000 m, with x- and y-position equal to zero. Also the parameters of the RCAM model, which are given in the vector `p`, are instantiated with their values: The first parameter is the mass of the RCAM model (120 000 kg), the next three parameter are the coordinates of the Centre of Gravity in bodyfixed coordinates (delx = 0.3, dely = 0, delz = 0).

Initial guesses for `alpha0`, `beta0` and `phi0` are set to zero.

After having adjusted those values to the desired flight condition, the routine `trimrcam` can be started. The result will be the initial state vector of the system (x0), the initial input vector (u0), the initial output vector (y0), and the parameter vector (p), which will all be used for simulation within Simulink.

Additionally `trimrcam` linearises the model for this trim condition. The resultant A, B, C, and D matrices of the linear system and the eigenvalues are computed and stored in the workspace.

All these values and also the parameters of control matrices `control.mat` are saved in Matlab binary format to `init.mat`, which contains all necessary information for the following simulation run within Simulink.

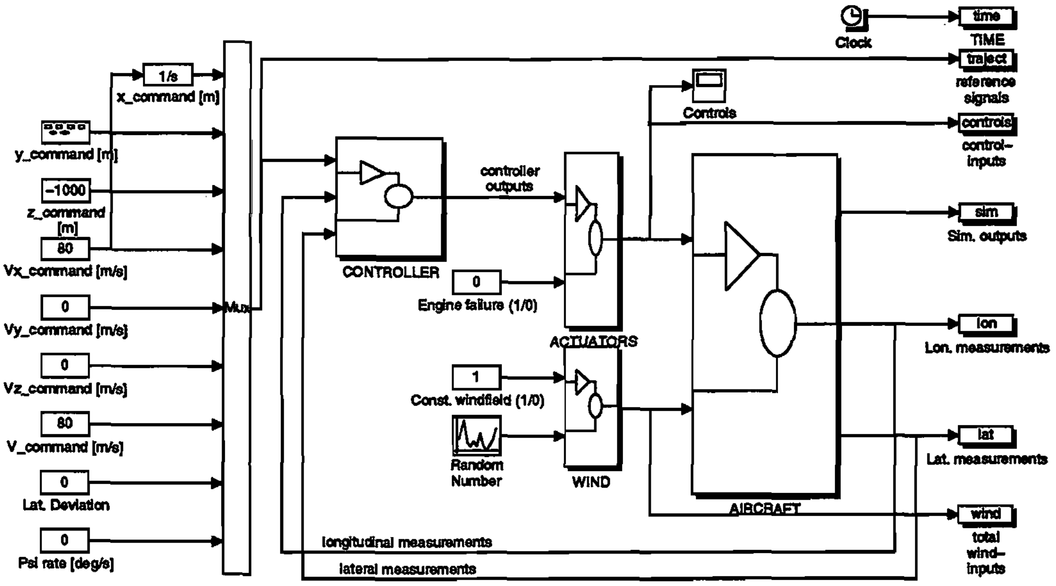

*Fig.A.1 Simulink design model* `rcam_des.m`

The Simulink-file `rcam_des.m` (see Fig. A.1) includes an example trajectory generator, the controller interface, the actuator model, and the S-function of the RCAM dynamics.

You are free to vary parameters of the trajectory generator, the wind inputs, and the controller, which is given as an extra Simulink function `control.m` (see Fig. A.2). No changes should be made to the structure of the overall Simulink-file `rcam_des.m`: especially the number and order of the defined reference signals, measurement signals and control inputs should not be changed to prevent problems with the evaluation procedure described in appendix C.

A change of initial conditions can most easily be performed by running `trimrcam`, although the x0-, u0-, and y0-vector can also be changed directly in the workspace. The same holds

