Flight Dynamics and Control Challenges of Hypersonic Glide Vehicles: A Case Study on the GHGV-2

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Abstract The Generic Hypersonic Glide Vehicle 2 (GHGV-2), developed at the German Aerospace Center (DLR), provides a reference platform for analyzing the physical and technical capabilities of hypersonic glide vehicles. The vehicle exhibits several interrelated challenges, including unstable modes, rapidly varying operating conditions, strict state constraints, and actuator redundancy with asymmetric and state-dependent limitations. This work introduces the GHGV-2 configuration and mission profile, and systematically reviews the principal control challenges that have been identified. Potential solution strategies, such as nonlinear inversion with incremental and adaptive extensions, advanced constraint-aware allocation, and safety-critical methods based on control barrier functions, are discussed in the context of current research. In this way, the study provides a structured perspective that links the challenges of GHGV-2 to ongoing developments in hypersonic flight dynamics and control.

Introduction

Hypersonic vehicles, typically defined as systems operating above Mach 5, have become a focal point of current aerospace research due to their strategic potential. Their combination of high speed, maneuverability, and relatively low altitude flight compared to classical ballistic missile systems makes them particularly attractive in the defense sector, as it complicates detection and interception. Two main concepts dominate current developments: boost-glide systems, which execute a sustained atmospheric glide after a boost phase, and air-breathing cruise systems, which rely on advanced propulsion. While significant progress has been made, and some nations claim to posses operational HGVs, the technology cannot yet be considered fully mastered. There is no established design framework that guarantees robust performance across missions, and many critical aspects of flight dynamics and control remain only partially addressed in the open literature.

Control design for hypersonic systems is complicated by unstable open-loop dynamics and rapid changes in operating conditions [1]. In addition, actuator limitations, aerodynamic heating, and constraints on angle of attack, load factor, and altitude pose additional challenges to the controller [2]. Classical design methods often prove inadequate, and solutions shared within the research community remain fragmented. Investigations in programs such as NASA's X-43 and DARPA's

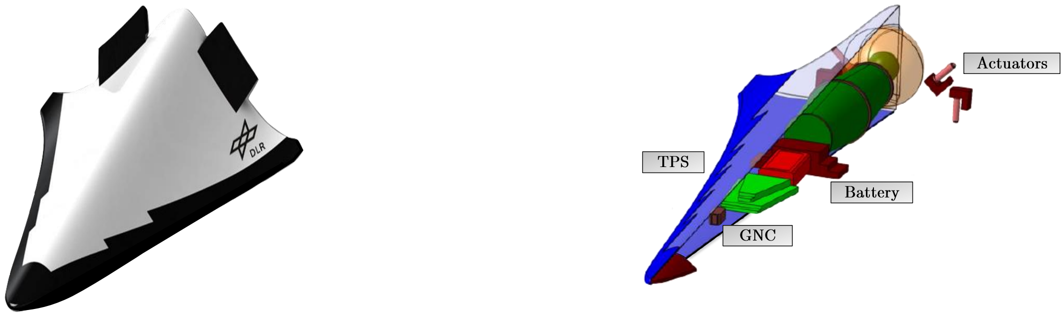
HTV-2 have underlined the importance of accurate modeling and robust control, with early flight failures highlighting the intrinsic difficulty of the problem [3].

To study these challenges systematically, the German Aerospace Center (DLR) has developed the Generic Hypersonic Glide Vehicle 2 (GHGV-2) [4]. The vehicle provides a controlled research platform to investigate critical aspects of guidance and control under representative mission profiles. During the GHGV-2 studies, a number of specific issues have been identified, including unstable open-loop dynamics, broad flight envelope requirements, actuator redundancy with state-dependent asymmetric limits, and strict operating point-dependent state constraints. While some of these have been addressed in earlier work by other researchers, others remain largely unexplored.

This work provides a concise overview of the GHGV-2 concept and highlights the key flight dynamic and control challenges identified within the program. Additionally, it examines how these challenges relate to approaches proposed by the broader hypersonic research community and how novel methods are being developed to address them within GHGV-2.

