FASTREC

EXECUTIVE SUMMARY REPORT

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1. INTRODUCTION

1.1. CONTEXT AND BACKGROUND

Today's launch campaigns involve several months of mission preparation for a payload delivery, involving a significant recurrent cost for each mission. The costs of the recurrent mission preparation activities do not tend to reduce with increasing launch rate and are not significantly dependent on the size of the launcher. However, modern on-board computing and sensor technologies enable a range of improvements in GNC design and performance, thus rethinking the launch preparation process using currently available technologies has the potential to make significant improvements, employing an integrated process.

1.2. OBJECTIVE

The main goal of the FASTREC (*Fast Reconfiguration Technologies For Recurrent Space Transportation Flight*) project was to exploit design tools/techniques and advanced GNC algorithms whose application aim for a reduction in the reconfiguration effort and turnaround time of a launch vehicle while increasing the operational availability and safety.

1.3. APPROACH

Within the activity, a critical review of the current end-to-end GNC mission preparation, execution and validation process was performed with the goal of identifying the major drivers in terms of cost and timescale and categorize them into unavoidable or susceptible to improvements.

The activity focused on the trade-off and selection of solutions for each of the identified *Improvement Areas (IAs)* and, among the studied solutions, features the adoption of *advanced guidance and control techniques*. The work was divided into:

- The mission requirements and improvement areas definition gather the outputs of the first tasks of the activity, presenting a review of the current Mission Preparation Process, presenting a set of Improvement Areas stemmed from the considerations made.
- Preliminary design of the solution of the IAs that consider both the invariant and variant parts of the GNC. It addresses the design of advanced and versatile guidance and control strategies to meet responsive mission configuration objectives.
- Subsystem level strategies designed regarding advanced and versatile guidance and control strategies to meet responsive mission configuration objectives. It provides the detailed design of the solutions needed to solve the IAs regarding the GNC.
- Results of the defined test plan needed to validate the algorithms implemented. Unit test results for each of the improvements and end-to-end tests covering all of them.
- Critical comparative analysis, comparing the improved process against the baseline. Also, a recommendation of further work required to put the improvements into industrial practise was done.

2. PROJECT ACHIEVEMENTS AND RESULTS

The main outcome of the activity is, apart from the design and implementation of the adopted algorithms, the assessment of the solutions of the Improvement Areas in terms of impact on the GNC preparation improvement with respect to the baseline and a roadmap for future work required to put the improvements into industrial practise.

2.1. Cost and timescale drivers

The following cost and timescale drivers were identified: *Trajectory generation; Mission timeline; Control Synthesis; Dispersion analysis; Iterative nature of the GNC Final Studies; Documentation*.

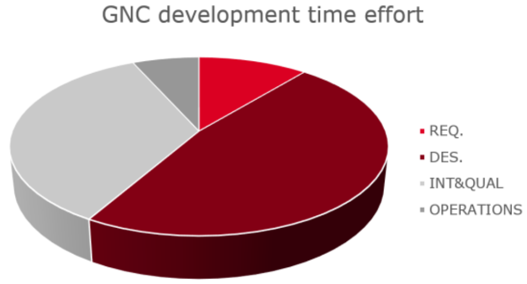


Figure 2-1 Allocation of the time effort among phases during a GNC development

2.2. Proposed Improvement Areas

IA-1	Improve task automation for the GNC mission configuration and V&V (MBSE approach)
IA-2	Improve the processes for the GNC mission configuration and V&V (MBSE approach)
IA-3	Application of adaptive guidance schemes that by design adapt to different missions and payloads
IA-4	Application of robust control techniques that by design adapt to different missions and payloads

IA-1: The tools compared were FRET, ReqView, STIMULUS, CoCoSim, MATLAB Simulink, Scade, VEMIPRO prototype. The features assessed were such as: Interoperability, Traceability, Reuse, Configuration management, Document generation, Requirement management. The following MathWorks toolboxes were analysed: Requirements Toolbox, Simulink Test, MATLAB Report Generator, System Composer. From here the implementation plan consisted of: Using MATLAB/Simulink, with Requirements Toolbox and Report Generator; Extending VEMIPRO Missionization Tool prototype; Leveraging Data Dictionaries.

