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Space engineering — Control performance guidelines

National foreword

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European Foreword

This document (CEN/TR 17603-60-10:2022) has been prepared by Technical Committee CEN/CLC/JTC 5 "Space", the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-60.

This Technical report (CEN/TR 17603-60-10:2022) originates from ECSS-E-HB-60-10A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

Introduction

This document focuses on the specific issues raised by managing all performance aspects of control systems in the frame of space projects. It provides a set of practical definitions, engineering rules, recommendations and guidelines to be used when specifying or verifying the performance of a general control system; attention was paid by the authors to keep the application field as open as possible, and not to restrict to a specific domain – such as spacecraft attitude control for example.

It is not intended to substitute to textbook material on automatic control theory. The readers and the users are assumed to possess general knowledge of control system engineering and its applications to space missions. Nevertheless when required – to avoid any risks of ambiguity for example, or for the clearness of the presentation – some basic definitions and rules are provided in dedicated annexes.

This document was originally intended to focus on the specific case of pointing systems and AOCS, starting from an existing ESA handbook [Pointing Error Handbook, ESA-NCR-502], to be updated, completed, and extended to be built up as an applicable ECSS document. But after reviewing the scope, this approach appeared somewhat restrictive:

- restricting performance concepts to “pointing” does not allow to deal with problems such as thermal control, position control (robotics), or more generally any other type of control systems, even though these problems share the same theoretical framework;
- AOCS is one major contributor to the overall system pointing performance, yet not the only one: misalignments, thermoelastic effects, payload behaviour, etc. all contribute to the final performance. This remark can be extended to general systems, considering that the controlled part is but one of the contributors.

Accounting for these remarks led to extending the initial scope of this document. The upgraded objective is to set up a generalised framework introducing performance definitions, performance indices and budget calculations. “Generalised” is understood here in two directions:

- transversally, so as to be applicable independently on the physical nature of the control system (not only pointing),
- and vertically, in the sense that in many practical situations the proposed definitions and techniques can also apply to any part of the system (basically to the controlled part, but not restrictively). This should assure consistency between the performances indices (error budgets) of the complete system and of the controlled system part. Motivation is also that dedicated but generic methods for budget breakdown can be applied on different levels i.e. on system level and on controlled system level.

NOTE 1 The idea of defining a general framework applying from equipment level to system level is driven by a concern for technical and conceptual consistency. In a later phase, relevant system aspects can be transferred or copied to the appropriate System Engineering standard – if found more convenient.

NOTE 2 The general control structure from the Control Engineering handbook [ECSS-E-HB-60A, Figure 4-1] has been extended in support, showing also the system performance in the output (Figure 4-2 of this handbook)

NOTE 3 The objective of this document is not to cover the high level system or mission performance aspects, which clearly belong to a different category.

In addition to this will for general and generic concepts, a clause of this document covers the performance issues which are more specific for the controlled systems themselves (mainly involving feedback loops in practice) or which are based on well-known control methods. The need for this clause arises as such systems call for particular technical know-how and feature specific performance indicators that require additional insight. For example: stability and robustness properties, transient responses (settling time, response time etc.) and frequency domain indicators.

Although this document is designed to be as general as possible, clearly in practice pointing and AOCS issues are the most demanding space engineering disciplines in terms of control systems. They are covered by an informative annex of the document which declines the general concepts and illustrates how pointing issues can be managed as a special case of vector-type data on a high resolution Earth observation mission.

Driven by a similar concern for illustration on space engineering applications of practical interest, another annex of the document shows how to decline the general concepts to deal with the control performance issue arisen by robotics applications.

1

Scope

This Handbook deals with control systems developed as part of a space project. It is applicable to all the elements of a space system, including the space segment, the ground segment and the launch service segment.

It addresses the issue of control performance, in terms of definition, specification, verification and validation methods and processes.

The handbook establishes a general framework for handling performance indicators, which applies to all disciplines involving control engineering, and which can be declined as well at different levels ranging from equipment to system level. It also focuses on the specific performance indicators applicable to the case of closed-loop control systems.

Rules and guidelines are provided allowing to combine different error sources in order to build up a performance budget and to assess the compliance with a requirement.

This version of the handbook does not cover control performance issues in the frame of launch systems.

2 References

EN Reference	Reference in text	Title
EN 16601-00-01	ECSS-S-ST-00-01	ECSS System - Glossary of terms
EN 16603-10	ECSS-E-ST-10	Space engineering – System engineering general requirements
EN 16603-60-10	ECSS-E-ST-60-10	Space engineering – Control performance
EN 16603-60-20	ECSS-E-ST-60-20	Space engineering – Stars sensors terminology and performance specifications
TR 16703-60	ECSS-E-HB-60	Space engineering – Control engineering handbook
EN 16601-40	ECSS-M-ST-40	Space project management – Configuration and information management

Terms, definitions and abbreviated terms

3.1 Terms from other documents

For the purpose of this document, the terms and definitions from ECSS-S-ST-00-01 apply.

3.2 Terms specific to the present handbook

3.2.1 control performance (state)

quantified output of a **controlled system**

NOTE 1 Depending on the context, the control performance is realised either as **signal performance** or as **control loop performance**.

NOTE 2 Can also be applied to a **control system**.

3.2.2 control (performance) knowledge (state)

estimated **control performance** after measurement and processing, if any

NOTE The control performance knowledge is not necessarily the best available knowledge of the **control performance**. The achieved accuracy and the allowed deviation (control performance knowledge error) depends on the application.

3.2.3 control reference (state)

ideal reference input, desired state or reference state of controlled part of the plant

3.2.4 domain variable

independent variable which can be used to put some dependent quantity into a certain order

NOTE This comprises continuous time, discrete time, N-dimensional space, etc.

3.2.5 ergodicity

property of a stochastic process such that its ensemble and time statistical properties are identical. Ergodicity allows to transfer the statistical results of a single realisation of a stochastic process to the whole ensemble

NOTE (Weak) **stationarity** is prerequisite for (weak) ergodicity.