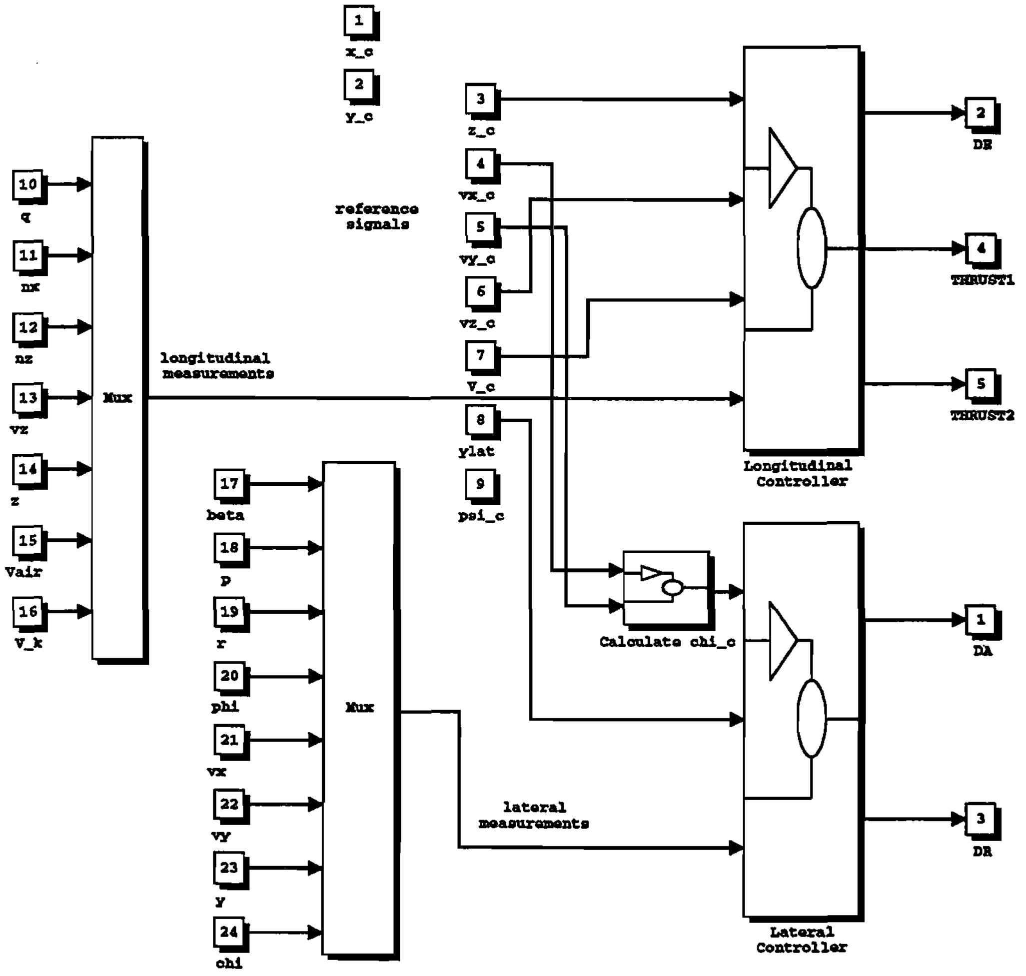

*Fig.A.2 Simulink example controller model* `control.m`

for variations in the parameter vector p. These vectors are automatically loaded from the workspace by the RCAM design model `rcam_des.m`, when a new simulation run is started.

## A.2 Other RCAM model software

The model of the RCAM dynamics can also be supplied in several alternative forms:

- a Matlab/Simulink S-function in m-file format,
- a Matlab/Simulink S-function in Fortran code,
- ANDECS-DSblock code,
- 'plain' Fortran or C code,
- the symbolic mathematical model of RCAM in Dymola.

To obtain any of these alternatives, contact:
Dieter Moormann, DLR
via e-mail: Dieter.Moormann@dlr.de
or Tel: +49 8153 28 2428 / Fax: +49 8153 28 1441.

# B The standard design challenge entry document layout

This manual is provided with a framework document that can be used as a starting point for your design challenge entry document. It is set up in LaTeX and set in the GARTEUR style that we would like you to use (this manual is also set in this style). We strongly advise the use of LaTeX: it is public domain, it runs on many different platforms, and it is well accepted in academia. If you are committed to a different wordprocessor, or if you have any other problems with the software described here, please contact:
Paul Lambrechts, NLR
via e-mail: lambo@nlr.nl
or Tel: +31 20 511 3740 / Fax: +31 20 511 3210.

## B.1 Installation

We assume you have a correctly installed version of LaTeX on a workstation or PC (for instance EMTeX) and the possibility to make use of a Postscript printer (or Ghostscript). All files, which are required for the creation of your design challenge entry document can be arranged into a single directory, for which we suggest:

```
....\GARTEUR\RCAM\RCAM-FRA
```

Similar to the RCAM model and design environment software as described in appendix A, you can obtain these files on floppy disk (supplied with this manual) or from anonymous ftp.

### B.1.1 From floppy disk

The following procedure should be executed for installation from floppy disk onto an IBM compatible PC:

- insert floppy disk into drive A: (or B:),
- create on your harddisk a new directory to work in and make this your current directory,
- enter the command: `copy A:\RCAM\RCAM-FRA\*.*`

### B.1.2 From anonymous ftp

See appendix A: after installation of the design environment the framework document is in directory `./rcam/rcam-fra`.

### B.2 The first test

To check correct transfer of all files and correct operation of your version of LaTeX, it is possible to immediately test whether the document can be compiled and printed:

- go to your intended work directory,
- run LaTeX on the file `RCAM-FRA.TEX`,
- after compilation, run `DVIPS` on the file `FRAME.DVI`,
- print `FRAME.PS` to your Postscript printer (or use Ghostscript).

### B.3 The use of `.STY` files

After successful completion of the first test, you may consider a more permanent installation of the provided software. For this you should locate the subdirectory in which your implementation of LaTeX stores its style files: usually this is the subdirectory `....\TEXINPUT`. You may also consider a separate subdirectory for the provided `.STY` files, as long as LaTeX knows where to find them. Next, move all `.STY` files to this subdirectory.
Most of the style files are standard, like `BK11.STY` and `EPSF.STY`: they are included for completeness. Two of them are specially designed for the GARTEUR FMAG-08 group: `GARTEUR.STY` and `FMAG.STY`. `GARTEUR.STY` replaces standard style files like `BOOK.STY` and `ARTICLE.STY`; `FMAG.STY` is used for some additional definitions. See `RCAM-FRA.TEX` for more information on the use of these style files.
The two Encapsulated Postscript files `GARTEUR.EPS` and `GARTHEAD.EPS` must remain in the same directory as `RCAM-FRA.TEX`.