IA-2: The Flow for the GNC Final Studies and Mission Data generation Process was critically revisited. The trade-off was partially based on a brainstorm performed to assess the critical parts of the classical GNC preparation process. The main points extracted by this brainstorming are e.g.:

- Integration of several steps into a single one.
- Capability to avoid steps of the classical approach.
- Feedback from previous missions is in the pipeline.
- Easier requirements management.
- Lighter MC campaigns.

The GNC Re-Missionization improved workflow shows how the classical GNC missionization process has been challenged to improve its flexibility. One of the most important points analysed was the differentiation between a change in mission parameters that it is within the validated domain of the GNC domain, one that is slightly outside of it and one that it is considerably far out. Based on that, the user can avoid some of the steps using the reconfiguration capabilities (ADAGUI and Robust Control).

IA-3: Advantages and disadvantages of guidance methods were evaluated: Open-Loop Guidance, Explicit Methods (Convex.), and Implicit Methods (Pontryagin) were compared in terms of e.g.: Computational Requirements, Closed-loop feedback, Thrust Control Effort, Trajectory Design Effort, Previous Mission Reusability, Launcher Performance, MECO discontinuity. The work of implementing the adaptive guidance algorithm was broken down in:

- ADAGUI software adaptation to a generic two-stage-to-orbit launcher;
- Generation of guidance initial guess in open loop for the benchmark scenarios;

- Simulink implementation to study the closed-loop performance of the algorithm;
- MC campaign to check robustness against uncertainties in mass/inertia/thrust/aerodynamics.

The main objective of this improvement area is to shorten the V&V missionization process and reduce costs by having an adaptive guidance algorithm that can handle small changes from a reference mission, like payload mass, without the need of repeating the verification or the tuning process.

IA-4: The trade-off analysis and implementation plan for the improvement area 4 aimed to explore the use of advanced control techniques that guarantee by design the robustness to system uncertainties and provide a design framework that can be formulated to cover multiple missions. Structured $\mathcal{H}_\infty$ and Full-order LPV synthesis were analysed for advantages and disadvantages. The following generic implementation plan was set:

Tasks	Description
First mission	a) LFT modelling for the first mission b) Preliminary design at max $Q\alpha$ c) Design full TVC control system for the ascent-atmospheric flight d) Implement/evaluate vertex cases to assess performance of the 1st TVC design
Delta mission(s)	a) LFT modelling for the second mission b) Preliminary design at max $Q\alpha$ c) Design full TVC control system for the ascent-atmospheric flight d) Implement/evaluate same vertex cases to assess performance of the 2nd TVC design
Across missions	a) Compare LFT models and controllers for the missions b) Find commonalities and differences across the missions

Advanced Guidance and *Advanced Control effects* were considered against a Traditional G&C design. Its design was broken down in: *LFT modelling of the launcher system; Problem formulation; Rigid-body control design; Joint rigid-body controller and bending filter design; Robust control analysis*.