3.2.6 error index

parameter isolating a particular aspect of the time variation of a performance error or knowledge error

3.2.7 extrinsic performance

element of performance related to the response of the system to its interaction with the outer world (control reference signal, error sources and other disturbances)

NOTE 1 for example the pointing error of a satellite is relevant to this category of extrinsic performance (it depends on the disturbing torques and on the measurement noises)

NOTE 2 can also be defined in opposition to **intrinsic performance**

3.2.8 intrinsic performance

element of performance related to the intrinsic properties of the system, independently on its interaction with the outer world (control reference, the nature and the amplitude of the error sources and other disturbances)

NOTE 1 for example the **stability** of a closed-loop controlled system is relevant to this category of **intrinsic performances**

NOTE 2 can also be defined in opposition to **extrinsic performance**

NOTE 3 "I have some of my properties purely in virtue of the way I am. (My mass is an example.) I have other properties in virtue of the way I interact with the world. (My weight is an example.) The former are the intrinsic properties, the latter are the extrinsic properties" [Weatherson, Brian, "Intrinsic vs. Extrinsic Properties", The Stanford Encyclopedia of Philosophy (Fall 2004 Edition), Edward N. Zalta (ed.)]

3.2.9 individual error source

elementary physical characteristic or process originating from a well-defined source which contributes to a **performance error** or a **performance knowledge error**

NOTE For example sensor noise, sensor bias, actuator noise, actuator bias, disturbance forces/torques (e.g. micro-vibrations, manoeuvres, external or internal subsystem motions), friction force/torque, misalignments, thermal distortions, assembly distortions, digital quantization, control law performance (steady state error), jitter, etc.

3.2.10 performance error (state difference)

deviation of a performance from its reference; realised as **control (signal or control loop) performance error** or **system performance error**, depending on the context

3.2.11 performance error indicator (state difference)

any quantity suitable to define the **performance error** or **performance knowledge error** of a **controlled system** or one of its parts. Examples are signal error functions, signal error indices or control loop performance indicators

3.2.12 performance knowledge error (state difference)

deviation of a performance from its performance knowledge; realised as **control (signal or control loop) knowledge error** or **system performance knowledge error**, depending on the context

3.2.13 robustness

ability of a controlled system to maintain some performance or stability characteristics in the presence of plant, sensors, actuators and/or environmental uncertainties

NOTE 1 Performance robustness is the ability to maintain performance in the presence of defined bounded uncertainties.

NOTE 2 Stability robustness is the ability to maintain stability in the presence of defined bounded uncertainties.

3.2.14 signal performance (state)

characteristic output signal of the plant; either a **control performance** or a **system performance**

3.2.15 stability

property that defines the specified static and dynamics limits of a system

[ECSS-E-HB-60A]

3.2.16 signal stability

variations of a signal over a given time frame

NOTE The signal stability belongs to the category of extrinsic performances.

3.2.17 system stability

ability of a system submitted to small external disturbances to remain indefinitely in a bounded domain around an equilibrium position or around an equilibrium trajectory

NOTE 1 This property is essential for closed-loop control design. But it also applies to uncontrolled systems; for example a free body spinning about an intermediate axis of inertia is unstable.

NOTE 2 As clearly stated **signal stability** and **system stability** are different properties which apply in different contexts. The risk for confusion is minor in practice. It is proposed to keep the wording “stability” unchanged in the frame of this standard, clarifying the current meaning should any ambiguity occur.

3.2.18 stability margin

maximum excursion of the parameters describing a given system for which the system remains stable

NOTE 1 **Stability margins** belong to the category of **intrinsic performances** (they do not depend on the system inputs and disturbances).

NOTE 2 The most frequent **stability margins** defined in classical control design are the gain margin, the phase margin, the modulus margin, and – less frequently – the delay margins (see Clause 6 of this document).

3.2.19 stationarity

property of a stochastic process such that its statistical behaviour is time independent

NOTE Weak stationarity comprises only the time independence of the first two statistical moments (mean and variance).

3.2.20 statistical ensemble

set of all physically possible combinations of values of parameters which describe a **controlled system**

3.2.21 steady state

situation where all internal and external parameters of a system (states, control reference, environment, disturbances) vary slowly compared to the intrinsic time constants of the system

NOTE 1 **steady state** can also be defined by opposition to transient events

NOTE 2 “steady” does not mean that all parameters are invariant. For example a **controlled system** can be in steady state although its **control reference** is moving (**tracking systems**).

3.2.22 stochastic process

function defining a **random variable** for each time instance (discrete or continuous) and each realisation of a **statistical ensemble**

3.2.23 system performance (state)

quantified output of the sum of the controlled and uncontrolled parts of the plant. In most cases, the system performance is realised as a **signal performance**

3.2.24 system (performance) knowledge (state)

estimated **system performance** after measurement and processing, if any. If no additional open-loop sensor is available, the system performance knowledge is identical to the **control performance knowledge**

NOTE The system performance knowledge is not necessarily the best available knowledge of the **system performance**. The achieved accuracy and the allowed deviation (system performance knowledge error) depends on the application.

3.2.25 system reference (state)

desired state or **reference state** of the sum of the controlled and uncontrolled parts of the plant

3.2.26 transient event

situation where one at least of the internal or external parameters of a system (control reference, environment, disturbances) exhibits a stiff variation compared to the intrinsic time constants of the system

NOTE Can also be defined by opposition to **steady state**.

3.2.27 tracking system

control system requested to follow a given reference profile

NOTE Table 3-1 summarizes the main relationships for the definitions of the different kinds of performance, performance knowledge and their corresponding errors. Quantities not defining some kind of state like settling times can only be addressed in terms of control loop performance.

