1. Introduction

The GNC Design Process usually comprises a set of different disciplines and requires involvement of a team composed of people with different background knowledge and formation. The set of knowledge areas usually involved to a certain extent in the GNC design process includes the following ones:

- Mission design and planning
- S/C systems knowledge
- Trajectory design
- Control design
- Sensor technology
- Navigation strategy and Navigation filters design
- Onboard SW coding
- SW verification
- System verification (including HW in the loop)

The GNC design loop is, in general, an iterative process, where the designer moves forward and backward through the several steps of the sequence, in order to refine the functions being developed. Due to this iterative nature of the work, the handling of the GNC design process data, including inputs and outputs to the process (requirements, synthesis models, parameterisation of the models, mathematical representation of the navigation and control functions, etc...) needs to be managed in a coherent way and made available in a suitable shape to every support tool being used in the process. All these facts point to the need for integrated GNC development environments that not only provide the tools able to support the analysis, synthesis and evaluation activities required but that also manage, in an integrated way, the data being used within the process. GNCDE (GNC Development Environment) is such a kind of integrated GNC development environment, result of subsequent ESA contracts and a large and fructiferous cooperation between ESA and GMV to refine the tool features in view of real user needs.

The paper describes the main concepts applied to the design of this environment and the rationale behind them as well as major conclusions derived from facing GNCDE to the real GNC design steps.
2. GNC Design Loop

The main steps of the GNC design process are graphically depicted in Figure 1. In parallel, we show how these activities are supported by GNCDE resources (Tools, Templates, Libraries). Each step and the approach for supporting it, is explained in the following sections.

![Figure 1: GNCDE support along the GNC Design Process](image-url)
3. Requirements Analysis/Consolidation and Equipment Selection & Sizing

The first phases of the GNC design process involve the analysis and completion of the requirements and a set of preliminary analyses devoted to:

- Supporting the sensors and actuators trade-off and selection.
- Defining a preliminary mission profile, that, at the same time, allows having a first estimation of consumed propellant and timeline for completion of the mission.
- Assessing the feasibility of the requirements imposed, given the preliminary selection of S/C equipment and the first design of the mission profile. In view of its results, it could lead to the review of the equipment trade-off, the preliminary mission profile or indeed the revision/completion of the requirements imposed in the case that they cannot be fulfilled or they are not properly specified under the current technology limitations.

In order to support these tasks, GNCDE provides a set of tools (generally based on analytical formulations) characterised by allowing quick setting of the problem to be analysed, and quick evaluation of the solution. They give the user the possibility of performing complete trade-offs or checking preliminary mission assumptions without the need for spending a large amount of time and effort. These tools are:

- **Guidance Analysis Tool (GATO)**. See details on following sections.
- **Covariance Analysis Tool (COVATool)**, aimed to perform quick analytical covariance propagation analyses. This tool is able to work with LTI models or LTV (user provided) models that can represent the dynamics of the S/C, of its sensors and indeed the GNC functions (estimator and control) that close the control loop. Figure 2 (left) illustrates the tool configuration window and the graphical results of a 3D example analysis of the evolution of a chaser S/C performing an approaching manoeuvre to a target vehicle. The tool helps evaluating and deciding whether some additional action is needed or not (e.g. intermediate correction manoeuvres, thrust type selection, splitting the manoeuvre arc, or re-considering the initial requirement on final state covariance).
- The problem of actuators sizing, considering the control requirements imposed and the expected perturbation environment in the selected orbit, is also supported in GNCDE through a numerical tool. This tool allows the computation of perturbation effects on a given S/C by defining a given S/C geometry through a CAD model. The GNCDE **CAD Tool** provides CAD Model specification (by combination of a set of basic primitives: Sphere, Ellipsoid, Cylinder, Prism, Paraboloid, N-points body), importation, visualization, surface meshing and perturbation computation. Three-dimensional views are possible for easy user feedback on vehicle layout (see Figure 2, right side).
4. Modeling

The GNC design process requires from a set of models that represent the S/C dynamics in its real environment. The fidelity and shape of the models depend on its use purpose:

- Control and state estimator synthesis and analysis.
- Detailed performance evaluation of each GNC mode.

The first of the two above mentioned activities requires models that directly fit to the synthesis and analysis technique selected, while the second task requires from higher fidelity models able to represent with high accuracy the real S/C properties and the real dynamic effects to which it is subject in orbit. Linear model representations are widely used in control synthesis and analysis while, in general, non linear models allow describing with a higher fidelity level S/C dynamics and environment effects on them. The solution proposed to cope with both kinds of requirements is relying on two different model environments that, however, are coherent in terms of S/C and scenario parameterisation data in order to make easier and smoother the designer’s work. The GMV GNC Development Environment (GNCDE) supports this approach, since it is prepared to work with these two different model environments (called Templates in GNCDE terminology):

- **Analysis and Design Template** (composed of linear models and devoted to synthesis and analysis activities)
- **Mission Template** (composed of high fidelity non-linear models and devoted to detailed performance assessment).