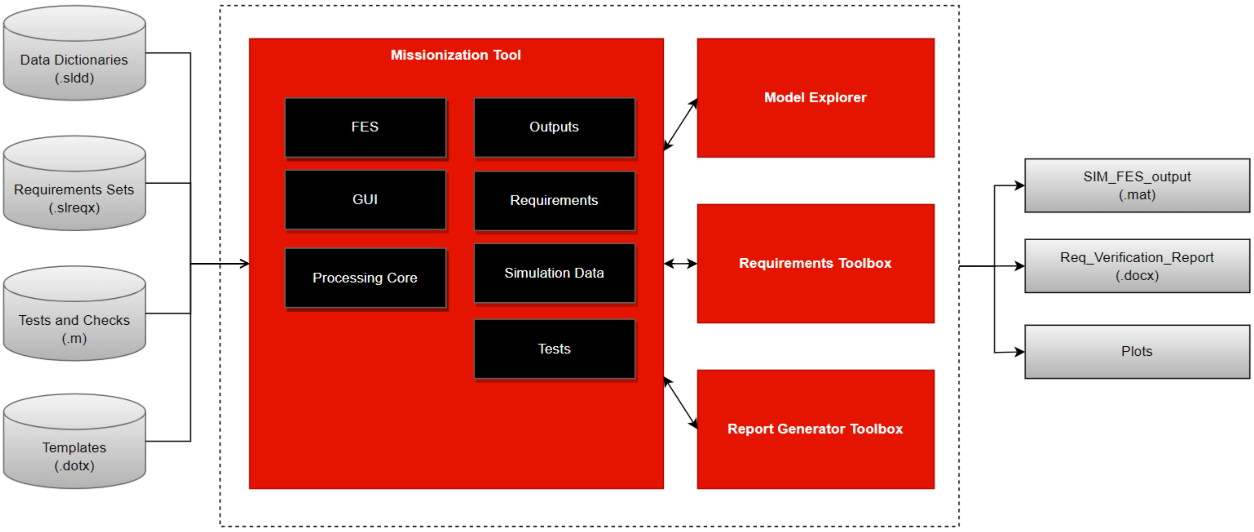
2.3. USE CASE DEFINITION

Launch scenarios may vary due to different reasons. As an example, changes in wind profile, launch date or launch sites may occur. Due to these variations, defined here as deltas, the GNC analysis can require modifications to comply again with the mission. Thus, use cases that highlight the improvements were defined and their impact in GNC was explained. Impacts were analysed for: *Trajectory*, *Adaptive Guidance*, *Robust Control*, *V&V*.

Use case #1 Launch window shift	Wind profile change
Use case #2 Commercial changes	Payload mass change *System level interactions: Trajectory*
Use case #3 Different launcher instance	Slight thrust level variation w.r.t. nominal *System level interactions: Trajectory, Propulsion*
Use case #4 Launch sites	Launch site coordinates *System level interactions: Trajectory*

2.4. DESIGN AND IMPLEMENTATION OF THE ADOPTED ALGORITHMS

Missionization Tool: The improved Missionization Tool serves as a centralized management tool for mission data, with a focus on the launcher scenario. Its purpose is to streamline the missionization process by providing configuration control, automated data checks, report generation capabilities, and simulation test execution. The tool features an improved GUI divided into four main menus: *Mission Data Repository, Tests, Requirements, and Outputs*.