Table 3-1: Relationships of the definitions of the different kinds of performance, performance knowledge and their corresponding errors

Performance		Performance (states and non-states)		Performance error (states difference)		Performance knowledge error (states difference)	
Form in which the quantity contributes to the performance		Signal performance	Control loop performance	Signal performance error	Control loop performance error	Signal performance error	Control loop performance error
Quantity	System (states)						
	• Reference		X	X			
	• Performance	X	n/a	X	n/a	X	n/a
	• Performance knowledge					X	
	Control (states)						
	• Reference			X	X		
	• Performance	X	X	X	X	X	X
	• Performance knowledge					X	X
	Others (non-states)	n/a	X	n/a	n/a	n/a	n/a

3.3 Abbreviated terms

The following abbreviated terms are defined and used within this document:

Abbreviation	Meaning
AKE	absolute knowledge error
AOCS	attitude and orbit control system
APE	absolute performance error
BOL	beginning of life
EKE	expected knowledge error
EOL	end of life
EPE	expected performance error
GNC	guidance, navigation and control
GPS	global positioning system
HW	hardware
INR	image navigation and registration
IOT	in-orbit tests

KRE	knowledge reproducibility error
LTI	linear time invariant
MDE	measurement drift error
MIMO	multiple input multiple output
MKE	mean knowledge error
MOL	middle of life
MPE	mean performance error
PDE	performance drift error
PDF	probability density function
PID	proportional integral derivative
PRE	performance reproducibility error
PSD	power spectral density
RKE	relative knowledge error
RMS	root mean square
RPE	relative performance error
RSS	root sum of squares
SADM	solar array drive mechanism
SC	spacecraft
SISO	single input single output
SW	software
TBC	to be confirmed
TBD	to be defined

General outline for control performance process

4.1 The general control structure

4.1.1 Description of the general control structure – Extension to system level

A general control structure is introduced and described in [ECSS-E-HB-60A, Clause 4.1.1]. The controlled system is defined as the control relevant part of a system to achieve the specified control objectives. As shown on Figure 4-1 hereafter, it includes the control system (consisting of all relevant functional behaviour of controllers, sensors and actuators) and the controlled plant.

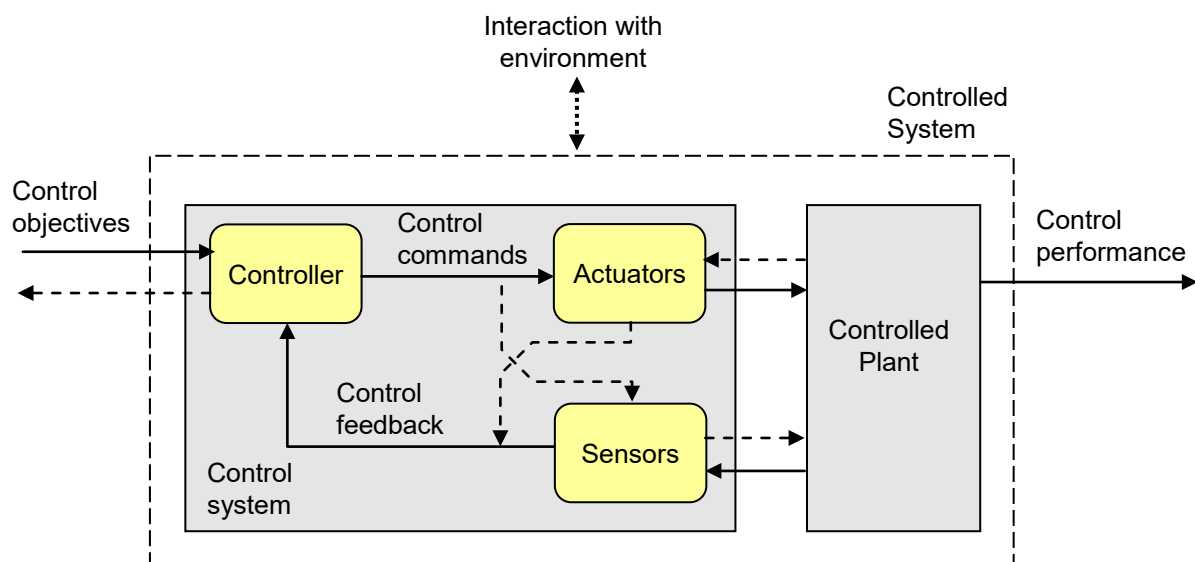


Figure 4-1 General control structure, ECSS-E-HB-60A

In the most general situation, this controlled system itself is embedded in a higher level system layer which also includes additional elements that contribute to the final system performance, but that are not directly monitored by the control commands. This configuration is illustrated on Figure 4-2 hereafter; on this figure the plant is split into two sub-elements:

- the part of the plant which is inside the control loop, G_1 . The states of interest associated to this part can be identified from the sensors outputs, either by direct measurement or by a dedicated processing. They also can be driven so as to match the control reference by the closed-loop actions applied by the actuators.
- the part of the plant which is outside the control loop, G_2 . The states associated to this part are not fully known by the control system, and they cannot be fully driven by the control commands.

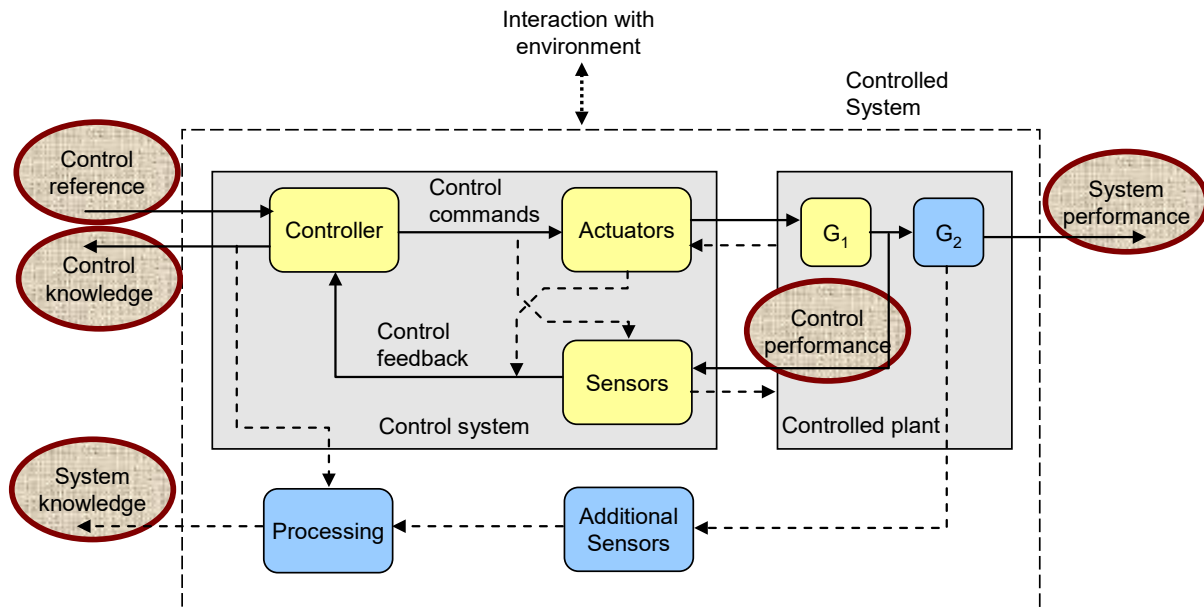


Figure 4-2 General control structure extended up to system level

An example is proposed in clause 4.1.2.3 (based on a typical Earth observation satellite) to illustrate the physical meaning of the different elements involved in this general, extended control structure in terms of hardware, software and functions.

