2024 European Control Conference (ECC)
June 25-28, 2024. Stockholm, Sweden

Advanced GNC Technology for Inflatable Heat Shields: preliminary design

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***Abstract*— This paper aims to describe and provide a preliminary assessment of Guidance, Navigation, and Control (GNC) technologies for a re-entry system with an Inflatable Heat Shield (IHS), within the scope of the EFESTO2 project funded by the European Commission (EC). The work performed is focused on the development of i) a novel closed-loop guidance approach, ii) a hybrid navigation subsystem based on a Consider Extended Kalman Filter (CEKF), and iii) a controller designed accounting for robustness and performance goals. The objective of the GNC is set to initial re-entry dispersion of the vehicle, to allow for an easier and less costly a Mid-Air Retrieval (MAR).**

I. INTRODUCTION

RE-ENTRY vehicles are critical elements in space missions that require bringing a payload from space to ground on a planetary body with an atmosphere. The hypersonic conditions in a dense atmosphere generate a plasma flow-field around the entry vehicle resulting in extreme thermal heat fluxes and thermal heat loads. One of the key design parameters driving the conditions experienced by the re-entry vehicles is the ballistic coefficient, inversely proportional to the drag area and drag coefficient, that governs the deceleration profile as a vehicle descends through the atmosphere. In order to have higher levels of deceleration, the ballistic coefficient should be as small as possible, which results in larger drag area and drag coefficient. Current planetary entry systems use rigid heavy heat shields designed to provide re-entry vehicles with enough drag and stability while keeping the heat fluxes within the available materials limit. However, they are constrained in size and mass to fit within the launcher fairing volume, which could yield a high ballistic coefficient. For these reasons, innovative Inflatable Heat Shield (IHS) solutions are needed to break the current design limits and extend the applicability range. Due to their ability to be folded during launch, they allow to achieve lower entry ballistic coefficient and larger entry mass. The aim of this work is to present an innovative GNC technology design for a re-entry application of Earth, which could allow to increase the knowledge about this new re-entry solution and be used for Mars application in the future.

II. PROBLEM FORMULATION

Typically, re-entry systems are affected by non-negligible uncertainties during de-orbit that cause a dispersion at the Entry Interface Point with the Earth's atmosphere (EIP) in the order of hundreds of kilometers. This dispersion is directly impacting the capability of the re-entry system to reach a precise location at the end of the mission. In the case of the present project, the reference Concept of Operations (ConOps) is designed to end with a Mid-Air Retrieval (MAR) after a parachuted phase, hence implying a great uncertainty on the location where the MAR will be carried out. If the Parachute Target Area (PTA) is bigger than capture helicopter's range, then it will be necessary to have more than one helicopter available, thus substantially increasing the costs and complexity of the operation. In this scenario, the implementation of a GNC capability on board the re-entry system is of paramount importance to solve the great dispersion issue and comply with the objective to deliver the vehicle to a target point with a sufficient accuracy to allow for helicopter(s) to execute the MAR in compliance with their range limitations. This need can be satisfied through the implementation of a GNC algorithm which allows to actively control/plan the down-range and cross-range.. The control means adopted to carry out those functions are Mass Control System (MCS) or Centre of Gravity (COG) offset system, Reaction Control System (RCS), Aerodynamic Control System (ACS), and Shape Morphing System (SMS).

A. *Vehicle*

In the context of this work, a trade-off analysis has been performed among the possible actuator solutions. As result of the trade-off analysis, the final solution consists in the use of RCS and MCS devices. These options demonstrated their strength across a range of criteria i.e., system complexity, weight and volume, maturity, accuracy, robustness, and others, aligning well with the mission's goals. A sketch of the final re-entry system configuration is presented in Fig.1. The group of sensors is composed by an Inertial Measurement Unit (IMU) and Global Navigation Satellite System (GNSS) [1].

Manuscript submitted on February 15, 2023. This work is part of the EFESTO2 project that has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101081104.