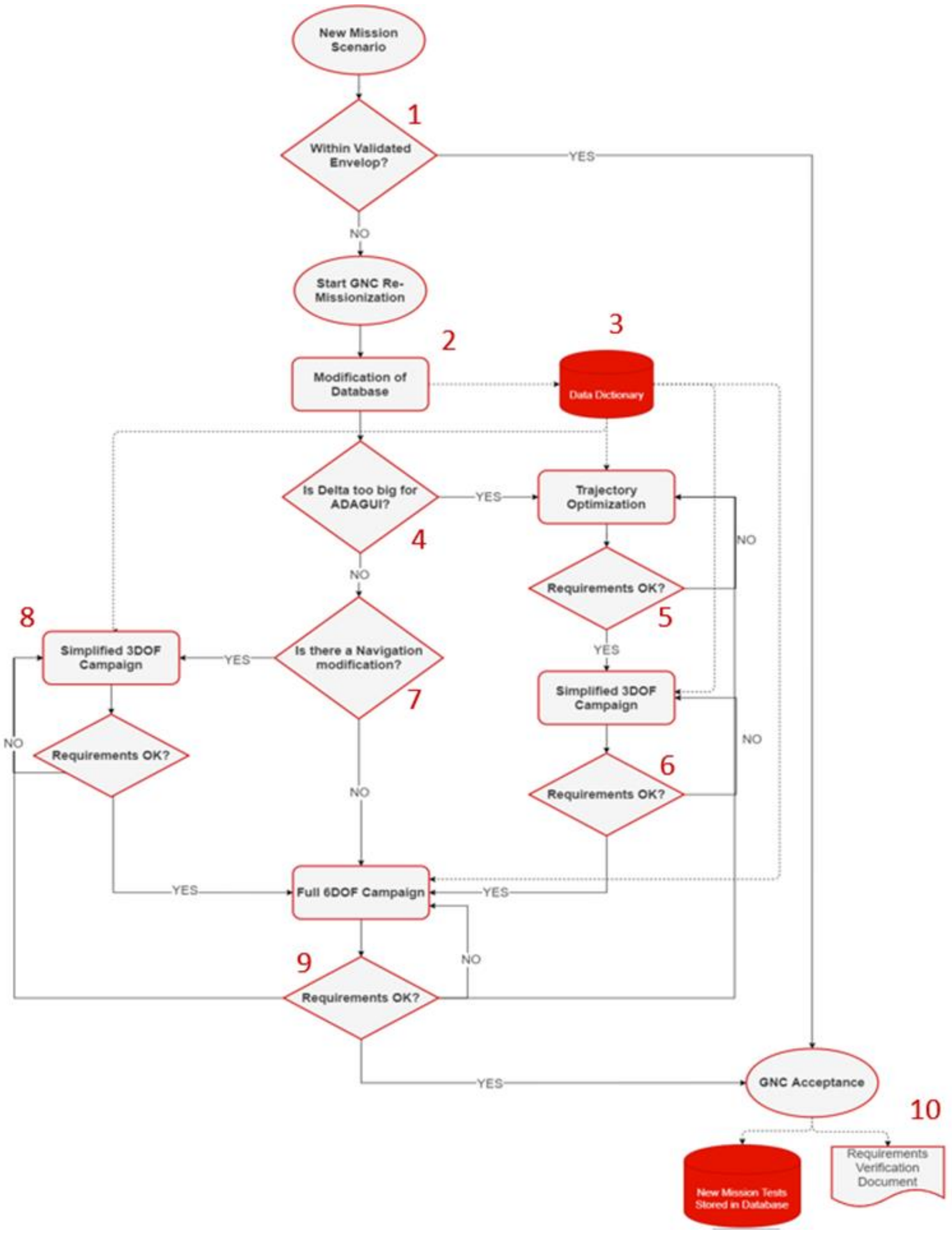


Data Dictionaries (DD): Due to their advantages related with e.g. - *Model Linkage, Version Control, Entry comparison, Data grouping, Unified Interface, and Connectivity with MathWorks Toolboxes* - it was decided to base the infrastructure in DDs. The connection with the rest of the toolboxes can be done with a relative low effort as DDs are a standard MathWorks feature.

Process Improvement: The improved missionization process was detailed for its ability to support:

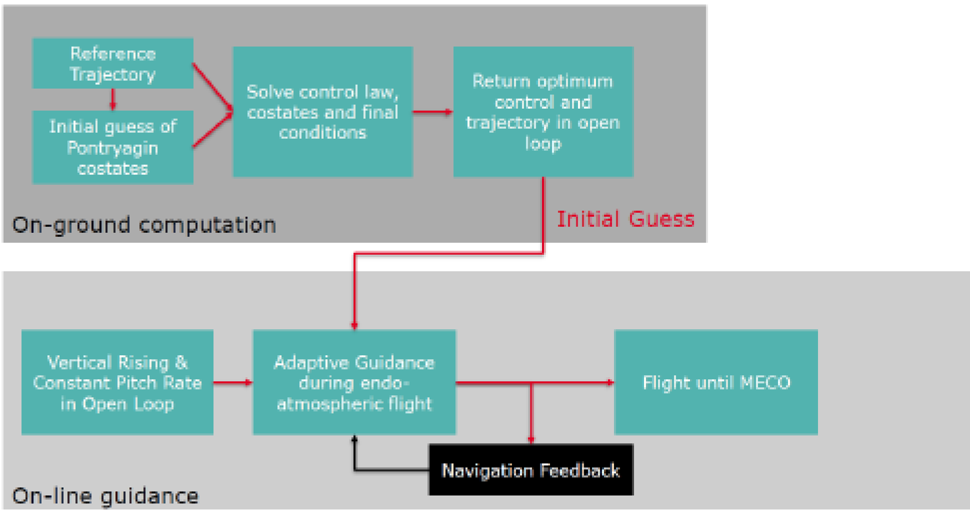
- Depending on the use case, the steps to follow differ because changes affect the reconfiguration functions differently. E.g., it is not the same to change the wind profile than to change the launch site, in terms of the guidance and control algorithms. Small changes can be absorbed by the algorithms without implying any tunning or modification on them;
- Thanks to the implementation of the Adaptive Guidance, the Trajectory Optimization step is no longer compulsory so, depending on the new mission, it is possible to skip this step;
- There are not two different simulators, one for 3DOF and one for 6DOF. The same simulator is being used for running both kind of simulations so that the simplicity of the repository is benefited;
- The integration of ADAGUI also allows to, in some cases, skip the 3DOF analysis and go directly into the 6DOF simulations, cutting off much time;
- It is important to say that this process and also the one for the 3DOF validation, is iterative;

Note that a GNC expert with knowledge on the Guidance and Controller capabilities will always be a critical asset. The new tool integrates all the important parts of the process into the same environment. The user can manage the data of the Use Case using the Data Dictionaries, to run simulations using the FES as well as tune the algorithm or make changes to the models directly or she is also able to verify the requirements in an easy and quick way.