4.1.2 General performance definitions

4.1.2.1 General

For completeness and to avoid ambiguity this extended control system requires some additional definitions, presented in 4.1.2.2.1 to 4.1.2.2.4 (it is recommended to refer to the example proposed in clause 4.1.2.3).

4.1.2.2 Definitions

4.1.2.2.1 control performance

quantified capabilities of a controlled system – refer to [ECSS-E-HB-60A, 3.2.11]:

NOTE 1 More precisely according to [ECSS-E-HB-60A, 3.2.11, NOTE 1] this is the quantified output of the part of the controlled plant which is directly monitored by the control system.

NOTE 2 On Figure 4-2 this part of the plant corresponds to the block G_1 .

4.1.2.2.2 system performance

quantified output of the overall controlled plant, including its extension (if any)

NOTE 1 It can be or not directly monitored by the control system.

NOTE 2 On Figure 4-2 this part of the plant corresponds to the block G2.

4.1.2.2.3 control knowledge

knowledge of the system behaviour, restricted to the part of the controlled plant which is directly monitored by the control system, gained by processing the information provided by the sensors of the control system

4.1.2.2.4 system knowledge

knowledge of the system behaviour, including its extension (if any), gained by gathering all the information available inside and outside the control system

NOTE 1 It can be or not directly monitored by the control system.

NOTE 2 If no additional observable is available, the control knowledge is the best knowledge that can be obtained on the behaviour of the system. However in some cases it can happen that additional sensors are available outside the internal control loop, which allow for improved (complete or partial) observation of the system performance, possibly requiring a dedicated processing.

4.1.2.3 Discussion

The diagram of Figure 4-2 and these definitions show that there is no qualitative difference between control and system performance – nor between control and system knowledge. Both can be handled by a common formalism, to be presented in the following of this document.

4.1.3 Example – Earth observation satellite

As a typical illustration consider an Earth observation spacecraft, featuring a three-axis stabilised platform and an imaging payload.

The platform is controlled by the AOCS to follow a given reference pointing profile (Nadir pointing, slow slew motion for example). A set of sensors monitors the attitude of the platform (gyros, star sensors for example) and feeds the on-board navigation (GPS for example); the AOCS control loops generate the appropriate commands for the actuators (reaction wheels, control moment gyros, magnetic torque rods...) so as to maintain the platform attitude close to the reference profile.

Meanwhile the instrument is submitted to effects that cannot be controlled by the AOCS loops – such as misalignments, thermoelastic, microvibrations, payload distortions, etc. – that also affect the final system performance, and which can be in part identified and corrected on ground using additional information (such as image processing and landmarks identification).

Table 4-1 maps this system to the extended structure of Figure 4-2:

Table 4-1 Example of a control structure breakdown for an Earth observation satellite

Controlled part	Controller	AOCS control loops, on board navigation functions, attitude estimation functions
	Actuators	reaction wheels, control moment gyros, torque rods
	Sensors	GPS, DORIS (position navigation) gyros, star sensors (attitude measurement)
	Plant (G1)	platform attitude dynamics (rigid body plus appendages)
Uncontrolled part	Plant (G2)	misalignments, thermoelastic, microvibrations, payload contributors (mechanical, optical, etc.)
	Additional sensors	raw images, landmarks, ranging
	Processing	instrument calibration, INR techniques for improved localization, image geometric correction techniques, etc.
	Control performance	platform absolute pointing, pointing stability
	Control knowledge	platform attitude estimation
	System performance	real image position, registration, image quality (geometric, radiometric)
	System knowledge	image localization, estimated image quality indicators before/after correction

4.2 Review of generic performance specification elements

4.2.1 General

This clause develops a short review of the usual elements of performance specifications met on most control systems – independently on their physical nature and on the nature of the error signal to be monitored. These elements are associated to performance domains and contributors that can be listed in quite a generic manner:

- extrinsic performance elements: performance in steady state (converged) conditions, expressed in time or frequency domains; performance with respect to transient events
- intrinsic performance elements, mainly – but not exclusively – for closed-loop controlled systems, focused on the properties of the feedback loops (e.g. stability, stability margins, robustness, noise rejection).

4.2.2 Preliminary remark on intrinsic and extrinsic performance properties

It is important to make a distinction between intrinsic and extrinsic properties. As stated by the corresponding definitions in clause 3,

- “extrinsic” corresponds to those properties that depend on the interaction between the system and the exterior conditions,
- “intrinsic” corresponds to those properties that do not depend on this interaction.

From these definitions it appears clearly that a control error – say, an absolute pointing error – is a performance indicator belonging to the “extrinsic” category, whereas a stability margin – say, a gain margin – belongs to the “intrinsic” one.

A natural consequence is that assessing extrinsic performances requires quantified hypotheses on the system environment (in practice, control reference, measurement noise level, disturbance amplitude), whereas assessing intrinsic performances does not.

Generally the distinction is clear, but sometimes some ambiguity can arise – often due to the fact that a same word covers two different meanings. This is why for instance it is important to introduce a distinction between signal stability (extrinsic) and system stability (intrinsic), which physically describe two very different properties. The same kind of confusion can occur for terms such as “overshoot”, which according to the context can be understood as the maximum magnitude of a closed-loop transfer function (intrinsic property), or as the peak response of a system submitted to a step, an impulse or more generally a transient input or disturbance (extrinsic property).

