Summary

There are many different types of advanced concepts for rocket engines relating to propulsion, control, reusability. The following concepts were investigated by the author, and the results are presented in this dissertation:

- combustion chamber Hartmann–Sprenger resonance tube-based acoustic igniter for mission profiles requiring multiple ignitions: characterization of thermoacoustic effects and flow characteristics;
- dual-bell shaped nozzles for space launchers with fluidic control of transition: characterization and design;
- thruster-plume induced contamination control for powered spacecraft landings onto airless bodies: characterization of highly underexpanded plumes in a space-like vacuum environment.

The work is based on both numerical and experimental validation, and includes collaborations with outside laboratories, including the Jet Propulsion Laboratory (JPL), California Institute of Technology and the Deutsches Zentrum für Luft- und Raumfahrt (DLR). It contains original contributions for the automation of slow, iterative numerical processes and to numerical methods developed in-house at Politecnico di Torino (PoliTO), in collaboration with other researchers. The results are an increased understanding of some of the underlying physics behind the implementation of these concepts to future flight systems, and a strong case as to why these concepts should make their way into the design of these future systems.

Rocket engines vary in size and propellant types. Rocket propulsion, both mono- and bi-propellant, has been a mainstay for a variety of in-space spacecraft applications, launch vehicles. To initiate combustion in liquid rocket engines, electrical energy to drive spark systems is needed, as well as, for example, a catalyst with a limited life except for hypergolic combinations. A candidate for cost, weight, and complexity reduction is acoustic ignition, which uses Hartmann-Sprenger resonators to passively heat up propellants beyond their auto-ignition temperature,

without the use of movable parts, electrical systems or external power supplies. From a system perspective, this renders the propellants quasi-hypergolic, providing all of the benefits of classical hypergolic substances without the undesirable side-effects. These advantages are important for long missions, where a high number of ignitions are required along with the growing trend in the use of green propellants. To initiate and maintain the resonance conditions necessary for heat generation, various parameters must be fine-tuned. While the concept of an acoustic igniter has existed for years, attempts to design and manufacture one for space propulsion have recently been made. Due to the complexity of the resonance heating phenomenon and the lack of an analytical solution, a combination of Computational Fluid Dynamics (CFD) analysis and experimental investigation is required. The author used an in-house CFD tool to investigate the gas dynamic oscillatory processes that control the igniter's behavior and compared the results to available experimental data in order to derive some guidelines for developing more efficient design. The author modified an already-existing experimental testbed and developed LabVIEW programs for data acquisition in preparation for a cold-flow experimental test campaign at Laboratorio di Aerodinamica "Modesto Panetti" on 3D printed resonant cavities in Inconel 625 realized by the Department of Applied Science and Technology (DISAT) at PoliTO.

In a rocket engine, propellants are burned in a combustion chamber, and the resulting gases expand through a nozzle to generate thrust. The performance of a rocket engine is highly dependent on the design of the expansion nozzle, the most common of which is bell-shaped. The background pressure regulates the expansion of the hot exhaust within the nozzle; optimum performance is achieved only when the nozzle is adapted. When the jet exiting the nozzle has a pressure less than the ambient pressure, overexpansion occurs, possibly resulting in flow separation from the nozzle wall. Uncontrolled separation is undesirable because it can result in dangerous side loads, which is a significant concern for launch vehicles. The main stage engine, such as the Vulcain 2 cryogenic engine used in the Ariane 5 launcher, operates from sea level to near vacuum in parallel staged launchers; the same is true for single-stage-to-orbit launchers. Expanding the payload capability of current space launchers is critical for the future of space exploration, and reducing non-adaptation losses could result in a significant performance boost. While advanced nozzle concepts have been investigated over the years and some have demonstrated promising characteristics for use in launch systems, they have found limited application in small-scale rockets due to the reliability and maturity of traditional expansion systems. It is a current challenge to rapidly and safely develop optimized advanced nozzle concepts based on overall launcher architectural and mission constraints. Separation and associated side loads must be analyzed and evaluated in order to develop a safe and effective nozzle design methodology that can be used in practice to optimize reusable launchers. To this purpose, the author optimized and validated the same in-house CFD tool mentioned above to be used for advanced rocket nozzle performance prediction. The importance of adopting a realistic geometry for the nozzle lip was observed by the author during preliminary studies of rocket nozzle flows and the computational models in this dissertation were therefore built taking into account this foresight. A dual-bell nozzle resulting from trajectory and nozzle optimization studies conducted at PoliTO, Università degli Studi della Campania "Luigi Vanvitelli" and Sapienza Università di Roma was identified to upgrade the cryogenic Vulcain 2 engine of the Ariane 5. The range of NPR for which the flow separates from the nozzle wall of the second bell was identified by the author as well as it was demonstrated the effectiveness of fluidic control.

In contrast to overexpansion, underexpansion of the flow causes the exhaust gases to expand further downstream from the rocket nozzle. The plume is shaped like a diamond or a barrel, depending on the degree of underexpansion. In a high-vacuum environment, the exhaust flow expand freely. Continuous flow is maintained a few nozzle diameters beyond the nozzle in this case, and the transition to free molecular flow occurs further downstream, or at some expansion angle with respect to the nozzle exit, until pressure is matched. Although thruster flows expanding into a vacuum do not experience separation as they do in the atmosphere, a phenomenon known as the nozzle lip problem is possible. In this case, plumes can flow backward around the nozzle and reach flight vehicle components. Contamination from plumes is a significant concern for interplanetary space missions, particularly those that include landing and surface sample elements for the detection of organics and biosignatures, such as NASA's proposed Europa Lander. The author modeled thruster plume expansion within the DLR High Vacuum Plume Test Facility for Chemical Thruster (STG-CT) with the goal of predicting and interpreting the results of a JPL / DLR testing campaign conducted as part of the Europa Lander Plume-Induced Contamination technology development task. One goal of this campaign is to demonstrate the plume models' scalability up to the scale of the Europa Lander Engines. Plume scalability laws are currently available in the literature for simple nozzle geometries; the author identified and discuss in this dissertation the major characteristics of the plume expanding from contoured nozzles. Modeling multi-regime plume expansion flows requires hybrid solution schemes, and the plume expansion within the STG-CT chamber was modeled using a hybrid CFD / Direct Simulation Monte Carlo (DSMC) solution scheme. Manual coupling is time-consuming, so automating this process is a wise and necessary step. The author developed the CS-AUTOMN tool to automate the process of coupling surface identification and generation of DSMC simulator inputs. Algorithms power the tool, enabling it to be used for a wide variety of landing simulations. This dissertation discusses the algorithms' logic, as well as predicted results for thruster plume expansions in the STG-CT chamber and certain relevant predicted measurements. The author conducted comparisons of the CFD / DSMC and DLR Fokker-Plank (FP) schemes, which revealed a high degree of agreement in terms of both nozzle exit plane and far-field properties. The author compared Bird's serial particle-selection implementation to Haas's particle-selection prohibiting double relaxation method in the DSMC framework.