Adaptive Guidance: The adaptive guidance algorithm allows to reconfigure a previously existing trajectory according to the current conditions. It offers these advantages over the traditional methods:

- Creating trajectories by modifying data of previous ones and the deltas. This speeds the process by automatizing the new scenario instead of requiring iterations and engineering effort.
- It can expand the conditions at which the launcher can fly, it can reduce risks and launching costs by reducing the abort condition caused by GNC.
- Having diverse flying conditions implies having more launch windows. Thus, launch services can occur more often, satisfying the expected growth required by future demands from the market.

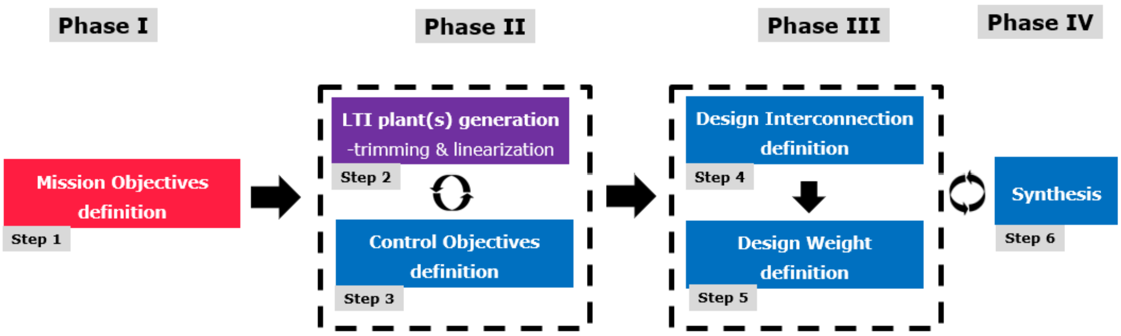


During the detailed design task, several improvements were introduced in the ADAGUI software:

- Guidance algorithm has been generalized and fully integrated in simulators 3 and 6 DOF.
- Wind models and turbulence incorporated.
- Code has been optimized, considerably cutting down execution time.
- Navigation performance model and control component integrated with guidance.

The SW addressed *Open Loop Vertical Rising, Reference Position/Velocity, Guidance-Control integration*.

Adaptive Control: Describes the synthesis framework capable of performing jointly the design of the rigid-body controller and bending filter for the ascent-atmospheric flight. The stability of the proposed control solution was first analysed via classical stability analysis and then via the structured singular value μ approach. An evaluation of the main performance metrics of the launcher system during the atmospheric-ascent flight was done. Finally, analyses were carried out on the robustness of the controller against last minute payload mass changes.



2.5. ASSESSMENT OF THE SOLUTIONS OF THE IMPROVEMENT AREAS

The focus was on the use cases in which Adaptive Guidance and Control were tested. The aim was to compare the traditional guidance methods with Adaptive Guidance, in 3DOF and 6DOF. Based on results obtained from the single run tests and the Montecarlo analysis, the process was discussed. The tool potentially improves the complete missionization process and steps can be skipped depending on the deltas.

Montecarlo campaigns were run to show how ADAGUI behaves when more uncertainties are introduced in the simulation. Regarding ADAGUI implementations, there is no clear advantage of one against the other. ADAGUI with drift shows lower Q alpha figures but larger TVC efforts than ADAGUI without drift. Thus, the decision of implementing ADAGUI depends on the circumstances.

- If ADAGUI is implemented in the missionization, and the deltas are known before launch, a change in wind, payload mass and thrust can be simulated in the 6DOF scenario directly without the need for the trajectory optimization and 3DOF.
- Having implemented the control, it is seen that in general the 3DOF simulation can be skipped and run directly the 6DOF simulation. Only in the case that the 6DOF fails, then performing the 3DOF to check if the failure comes from the guidance or the control.
- Trajectory optimization is required if the launch site is changed, in the case that the original launch site and the new one has a difference in latitude larger than 2.5 deg. Launch site longitude does not affect the process.