The DLR GHGV-2 Concept

DLR has developed the GHGV-2 as a reference configuration for research on guidance and control of hypersonic systems and to study their operational implications [5]. The vehicle is shown in Fig. 1 in external and sectional views, including subsystems such as the thermal protection system (TPS), guidance, navigation & control (GNC), battery, and actuators. It is designed as a waverider concept optimized for high lift-to-drag ratios at hypersonic speeds [4]. In the endoatmospheric regime, attitude control is provided by four aerodynamic flaps; in the exoatmospheric regime, small propulsors are used. With multiple redundant effectors in both phases, the vehicle is considered overactuated, requiring modern control allocation methods.



(a) External view

(b) Sectional view

Figure 1: The DLR generic hypersonic glide vehicle 2 (GHGV-2) [4].

Figure 2 compares the trajectory of a classical ballistic missile with that of an HGV. After boost and separation at around 100 km altitude, the GHGV-2 re-enters earlier and transitions into a long atmospheric glide at about 40 km of altitude. Compared to ballistic systems, such a vehicle's flight trajectory reduces radar detection range and increases maneuverability, making interception and prediction more challenging.

The overall GNC architecture of GHGV-2 is shown in Fig. 3. Precomputed trajectories, obtained through optimization, respect both physical and operational constraints. A trajectory-tracking layer generates flight path angle commands, which are converted by a nonlinear dynamic inversion (NDI)–based controller into aerodynamic angle demands. These are then passed to the nonlinear attitude control and control allocation modules, which together produce the actuator commands. The present work concentrates on the nonlinear attitude control and control allocation layers, where the main flight dynamic challenges arise, while the insights can, to some extent, be generalized to

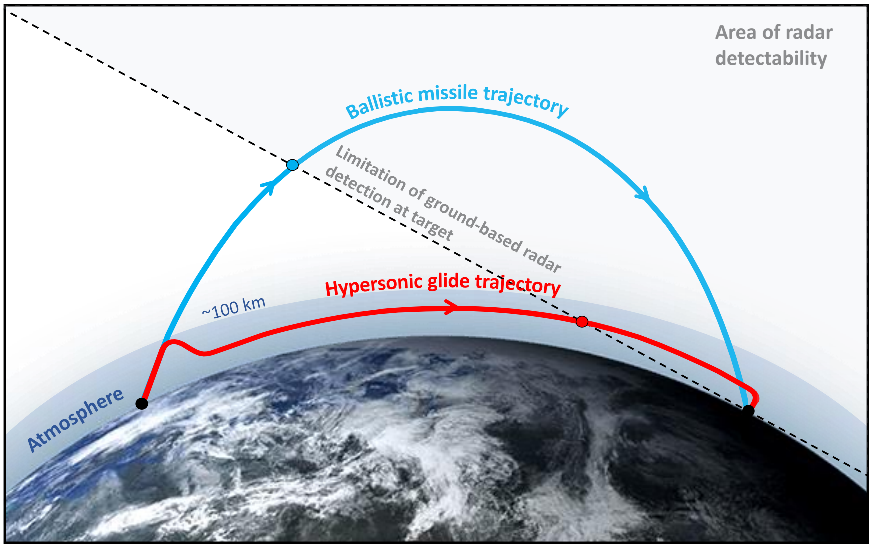


Figure 2: Comparison of ballistic missile and HGV trajectories during an exemplary mission [5].

