

Summary

This dissertation investigates tethered satellite systems as actively controlled distributed architectures for Earth-observation applications, with particular emphasis on sensing concepts requiring extended cross-track baselines. The work addresses the limitations of classical tether configurations, which are generally associated with gravity-gradient equilibria, and investigates whether prescribed non-conventional configurations can be maintained through suitable control and actuation strategies.

The research first develops a comprehensive dynamical modeling framework, including both a high-fidelity lumped-mass formulation and reduced-order analytical models. A reformulation of the relative dynamics based on inertial relative velocities is introduced to simplify the numerical treatment of perturbations, while an alternative angular parametrization is derived to provide a regular description of configurations close to the cross-track direction. The resulting models are assessed independently of the control system through open-loop benchmark cases covering orbital librations, structural modes, and the instability of the uncontrolled cross-track configuration. Building on the reduced-order model, an analytical and dimensionless control law is derived that guarantees local asymptotic stability about prescribed equilibrium configurations for the equal-terminal-mass dumbbell system considered in the derivation. Its scalability and robustness over the investigated parameter domain are subsequently assessed through high-fidelity numerical simulations and Monte Carlo campaigns.

The practical generation of the continuous stabilization forces is then investigated through three approaches: conventional low-thrust electric propulsion, aerodynamic-assisted stabilization in Low and Very Low Earth Orbit, and air-breathing electric propulsion. Conventional electric propulsion is retained as the reference solution because of its technological maturity and broad operating range. Aerodynamic control can reduce the required propulsive effort when the available lift-to-drag ratio exceeds the value required by the combined stabilization and drag-compensation problem, although its effectiveness depends strongly on gas-surface interaction properties. Air-breathing electric propulsion is identified as a promising option for reducing stored-propellant requirements, while its applicability remains dependent on intake, power, propulsion, and thrust-vectoring performance.

These developments are subsequently applied to a tethered distributed radar sounder. In the proposed architecture, multiple sensing elements are distributed along a positively tensioned tether maintained nominally in the cross-track direction. The tether mechanically couples the sensing elements and prevents independent relative drift. Under the nominal sensing assumptions adopted in the analysis, the principal advantage of the cross-track tethered satellite system is the persistence of its maximum projected cross-track aperture throughout the orbit. Formation flying can attain comparable instantaneous cross-track resolution when an equivalent geometry is reached, whereas the cross-track tether preserves the corresponding nominal aperture continuously.

The different elements of the research are integrated into a preliminary mission concept for Antarctic ice-sheet sounding. Radar-performance requirements are combined with system and propulsion sizing and with a high-fidelity dynamical consistency assessment of the selected cross-track configuration. A preliminary architecture-level Rough Order of Magnitude cost comparison is also performed. Under the adopted assumptions and cost scope, the reference tethered architecture results in a lower estimated architecture-level cost than the representative formation-flying reference, primarily because fewer complete spacecraft platforms are required.

Finally, the research is complemented by intellectual-property, experimental, and technology-transfer activities. An international patent was filed on the stabilization of tethered satellite formations through controlled tether tension. A dedicated hardware-in-the-loop facility was also developed and used to quantitatively reproduce a dynamically scaled planar trajectory and to investigate, through a reduced experimental model and dedicated controller, the recovery of a positively tensioned cross-track tether configuration. The research also contributed to the establishment of ASTRO S.r.l., subsequently recognized as an academic spin-off of Politecnico di Torino.

Overall, the dissertation provides a consistent framework connecting dynamical modeling, analytical control, actuation analysis, distributed radar sensing, preliminary mission design, and proof-of-concept experimentation. The results indicate that actively controlled tethered systems can provide promising architectures for distributed Earth-observation applications requiring persistent extended baselines, opening new perspectives for future Earth observation missions.