It is not intended in this document to redefine these possibly misleading terms in order to avoid ambiguity. Most of the control engineering wording is so well established that there is no way it can be changed. It is important that the requirement is clear and explicit enough when using a possibly ambiguous term so that the interpretation makes no doubt to the recipient.

NOTE In some exceptional situations the separation between extrinsic and intrinsic can be hardly applicable. This is the case for example for very non linear systems, whose system stability properties can be dependent on the current operating point.

For all control systems developed as part of a space project, the control performance requirements cover both extrinsic and intrinsic properties. To illustrate this, Table 4-2 gives an example of specifiable properties for the case of an AOCS loop:

Table 4-2 Example of AOCS extrinsic and intrinsic specifiable performances

	Extrinsic performance properties	Intrinsic performance properties
Steady state properties	absolute pointing error, pointing stability, absolute measurement error, etc.	measurement noise transmission, rejection of external torque disturbances
Transient properties	attitude overshoot (entering a thruster control mode), tranquillization time (end of thruster control mode, rate reduction mode), etc.	overshoot, response time, settling time, damping, logarithmic decay etc.
General properties	fuel consumption, average solar array illumination, etc.	system stability, stability margins, robustness

The intrinsic properties are – completely and exclusively – design dependent. They are fully determined by the quality of the design, independently on the nature of the environment. For instance correct stability margins, reduced closed-loop overshoot etc. are important indicators of the healthiness of the control tuning. Strictly speaking specifying most of these properties is relevant to

“control design rules” more than to “control performance”. Nevertheless for pragmatic reasons (i.e. considering the way control performances are specified in practice on real projects) these questions are addressed in this “control performance” document rather than in a separate one about “control design rules”.

4.2.3 Examples of high-level performance requirements

4.2.3.1 General

In practice many high-level performance requirements are expressed in very similar terms whatever the physical nature of the control system.

4.2.3.2 About steady state performance

4.2.3.2.1 Overview

In steady state the performance generally quantifies the ability of the system to achieve properly the control reference in spite of internal and external disturbances, measurement noise etc. The reference can be either fixed (maintain a temperature to a given value for example) or varying along time (tracking system, slew profile for example).

4.2.3.2.2 Time domain requirements

The needs can be expressed in time domain. The time domain performance specifications can deal with different temporal scales of the error signal (which can usually be seen as the difference between the reference and the actual states):

- systematic error or bias component,
- long term drift,
- repeatability error after a given time period,
- short term signal stability over given time frames.

The associated requirements can be formulated in terms of

- deterministic definitions. For example:
 - maximum absolute pointing error in converged conditions $< 0.1^\circ$
 - minimum Sun avoidance angle in converged conditions $> 30^\circ$
- statistic definitions (mathematical expectation, standard deviation, Allan variance, etc.). For example,
 - pointing variation over a 5 s sliding time frame $< 10 \mu\text{rad } 3\sigma$
 - RMS value of the rate measurement error $< 0.1^\circ/\text{s}$

NOTE All the examples (and figures) given in this clause and the following ones are for illustration only. None of them correspond to an identified, real mission.

4.2.3.2.3 Frequency domain requirements

The performance specifications in steady state can be also expressed in frequency domain (needs generally formulated in terms of PSD envelope).

For example consider a drag-free satellite with a high sensitivity accelerometer. In converged science mode a specification is formulated stating that

“The PSD of the residual acceleration experienced at accelerometer level shall remain below a given envelope”.

4.2.3.2.4 Mixed time and frequency domain requirements

Mixed time and frequency domains specifications can also be met.

NOTE For example:

“The following two conditions shall be met:

- 1. PSD of the error signal remains below a given envelope, **and***
- 2. the temporal extrema is smaller than a given value.”*

4.2.3.3 About transient performance

The performances during transient situations are usually handled by a distinct set of relaxed requirements, considering that the behaviour is locally more disturbed than in converged steady-state situations – as far as these events are short and exceptional. Such transient situations can be met in practice at system initialisation, during a switch between two control modes, or after a discontinuity of the guidance profile – for example.

The needs in transient situations are generally expressed in time domain:

- overshoot (in the extrinsic sense, that means peak temporal response triggered by the transient event).

NOTE For example (on a telecom satellite in station keeping),

“The maximum overshoot in pitch/roll shall be $<0.1^\circ$.”

- tranquillisation time (time required after transient triggering to return to converged conditions).

NOTE 1 For example (on an agile observation satellite),

“The short term line-of-sight angular stability shall be back $< 1 \mu\text{rad}$ in less than 10 s after the end of the worst case manoeuvre.”

NOTE 2 Transient performances are generally expressed in time domain. Formulating transient requirements in frequency domain, or in time/frequency domain, is exceptional.

Some performance requirements in transient situations can also be expressed in terms of intrinsic properties of the system (that means, independently on the external conditions):

- overshoot, here defined as the peak value of the closed-loop transfer function in frequency domain, mainly for closed-loop control systems (see Clause 4.2.2 on the possible ambiguities on the usual terms),
- response time, damping ratio, exponential decay, etc.

These properties are defined in clause 6 for linear time invariant systems.

4.2.3.4 Other types of performance requirements

Other types of performance requirements can also be met that do not belong to the “steady state” nor “transient” categories, properly speaking. Some of them are rather generic and can be met in many different situations; for example:

- Final state, final positioning accuracy,

- total consumption during a given phase (fuel, battery power),
- total duration of a given phase

Some are much more specific, associated to a particular type of application and of requirement. Taking some examples from spacecraft engineering:

- number and statistics of thrusters firings,
- average illumination of the solar array during initial acquisition,
- number of occurrences of zero-crossing for a reaction wheel, number of cycles at low speed

There is an almost unlimited number of similar customised requirements that can be imagined, according to the nature of the control system of interest. A detailed analysis is out of the scope of this document; nevertheless the methods, rules and recommendations further developed in the next clauses are also helpful to formalise and analyse these problems.