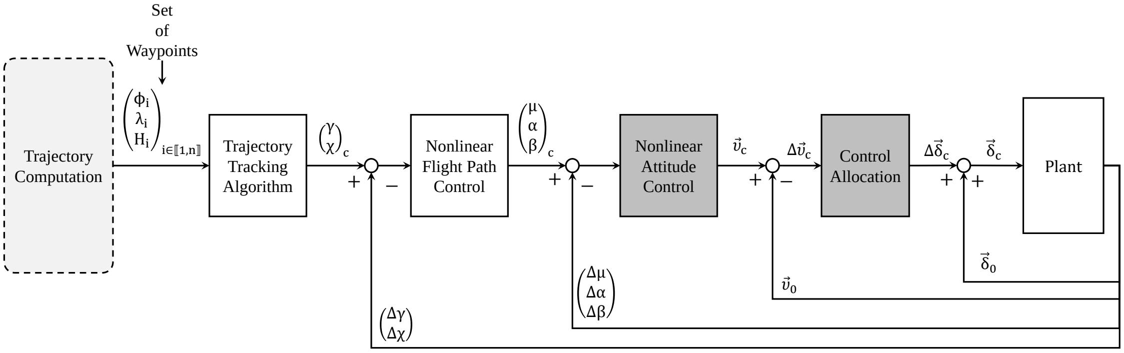


Figure 3: Conceptual guidance and control architecture of GHGV-2 [6].

the guidance layers as well.

Challenges in Flight Dynamics and Control of the GHGV-2

Researchers in [7, 8] observed that hypersonic waverider configurations tend to exhibit unstable open-loop behavior in both longitudinal and lateral-directional motion. This can also be confirmed for the GHGV-2. Eigenvalue analyses for different operating points, confirms that the GHGV-2 is longitudinally statically unstable and laterally dynamically unstable (Dutch roll). Such instability significantly complicates controller synthesis: the system must not only achieve accurate reference tracking, but also ensure stabilization of the unstable modes across a wide range of operating conditions.

To address this, nonlinear control methodologies have been investigated. A nonlinear dynamic inversion (NDI)–based feedback controller was first applied [9, 10]. NDI facilitates intuitive design and shows excellent performance for the nominal model, as well as acceptable robustness against bounded parameter deviations. However, the reliance of NDI on precise model inversion makes it sensitive to bigger model uncertainties and inversion errors, potentially leading to closed-loop instability [11].

An extension of NDI is incremental NDI (INDI), which substitutes parts of the needed model information with sensor measurements. INDI improves robustness but is sensitive to sensor quality

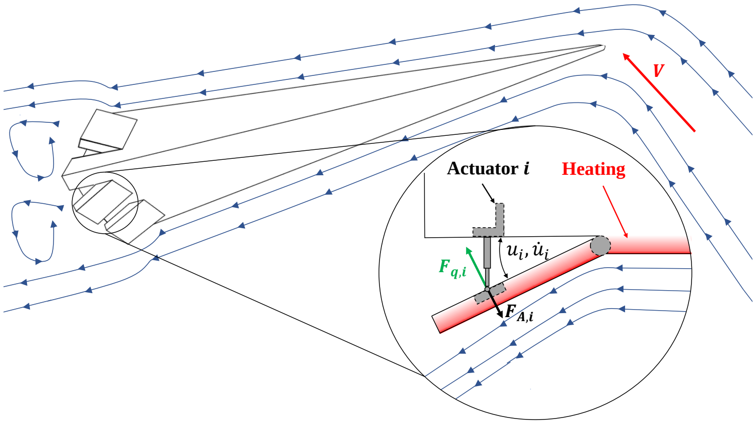


Figure 4: Overactuated hypersonic glide vehicle during high-speed atmospheric operations with high dynamic pressure and thermal loads [16].

and, for GHGV-2, is hampered by the absence of direct angular acceleration measurements. A hybrid INDI (HINDI) approach that fuses model knowledge with sensor information from a gyroscope, and with that allows for the estimation of the angular acceleration, was therefore applied [6]. HINDI demonstrated good tracking and robustness in both nominal and uncertain cases, even with sensor and time-delay effects included. Nevertheless, its robustness is limited: only uncertainties in unforced dynamics can be compensated, while uncertainties in control effectiveness remain unaddressed [12]. To overcome this, adaptive control is considered. Adaptive methods adjust parameters online to cope with unknown or time-varying uncertainties and have been successfully applied to hypersonic vehicles [13, 14]. Hybrid robust-adaptive frameworks [15] appear particularly promising, and nonlinear adaptive control is currently under investigation for GHGV-2, with results to be reported in future work.