2.6. ROADMAP FOR FUTURE WORK

Control related:

- Robust Modelling: It will be interesting, and it is thought of possible, to try automating both the selection of parameters to include uncertainty as well as the uncertainty model.
- Robust Control: A potentially semi-automated process can be envisioned that allows the designer to automatically obtain an optimal controller for a given plant.
- Robust Analysis: Automate for (i) selection of plant and ranges of the uncertainty and (ii) selection of analysis options in terms of classical gain/phase margins or robust stability/performance.

Guidance related:

- Complete implementation in a software tool for automatic trajectory computation and validation in the mission design process: Definition of inputs and outputs for the final user; Creation of interaction interface with the user.
- ADAGUI implementation in an onboard computer and its preparation for flight software e.g.: Adaptation to be compatible with a real navigation and control; Definition to consider more path constraints; Implementation in the onboard computer; Exploration the trust region.

GUI and tool related:

User Guidance	Implementing more tooltips or even a guided tour within the GUI to provide information about the various functionalities.
Real-time Feedback	Enhancing the GUI to display real-time progress indicators during lengthy operations like test execution.
Error Handling and Reporting	Strengthen the error-handling mechanism by providing more descriptive error messages.
Responsive Design for Devices	Ensure that the GUI is responsive and adaptable to various screen sizes.
Interaction with Tools	Enhance the GUI tool's capabilities for interaction with Simulink.
Accessibility and Usability	Incorporate accessibility features into the GUI design to ensure it is usable by individuals with disabilities.
Extend Toolbox support	Start the design phase of the GNC using System Composer and Simulink Test on top of the other toolboxes already used.

3. CONCLUSIONS

PROCESS AUTOMATION

The testing activities verified that the Missionization Tool performed as intended, effectively managing mission data, ensuring traceability and compliance with requirements, executing tests for GNC system performance, and generating necessary reports and plots.

ADAPTIVE GUIDANCE (not exhaustive)

- The Open Loop guidance is more sensitive to changes than ADAGUI with respect to the nominal values, especially in the Q alpha constraint.
- Payload mass must have at least 50% change with respect to the nominal value to modify the dynamics of the 1st stage.
- Open Loop guidance cannot recover from a thrust reduction, based on the Q alpha limitation. ADAGUI can, at the cost of not reaching MECO height and a reduced delta v.
- There is a significant difference between ADAGUI with drift and without drift in the TVC effort, clearly seen in the Use Case 1 Wind, but the remaining cases show similar figures of merit.
- The Open Loop guidance is very sensitive to uncertainties during the flight.
- When comparing ADAGUI feeding drift to the control or not, it was seen a slight improvement when the feed was active in terms of the Q alpha
- For the trajectory generation, ADAGUI reduces the time required by this task by implementing it to recompute the endo-atmospheric flight part.

In this work, it is seen that ADAGUI is more robust than the traditional methods when the dispersion is applied in wind and turbulence profiles, mass and inertia, and thrust.

ADAPTIVE CONTROL

A full process automation is neither possible nor warranted since a tool will not be able to substitute the accumulated knowledge of an expert designer nor be capable of encompassing generally the differences between launchers. There are parts of the design process that can be semi-automated to reduce the time and effort. With respect to control synthesis, what was demonstrated is that a general synthesis interconnection can be set-up, augmented and the robust synthesis quickly yielded improved controllers once the designer has tuned objectives.

- Decision was made to focus on the structured-Hinfinity from the traditional approach (i.e., a rigid, point-at-a-time design with a PID architecture) to more advanced ones (full-structure or augmented and joint rigid-flexible).
- It was shown that a control designer can effectively use the robust structured-Hinfinity to incrementally obtain a full valid design.

IAS IMPACT (not exhaustive)

- Ease iterations between steps, assuring consistency.
- Accelerate the transition from each step to the next.
- Minimize the need for retuning of the G&C algorithms.
- Going directly to the 6DOF analysis drastically reduces the time. However, as guidance and control are tested together, in case of non-compliance, the re-tuning time could be higher.
- For 3DOF step: cuts the necessity for MC Campaign that is the most time-consuming activity.
- Trajectory Optimization step: only used if the scenario modifications are very drastic.
- DDs interconnecting all the steps, requirement validation, documentation generation, reducing the time for tasks not directly related with the algorithms.

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