Both, Analysis and Design Template and Mission Template, implemented through Simulink blocks and a set of associated ASCII files (for parameterisation and initialisation purposes), contain representations of SC dynamics and equipment (sensors, actuators) and onboard software (basically GNC and mission management functions). These model environments can be created from single or individual models.
that represent each of the elements (SC dynamics, orbital environment, sensors actuators, GNC etc....) and that are joined to shape the full mission representation (Mission Template) or an specific GNC mode representation (Analysis and Design Template). GNCDE supports this "environment" modeling activity by providing a framework (shell) that allows automating many activities required to prepare and later use these model environments or Templates. Among them:

- Automates the process of initialising and running a Template.
- Automates the process of generating a unified user input data file that contains the parameters required for each individual model present in the Template.
- Automates the process of collecting output signal data from the Template and specifying which signals from those available need to be collected.
- Automates the process of generating usable outputs (plots and output data files) from output signals of the Template.
- Automates the process of updating the associated files when a modification in terms of models is implemented in the Template.
- Automates the process of extracting complete “plant” linear models by appropriately combining the elemental linear models included inside and Analysis and Design Template. The linear model representation used by default in GNCDE is the State-Space form, which is widely extended and convenient for most synthesis and analysis MIMO techniques. The linear model collected in state-space form from an Analysis and Design Template (as a Matlab object) can be later used by the GNCDE tools (Covariance Analysis Tool, Control and Estimator Design Tool).

Figure 3: Example of GNCDE Analysis & Design (left) and Mission (right) Templates

5. Guidance Profiles Design and Analysis

Guidance (both attitude and trajectories) design is normally the first (non preparatory) activity in the GNC development process. The task of designing the Mission guidance profiles is also an iterative activity, which needs to account for ΔV budgets while fulfilling a set of different requirements related to sensor operation ranges, safety constraints
etc... GNCDE provides a very complete tool **(GATO, Guidance Analysis Tool)** for that purpose. GATO is a tool providing rapid guidance and trajectory analysis for several possible scenarios: RvD, FF (Formation Flying), 3ASSC (3-Axis Stabilized SpaceCraft) and LA (Launchers Ascent). GATO can work integrated in GNCDE or as stand-alone tool for each scenario and it can be used through Graphical User Interface or Command Line Interface (CLI). This tool has been developed in order to guarantee fast computations (because based on analytical computation) and flexibility (it’s possible to change and define easily parameters through the input file, GUI or CLI).

![Figure 4: GATO main windows](image)

GATO 3ASSC provides preliminary analysis of the guidance attitude (euler angles/quaternions, angular velocities, torque, etc) allowing the possibility to make rapid simulation for several scenarios. The user can create, simulate and analyze his mission by using/composing the maneuvers inside the tool. Spacecraft (mass, inertia, etc.), scenario (central body, orbit, etc.), and the mission (type of manoeuver, time duration, etc) can be defined by the user in an easy way.

GATO RvD (circular and elliptical) allows preliminary analysis of the guidance features (in terms of required impulsive $\Delta V$, continuous thrust history and reference trajectory) through simplified dynamics models. This model makes available analytical solutions for
the guidance features and the reference trajectories computation allowing rapid analysis of a broad range of different mission scenarios for circular and elliptic rendezvous.

GATO FF allows obtaining analysis of guidance in attitude and trajectory for Formation Flying. User can set the desired mission in circular or elliptic orbit around a central body or in L2 scenario; In this case user can set the desired mission by modifying directly the input matlab file or through the Graphical user interface shown below.

GATO LA is a visualization tool for launcher ascent scenarios, which allows the definition of several types of plots. Two trajectories can be loaded in different formats and the user can define bidimensional and tridimensional plots of unprocessed variables and accuracies plots which allow the comparison between the two trajectories.

6. Control Synthesis & Analysis

GNCDE supports the synthesis and analysis of controllers via two major resources:

- **Analysis and Design Template.** Composed by linear models for DKE, sensors and actuators, it represents our “plant” model for control synthesis and analysis. It allows, also, closing the loop with the synthesized GNC functions so that fast analyses can be run in this linear-model environment before going to detailed performance assessment in the Mission Template.

- **Automatic Control and Estimator Design Tool (ACEDTool).** Supports a user in the process of synthesizing and analysing a compensator and/or state observer for our control problem. It is able to work with the plant model representations obtained from the Analysis and Design Template or with imported plant models. It provides:
  - SISO time-domain or frequency-domain analysis and synthesis features
  - MIMO control analysis and synthesis techniques, such as Pole Placement, LQG and robust control techniques such as $H^\infty$ and $\mu$-synthesis.