A further challenge arises from actuator redundancy and physical limitations that are rarely discussed in detail for hypersonic systems. The GHGV-2 employs four aerodynamic flaps for attitude control, forming the control input vector

$$u = \begin{bmatrix} u_1 & u_2 & u_3 & u_4 \end{bmatrix}^{\mathrm{T}}, \tag{1}$$

where u_i denotes the deflection of the i-th surface. The vehicle is therefore overactuated; however, in contrast to conventional aircraft, the control surfaces are subject to asymmetric magnitude and rate limits, as well as state-dependent restrictions. These constraints, to the best of our knowledge, have not yet been systematically incorporated into control allocation methods for hypersonic glide vehicles.

As illustrated in Fig. 4, high dynamic pressure generates significant counterforces on the actuators, while aerodynamic heating introduces asymmetric constraints on the upper and lower control surfaces. Minimizing thermal loads is crucial to protect the thermal protection system and reduce the vehicle's infrared signature. Together, these effects make the control allocation problem fundamentally more complex than for conventional aircraft. Classical pseudoinverse allocation often fails under such conditions; redistributed versions improve feasibility but remain suboptimal [17]. Optimization-based approaches, such as quadratic programming, handle constraints effectively [18], but their computational cost prevents straightforward real-time implementation.

To overcome this, a two-layer allocation strategy was developed for the GHGV-2 [16, 19]. First, an offline optimization computes baseline control inputs $u_r(t)$ along the nominal reference trajectory, accounting for all known actuator and thermal constraints using a quadratic program-based solver. These baseline inputs are stored in lookup tables. During flight, an iterative online algorithm

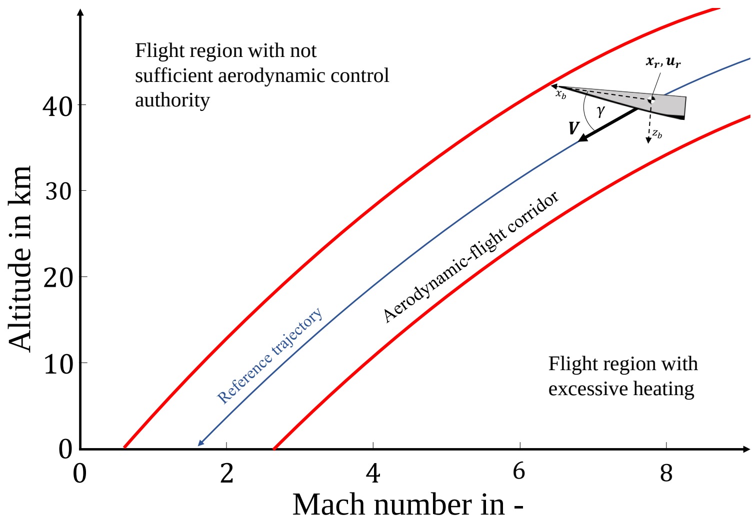


Figure 5: Operational flight corridor and reference trajectory for the GHGV-2 in Mach–altitude space [16].

determines only the corrective deviation command $\Delta u(t)$ by searching the attainable moment set (AMS). The final input is

$$u(t) = u_r(t) + \Delta u(t), \tag{2}$$

ensuring feasibility while minimizing the deviation from the commanded virtual control input. The approach converges rapidly, has been shown to be real-time capable, and compares favorably to classical control allocation methods.

Finally, strict state constraints must be enforced to ensure safe operation of the GHGV-2 during atmospheric flight. The vehicle must remain within a narrow flight corridor (Fig. 5), bounded above by loss of controllability and below by excessive heating. Similarly, the vehicle must respect aerodynamic load factor limits, typically visualized in V–n diagrams (Fig. 6), where aerodynamic and structural limitations define flight speed-dependent upper and lower load factor bounds. All the discussed constraints together define the operational flight envelope, within which controllability and structural integrity can be maintained.