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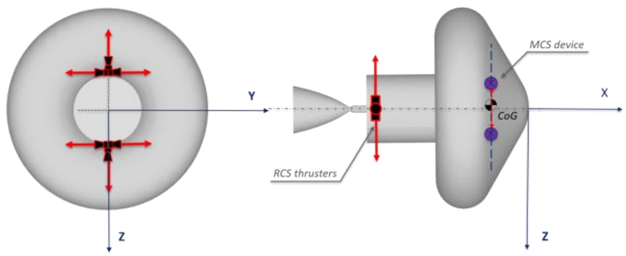

Fig.1. System configuration with RCS and MCS

III. METHODOLOGY

The design and development of a guidance, navigation and control system for re-entry vehicles has peculiarities and criticalities. From a *guidance* perspective, the objective is to compensate for the trajectory dispersions by providing the necessary attitude commands for the controller to track. It must be remarked that the considered re-entry capsule shape has a low L/D, meaning that the possible compensations are reduced. Furthermore, a re-entry trajectory imposes several constraints that the guidance system must respect in order to successfully complete the mission (e.g., heat loads, load factors). Several entry guidance algorithms are found in literature. For entry flight of vehicles with medium to higher L/D ratios, the Shuttle approach is still prevalent [3]. On the other hand, for low lifting vehicles, the predictor-corrector algorithm [4] becomes a popular choice. In this work, a high-level trade-off among the different possibilities has been performed. An NDI (Non-linear Dynamic Inversion) trajectory tracker algorithm was implemented as a first benchmark solution; however, a numerical predictor-corrector algorithm has also been implemented for sake of comparison analysis. The goal of the *navigation* function is to provide accurate and smooth estimates of the vehicle state fusing the available information from the different sensors. It must be ensured that the sensor uncertainties (i.e. sensor biases, misalignments) do not result in estimation accuracies non-compliant with the mission requirements. The baseline approach for the navigation solution in this work involves both attitude and translational states, using a coupled system, in which the Inertial Navigation System (INS) solution is hybridized with the observations provided by the GNSS receiver through an CEKF, which considers the effect of parameter uncertainty in the sensor models. Lastly, the *control* function is responsible for taking the guidance and navigation outputs and generating the actuator commands. The controller gains are generally chosen by analyzing the linear closed-loop behavior of the system. The main challenge is to ensure that the system has an adequate closed-loop behavior in order to meet mission requirements taking into account the significant uncertainties, especially on the knowledge of aerodynamics. In more detail, it is foreseen that the controller will have the following features: 1) Structured H-infinity with guarantees over the robust performance of the closed-loop system. 2) Decoupled control for longitudinal and lateral channels through RCS and MCS commands. 3) Gain scheduling along the trajectory, if needed, to tackle differing operating conditions and changes in the aerodynamic properties.

For a given set of initial conditions, the mission and range capability analysis can provide a possible feasible corridor that can be pathed by respecting the constraints imposed by the requirements. This allows the identification of a reference guided trajectory which presents a bank reversal maneuver, as shown in Fig 2.

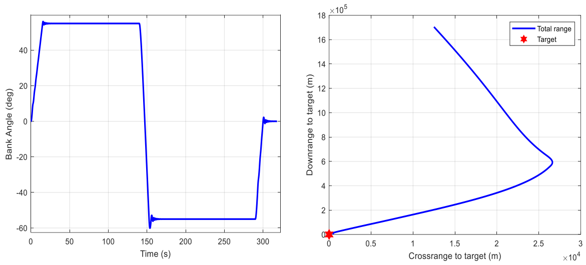

Fig.2. Reference trajectory in terms of bank profile (left) and latitude and longitude (right)

The reference trajectory is used for the implementation of the preliminary NDI guidance. The guidance algorithm exploits the inversion of aerodynamic laws to trace back from the state of the aircraft to its position. In this way a comparison with a reference value of dynamics, either rotational or translational, is made and the deviation between the two (actual and desired) is returned in the form of feedback within the simulation. Nevertheless, for the preliminary full GNC, an open loop guidance is adopted, providing the commanded aerodynamic angles. To follow the guidance commands, an attitude controller is needed to compensate for modeling errors and external disturbances such as wind. Preliminary results using ideal navigation show the possibility of addressing the problem with simple PID controllers. Namely, three independent PID-controllers which determine torques around the main body axis. Currently, the PID-controllers are being manually tuned but a structured H-infinity approach is being considered to validate this approach and provide more.

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