4.2.4 Formalising requirements through performance indicators

4.2.4.1 General

Clause 4.2.3 gives a (non exhaustive) list of usual high-level performance requirements that can be met on a large number of control systems. To be made applicable in practice these requirements are formalised so as to avoid any ambiguity or erroneous interpretation. This formalisation requires a set of mathematically well-defined performance indicators.

4.2.4.2 Extrinsic performance indicators

These indicators aim at quantifying the end-to-end behaviour of the control system submitted to environmental and measurement disturbances. As a consequence they are defined as one or several temporal or frequency properties of the separation between the true and the desired state(s) of interest.

A quite general template for building such extrinsic performance indicators is given on Table 4-3.

NOTE 1 The formalism introduced above is indeed very general and allows handling a large variety of problems. There is no limit in theory to the number of possible error functions, operators, and properties to be verified, according to the nature of the control system and to the type of performance to be verified.

NOTE 2 Nevertheless in practice most of the usual needs can be covered by a limited set of such error functions, operators and performance properties. For more details on how to define and to manage a separation function, for detailed definition of usual performance indices, and for guidelines on how to use them to formalise different types of requirements, refer to clause 5 of this document.

NOTE 3 In all cases these performances are related to a consistent set of hypotheses for what concerns the environment disturbances, the measurement disturbances, and all the system parameters in a very wide sense. It is important that a performance requirement (as well as a performance verification) states very clearly to which set of hypotheses it refers.

Table 4-3 General template for building extrinsic performance indicators

Step #	Step description
Step 1	Identify the state (or states) of interest for the performance NOTE: Euler angles for satellite AOCS performances, centre of mass position for launcher GNC, temperature value for thermal control, etc
Step 2	Define the error function (or functions): in a very general sense this is simply a mathematical function which quantifies the relevant difference between two state elements or vectors. NOTE: algebraic difference (for scalar signals), distance, angular distance, norm of vector difference, etc
Step 3	Define the operator applying to the error function (if any) NOTE: raw error value, sliding average, peak-to-valley variation over a sliding time interval of given duration, etc
Step 4	Define the performance properties to be verified: these properties can be either deterministic (e.g. maximum value), or statistical (e.g. 3σ value), or expressed in frequency domain (e.g. PSD below a given frequency envelope).

For illustration this is how the general process of Table 4-3 can be declined in the particular case of the roll pointing stability of a satellite:

- State of interest: roll angle
- Separation function: algebraic difference between actual and desired roll angles
- Operator: peak-to-peak variation over sliding time frames of 5 s duration
- Statistical property: 3σ value over a given mission scenario

4.2.4.3 Intrinsic performance indicators

Building intrinsic performance indicators relies on a different process, since by definition such performances do not depend on the end-to-end temporal behaviour of the system, and are not a function of the state vector.

The most usual intrinsic performance indicators for closed-loop control systems are (see also Table 4-2)

- the stability margins, which require to be carefully defined according to the nature and the complexity of the system,
- the transient response properties such as overshoot and damping ratio,
- possibly some relevant frequency domain properties

Other indicators can also be of interest, such as (for example) the convergence domain of a controlled system (envelope of initial conditions for which the system converges towards the desired equilibrium point).

Refer to clause 6 of this document for more material on how to define, handle and specify the usual intrinsic performance indicators for closed-loop control systems.

4.3 Overview on performance specification and verification process

4.3.1 Introduction

Performance specification and verification is a sub-process of the overall control engineering process described in [ECSS-E-HB-60A].

This clause presents an overview of the control performance management and verification process, covering all stages involved during the lifecycle of a typical space project.

The overall process naturally divides into two areas:

- a. Requirements capture and dissemination.
- b. Performance verification.

These are discussed in clauses 4.3.2 and 4.3.3 respectively. Typically these tasks are not performed sequentially: the results of the performance verification can lead to a change to the requirements dissemination and their subsequent re-verification. Several iterations can be needed to achieve a satisfactory performance budget which meets all top level requirements.

Clause 4.3.4 explicitly defines the various tasks required for managing a control performance budget, and the responsibilities of the various parties involved for carrying out these tasks.

It should be emphasised that different missions will have different structure and organisation: the discussions in this clause are for a general mission profile. This can need to be appropriately adapted for a particular mission.

Table 4-4 Summary of control performance engineering tasks

Control performance activity	Specific control performance tasks
Integration and control	- Contribution to system engineering database. - Definition of budget and margin philosophy for control performance. - Inputs to risk management.
Requirements engineering	- Allocation to control performance requirements from system and mission requirements. - Contribution to system requirements to meet control performance requirements. - Allocation of control performance requirements to sub-assemblies or equipment (sensor, actuators and controller HW). - Definition of control performance verification requirements.
Analysis	- Selection of adequate performance assessment tools and methodologies. - Requirements evaluation and budgets breakdown. - Disturbances evaluation. - Performance verification analysis (including simulation).
Design and configuration	- Identification of performance related design and tuning constraints. - Constraints on operational control architecture (modes, modes switching). - Performance driven design of control concepts and algorithms. - Control design trade-offs. - Generation of control budgets.
Verification and validation	- Inputs to the definition of control verification and validation strategy (including specification and requirements for test environments). - Preliminary verification of performance by analysis or prototyping. - Final verification of performance by analysis and simulation. - Contribution to verification and validation of controlled system (HW, SW and human operation) by hardware-in-the-loop tests. - In-flight performance validation of controlled system performance.

4.3.2 Requirements capture & dissemination

Typically, this process consists of the following stages:

- The mission objectives are used to derive a set of system level performance requirements. These are generated by the top level customer or end user. These captured system level requirements are then placed on the mission prime contractor.
- Then, the prime contractor divides the system level performance requirements appropriately, to produce requirements on the subsystems and on the equipment (sensors, actuators, control HW) such that if these requirements are met the system level requirements are also met.

- c. This is repeated at lower level, such that each subsystem supplier also generates lower level performance requirements for their subcontractors (for example down to unit level).

This process is illustrated in Figure 4-3. The requirements management is a top-down process, consisting of an initial **requirements capture** task at top level, followed by **requirements dissemination** at each lower level of the process.