The methodology usually followed when synthesizing and analysing controllers with GNCDE involves the above mentioned resources and comprises the following steps:

- Getting a synthesis model that represents the “plant” dynamics.
- Analysing the plant dynamics, e.g. to decide whether for a specific GNC mode, certain states can be considered as decoupled, significant perturbations, ...
- Selecting a synthesis method. GNCDE offers SISO and MIMO (Pole placement, LQG, $H^\infty$ and $\mu$-synthesis) but is flexible enough to allow the use of other external synthesis tools while taking advantage of the analysis, visualisation and manipulation features implemented within ACEDTool.
- Preparing the plant model for the synthesis, including subplant selection, discretisation (if required) and simplification (if required).
- Synthesis requirements specification, e.g. signal transient response, stability margins, closed-loop poles position or shape of the weighting functions when coping with robust synthesis techniques such as $H^\infty$ or $\mu$-synthesis.
- Synthesizing a compensator.
- Analysing stability and performances of the closed loop plant: Bode, Nyquist, Nichols, Pole-zero maps, Step response, or more specific analyses such as Analysis of feedback loop gain and phase margins (including worst case analysis), Analysis of feedback loop poles, Normalized coprime factor/gap metric robust stability margin, Robust performance margin, Robust stability margins and Bounds on worst-case gain of the uncertain system.
- Exporting the compensator for analysis outside ACEDTool.

![Figure 5: GNCDE ACEDTool - MIMO control feature layout](image)

7. Estimation Filters Synthesis & Analysis

Most of the times, the full internal state of our control system cannot be directly measured. Nevertheless, many control techniques are based on state feedback and thus it has to be estimated from available sensor measurements and knowledge of the input to the system (generally forces and torques in our SC control system). In state feedback control, the compensator and the observer can be independently designed since the closed-loop poles from the observer and the closed-loop poles coming from the compensator are independent of each other. In fact, the poles of the observer are usually selected so that the observer response is considerably faster than the system response (the only limitation to observer speed normally arises from noise sensitivity problems). GNCDE also supports the synthesis of state observers by two methods: MIMO pole placement and Kalman filter design. As well, as in the control synthesis problem, the support tools provided can use plant models imported from the linear model environment (Analysis and Design Template) that represents our problem.
8. Detailed Performance Evaluation

Once the synthesized controller and estimator are considered to be satisfactory in the view of analyses performed with the Analysis and Design Template, they can be evaluated within a higher fidelity model environment. In GNCDE, this high-fidelity model environment composed of detailed and, in general, non-linear models, is known as Mission Template. It is, in fact, a Functional Engineering Simulator, that allows full Mission simulation, including the possibility to reproduce transitions between the different GNC modes and the high level vehicle management functions acting. Preparation, data management, execution and results exploitation are features included in GNCDE. Additionally, the controllers can be imported in the same way as is done for Analysis & Design Templates. Moreover, GNCDE framework provides certain features and tools to make easier and faster the work with the high-fidelity Mission Templates simulators, such as:

- Easy creation of FOMs plots (2D and 3D) with any output variable.
- Statistical analyses of the output data collected, through a dedicated STATool.
- Sensitivity and worst case analyses. GNCDE provides a MonteCarlo Tool that is able to run both parametric or statistical MonteCarlo simulations with GNCDE Templates. This tool supports the selection of the deflected input variables and the associated parametric variation or statistical distribution for these variables. Then, it automates the process of loading the sets of deflected data, running each case and collecting the output data.
- A 3D Visualisation Tool is provided within GNCDE for increased situational awareness for the designer.
- Save project files in ASCII format at each state of the design process. These files can be recovered later or indeed be executed in command mode.

![Figure 6: GNCDE MonteCarlo Tool GUI with the above example configured](image)
9. GNC coding and verification

Once a GNC design has been positively evaluated in a Functional Engineering Simulator, it can be considered validated only from a functional point of view. The next development step is intended to face real HW architecture implementation constraints and requirements. The logical approach is taking advantage of the already existing implementation and migrating it to the final coding language (C) and target HW platform, where it needs to be validated. For that purpose, GNCDE already implements an Autocoding tool that is built on top of the Matlab tools Real Time Workshop and Embedded Coder. Some additional automation capabilities were added to obtain a user-friendly tool able to exploit the features of GNCDE Templates. These elements are:

- Input/Output variable selection and compilation options feature.
- Model Template import feature: it is in charge of importing the Template model specified by the user, as well as, the configuration options applicable to the model.
- Compilation feature: it manages the data and uses appropriately the different external tools (Real-Time Workshop, Embedded Coder, and external compilers) in order to get the compiled-model version.

Later on (outside GNCDE), the generated executable code must be verified and tested with specific tools available for debugging and analysing SW on the target platform (e.g. LEON2 or LEON3 processor board).

10. Conclusion

This paper has presented the GMV GNC Development Environment (GNCDE) as well how this integrated environment supports all the needed GNC design steps. GNCDE is now in commercial status and the first licenses have been already sold and delivered (among others, GNCDE is being used by ESA PROBA3 mission as core tool for the Formation Flying System design and by South Korea Aerospace Research Institute). GNCDE contact e-mail is gncde_support@gmv.com

11. References