### B.4 The example files

To make sure that the framework document `RCAM-FRA.TEX` can be compiled, we have added some example files that result from the automatic evaluation procedure described in appendix C. These files were generated using the example controller discussed in appendix A (`control.m` and `control.mat`). The files consist of a number of Encapsulated Postscript files (with extension .EPS) and the files `RCAM-TBL.TEX` and `RCAM-TBL.TXT`, which are also automatically generated and contain the numerical results of the evaluation procedure (`.TEX` is prepared for LaTeX use, `.TXT` is a simple ASCII file with the same results).

## C The automated evaluation software

The automated evaluation software can be used to evaluate any controller designed with the help of the design environment discussed in appendix A. It is the intention that you design your controller within the design environment, and that you also use this design environment to apply any evaluation techniques that you prefer to show that your controller meets the design objectives. The evaluation software should only be used for the automated evaluation procedure, to produce the results needed for an objective comparison of different control design methods.

### C.1 Installation

We assume that you have successfully installed the RCAM model and design environment software described in appendix A. Similar to this software, you should place all files required for the automated evaluation in a single directory, for instance:

```
....\GARTEUR\RCAM\RCAM-EVA
```

You can obtain these files on floppy disk (supplied with this manual) or from anonymous ftp.

#### C.1.1 From floppy disk

The following procedure should be executed for installation from floppy disk onto an IBM compatible PC:

- insert floppy disk into drive A: (or B:),
- create on your harddisk a new directory to work in and make this your current directory,
- enter the command:
  ```
  copy A:\RCAM\RCAM-EVA\*.*
  ```
- compile the cmex-files `RCAMEX.C` and `TRAJECT.C` by entering the commands:
  ```
  cmex rcamex.c
  cmex traject.c
  ```

#### C.1.2 From anonymous ftp

See appendix A: after installation of the design environment the evaluation environment can be found in directory `./rcam/rcam-eva`. You should compile the cmex-files `rcamex.c` and `traject.c` by entering the commands:

```
cmex rcamex.c
cmex traject.c
```

### C.1.3 Installed files

You should now have at least the following files:

`evaluate.m` `evalplot.m` `rcam_tbl.m`
`rcam_eva.m` `tdisplay.m`
`traject.c`
`control.m` `control.mat`
`rcamex.c`
`init.mat` `trim1.mat` `trim2.mat` `trim3.mat` `trim4.mat`

Note that some files supplied with the automated evaluation procedure are equal to files supplied with the design environment: the S-function of the RCAM dynamics `rcamex.c` and the example controller `control.m` and `control.mat`. None of these files should be changed, except `control.m` and `control.mat`, which contain the definition of the controller to be evaluated.

## C.2 The first test

The example controller is supplied with the evaluation environment to check whether all files are properly installed:

- start Matlab,
- change directory to the one in which you installed the automated evaluation software: e.g. `GARTEUR\RCAM\RCAM-EVA`,
- run the Matlab script file `evaluate.m`: ≫ `evaluate` [return],
- the results are now automatically generated: this may take quite a lot of time (3 hours on a 90 MHz Pentium PC); you can check the progress in the Matlab command window: there are four runs taking 500 to 1000 simulation seconds,
- plots are shown: press a key to go through them,
- some ASCII files are created: you see them scroll up in the Matlab command window,
- successful completion is indicated.

The results are now available in your work directory. To incorporate them into the framework document you should copy the following files to the directory in which you have your framework document (see appendix B):

- all `.EPS` files,
- `RCAM-TBL.TEX`.

Note that you will overwrite some of the files in the target directory.
Next, go to the directory with your framework document and use LaTeX to compile `RCAM-FRA.TEX`: the new results are automatically incorporated. The file `RCAM-TBL.TXT` is created for use with other wordprocessors.

### C.3 Use with your own controller

The controller used for the first test is an S-function named `CONTROL.M`. To use your own controller, simply replace this S-function with the one you created with the design environment. If you use the design environment as indicated, your controller should be an S-function with the correct number and order of inputs and outputs for use with the evaluation environment. The procedure for the evaluation is then as follows:

- save the controller S-function you created with the design environment as `CONTROL.M`
- save any parameters you need to define this controller in `CONTROL.MAT`; the following names should NOT be used as they contain evaluation procedure parameters:
  `Lg, gust, sigma, v0, wspeed, wx, wz, x, z`
- copy `CONTROL.M` and `CONTROL.MAT` to your evaluation software subdirectory (e.g. `GARTEUR\RCAM\RCAM-EVA`); overwrite the `CONTROL.M` file already existing,
- proceed with the procedure given in the previous section