The top-level requirements capture is generally performed at the start of development and then left unchanged. There can be exceptions to this: for example if the payload design is changed during development it can be necessary to modify the requirements accordingly. Requirements dissemination can need to be changed several times during development, depending on the outcome of the performance verification at each level.

4.3.3 Performance verification

At each level in the process, performance are verified against the appropriate requirements. The overall verification is a bottom-up process consisting of the following activities:

- a. At the lowest requirement level in the tree, the performance of the appropriate part of the system is calculated via preparation of an error budget.
- b. At higher levels, budgets are prepared by incorporating the budgets from lower levels, together with errors intrinsic to that level.

Thus, at all levels, the basic verification task consists of preparing a **control error budget** for that system or subsystem.

As the project matures, more information becomes available for incorporation into the error budgets. In later phases, when components have been built, it can be possible to obtain information on the errors directly from measurement.

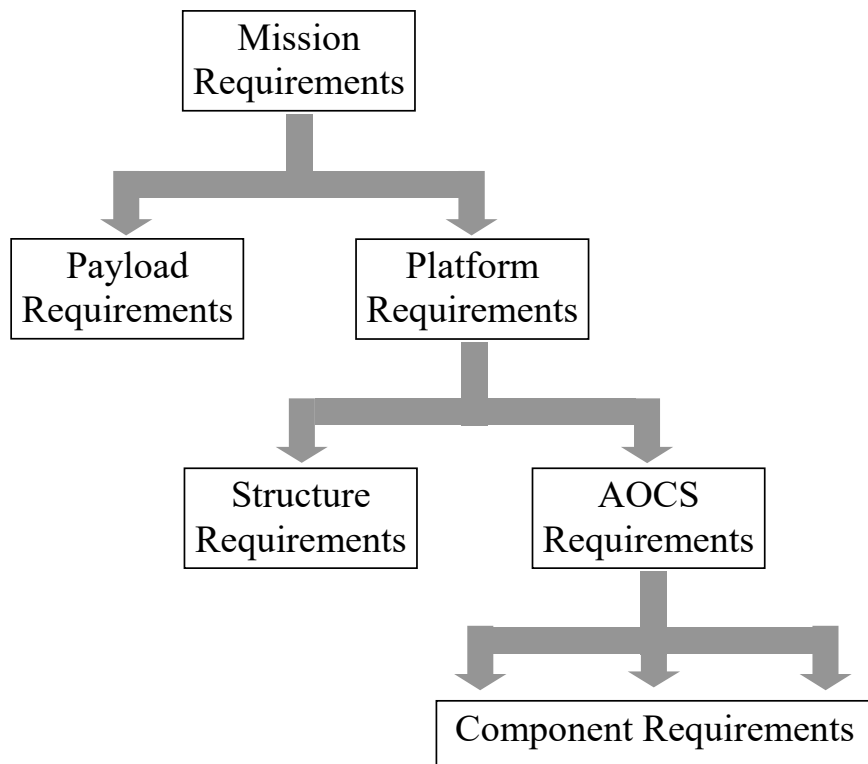


Figure 4-3 Example of requirements capture and dissemination for a typical AOCS case

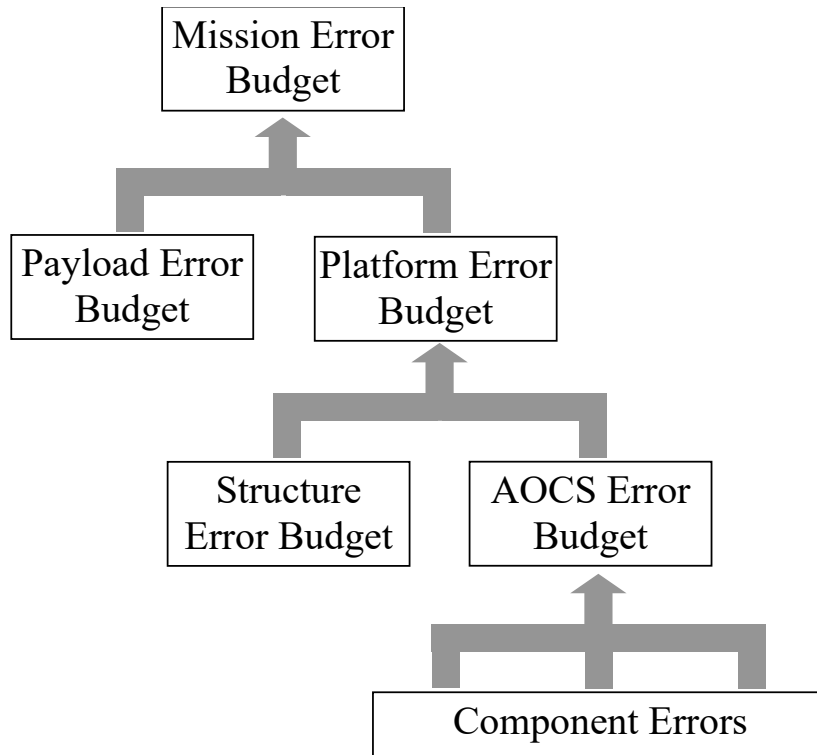


Figure 4-4 Example of pointing performance verification, for a typical mission profile

4.3.4 Control performance engineering tasks during development phases

4.3.4.1 Overview

This clause looks at how the performance activities discussed in Clause 4.3.3 break down across the different phases of the mission. Table 4-5 summarises the tasks required at each phase, which are discussed in more detail in the next clauses.

The discussion here is for guidance only. Every project is structured in a slightly different way, and the process of managing the performances varies accordingly.

Table 4-5 Summary of the control performance management activities during the phases of mission development (guidelines only)

Phase	Tasks required		
	Requirements capture	Requirements breakdown	Error budget preparation
0	Preliminary formulation	-	-
A	Detailed formulation	Preliminary breakdown for each proposed design	Preliminary budget for each proposed design
B	Update if payload design changes	Detailed breakdown. Iterate according to budgeting results	Refine budgets according to design selected
C	Update if payload design changes	-	Update budgets as design matures
D	-	-	Update budgets with measurement data as available
E	-	-	-
F	-	-	-

4.3.4.2 Phase 0/A: mission analysis, needs identification, feasibility

During these phases the mission is analysed and its needs defined. One (or more) solutions is proposed to meet these needs.