To satisfy these requirements for the GHGV-2, reference trajectories are precomputed offline, ensuring they remain within the admissible domain. However, offline design alone cannot guarantee constraint satisfaction in flight, since disturbances and model uncertainties may cause the trajectory to drift outside the corridor or exceed load and angle-of-attack limits. An additional online safeguard is therefore essential to enforce these constraints during execution.

Classical approaches, such as reference filtering or command limiting, can restrict control commands to stay within bounds but provide no formal guarantees under uncertainties [20]. More advanced safety-critical control methods have been proposed, in particular control barrier functions (CBFs) and barrier Lyapunov functions (BLFs), which encode constraints as forward-invariant sets [21, 22]. While BLFs can enforce constraints, they often generate extensive control inputs near boundaries [23], making them less attractive for hypersonic applications. CBFs provide a more flexible framework, and hence, it was decided to investigate this methodology in the context of hypersonic applications. Despite the benefits, practical issues remain, including the need for robust CBF formulations that can account for actuator saturation and model uncertainty effects [24, 25].

For the GHGV-2, CBF-based safety filters are being integrated to enforce the invariance of critical state constraints—flight corridor boundaries, aerodynamic load limits, and angle-of-attack

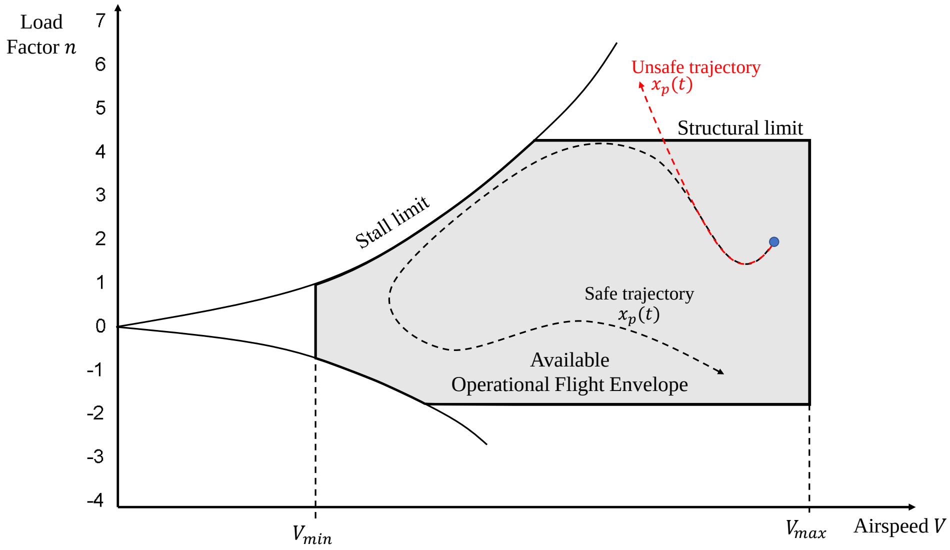


Figure 6: Example of a V–n diagram illustrating aerodynamic load factor limits as a function of airspeed.

constraints—in real-time. To address the issue of model dependency mentioned, the CBF framework was extended to incorporate adaptive control, compensating for uncertainties to ensure both safety and robustness in practical implementations. Preliminary studies on simplified models have shown promising results, and ongoing work focuses on extending these methods to the full nonlinear flight vehicle models with uncertainties and input limits [26, 27, 28, 29].

Conclusions

The GHGV-2 serves as a representative platform for studying the guidance and control of hypersonic glide vehicles, where unstable dynamics, broad operating envelopes, actuator redundancy with asymmetric limits, and strict state constraints create a highly challenging control problem. Within the program, nonlinear inversion with incremental and adaptive extensions, novel allocation strategies for state- and thermally-dependent actuator limits, and safety filters based on control barrier functions have been developed and assessed. These efforts demonstrate the need for integrated architectures that jointly address uncertainty, overactuation, and safety, and they provide a foundation for future work on real-time implementation and validation in realistic mission scenarios.

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