Control performance management activities required during this phase:

- Requirements capture: preliminary then detailed formulation of system requirements performed by the end user or top-level customer. These are the requirements to be met by the payload in order to perform the mission successfully.
- Requirements breakdown: a preliminary breakdown of requirements into subsystems, made by the top-level customer. These are used to provide performance requirements on the subsystem suppliers.

If more than one design has been proposed, this applies to each design.

The results of the error budget preparation can lead to an update of the requirements breakdown.

- Error budget preparation: Preliminary error budgets should be made for each of the subsystems, and hence for the system.

If more than one design has been proposed, this applies for each option. In this case it is important that the budgeting is prepared in sufficient detail to allow the alternatives to be compared.

At the end of phase A the feasibility is established and a preferred approach is identified. It should be ensured that the proposed approach is able to meet the performance requirements identified.

**Table 4-6 Control performance engineering inputs, tasks and outputs,
Phase 0/A**

0/A	Requirements engineering	Analysis	Design and configuration	Verification and validation
Inputs	System objectives Mission requirements System performance requirements	Controlled system performance objectives Preliminary control system requirements	Control system design concepts of similar space systems	System verification and validation approach
Tasks	Translate mission and system objectives into preliminary control performance needs Preliminary breakdown of performance requirements to sub-assemblies and equipment (sensors, actuators, and controller HW)	Preliminary disturbances evaluation Analysis of control performance requirements feasibility & control system alternatives Preliminary performance assessment Initial sensitivity analysis Identification of performance critical aspects	Establishment and trade-off of control system design concepts	Control engineering support for definition of performance verification and validation concepts Preliminary definition of control performance verification and validation methods and strategies
Outputs	Inputs to system requirements documentation	Control performance analyses Inputs to Phase A system performance budgets	Performance criteria for selection of a preliminary baseline control system design	Inputs to development and verification plan & planning

4.3.4.3 Phase B: preliminary definition

This phase covers the refinement of the selected solution to a coherent level. The control performance management tasks during this phase are:

- Requirements capture: the requirements identified in phases 0/A should be refined where necessary.

NOTE Although the generic requirements for the mission previously identified should remain the same, platform requirements can need to change according to payload design. For example for an imaging payload, the required pointing stability can be determined by the pixel size or imaging time, both of which can change as the payload design evolves.

- Requirements breakdown: the top level requirements should be distributed to suppliers in the form of subsystem requirements. These can in turn be broken down into requirements on lower level suppliers.

NOTE The requirements breakdown can need to be iterated several times to achieve a satisfactory allocation, depending on the results of the error budget preparation.

- Error budget preparation: the error budgets for each subsystem (and below where necessary) are assessed in as much detail as is possible at this stage. The aim is to confirm the feasibility of the adopted approach, identify any areas where margins are tight, and to provide information for use in deciding how to proceed with the design

NOTE The types of inputs which can be used at this phase are: comparison with previous missions, manufacturers information, analytical or a-priori models, etc

It is assumed that at the end of phase B there is a stable baseline for the design, with verifiable requirements established.

Table 4-7 Control performance engineering inputs, tasks and outputs, Phase B

B	Requirements engineering	Analysis	Design and configuration	Verification and validation
Inputs	System objectives Mission requirements Controlled system objectives and performance requirements	Phase 0/A simulation models Phase 0/A control analyses	Phase 0/A control design	System verification plan Phase 0/A control verification plan
Tasks	Generate controlled system performance requirements Detailed breakdown of performance requirements to sub-assemblies and equipment (sensors, actuators, and controller HW)	Assessment of disturbances and other performance contributors Controlled system performance analysis Controlled system sensitivity analysis Analysis of control performance constraints induced on sub-systems and components	Identify performance constraints for the preliminary design of control laws Definition of control system baseline Establishment of control related budgets and margins	Contribution to preparation of controlled system verification plan Provide inputs to lower level verification plans
Outputs	Inputs to system requirements documentation	Inputs to controlled system analysis report	Inputs to control system design report (including design justification from a performance point of view) Preliminary control performance budgets	Inputs to development and verification plan & planning

4.3.4.4 Phase C/D: detailed definition, production and ground qualification testing

Phase C involve detailed study of the solution identified in the previous stage, and covers all remaining activities relating to the mission design. Phase D comprises the manufacture and qualification testing. The control performance management tasks during these phases are:

- Requirements capture: no significant changes to the performance requirements should be made after the PDR at the end of phase B. Minor changes can be needed to reflect modifications to payload design: these should have no significant impact on the design activities.
- Requirements breakdown: this should be updated as the design evolves. Ideally the fewest possible changes should be made to the requirements breakdown, however improved

knowledge of the error budgets at all levels can require a reallocation of requirements to be made.

- Error budget preparation: the error budgets at each level prepared at phase B are refined as the design evolves.

NOTE 1 During phase C, the components to be used should be selected, the functional modes analysed, etc. The information used to produce the performance budgets should therefore come to more accurately reflect the actual system behaviour.

NOTE 2 In addition to providing an updated budget at the end of this phase, it is recommended that the budgets are continually updated throughout the phase, with new or updated data being incorporated as soon as available. This should ensure that any potential problems are identified as early as possible, and not at the end of the phase when the design is supposed to be finalised.

NOTE 3 As each component and subsystem becomes available and is tested, any actual measurements should be incorporated into the error budget to give a more realistic assessment of the actual errors for the actual SC.

NOTE 4 In the case of systematic errors (biases, misalignments, etc.) earlier budgets should have assumed a range of possible values. Measurements on the actual equipment should allow an assessment of the actual error, with only measurement errors leaving any uncertainty.

NOTE 5 For other error sources, such as sensor noise, it is not possible to obtain an actual value for the error, but repeated measurements should allow more accurate assessment of the error distribution to be made.

It is assumed that at the end of phase C the final design has been established, and it has been confirmed that each component and subsystem meet their performance requirements and that sufficient margins for uncertainty have been established.

At the end of phase D, the production activities end. At this point it is very important that the end user or top level customer ensures that, given the current knowledge of the errors, all performance requirements are in the conditions of the mission.