H9.03  Flight Dynamics and Navigation Technologies

Lead Center: GSFC

Participating Center(s): JPL, JSC, MSFC

Scope Title
Advanced Techniques for Trajectory Design and Optimization

Scope Description
NASA seeks innovative advancements in trajectory design and optimization for Earth orbit, cislunar, and interplanetary missions, including:

- Low-thrust spiral trajectories.
- Low-thrust trajectories in a multibody dynamical environment.
- Small-body (moons, asteroids, and comets) exploration.
- Distributed space systems (swarms, constellations, or formations).
- Advanced interactive visualization for spacecraft trajectory design and optimization.

NASA is seeking innovative techniques for optimization of trajectories that account for:

- System uncertainties (i.e., navigation errors, maneuver execution errors, missed maneuvers, etc.).
- Spacecraft and operational constraints (power, communications, thermal, etc.).
- Trajectory constraints imposed by navigational and/or science observation requirements.

Furthermore, innovative techniques that allow rapid exploration of mission design trade spaces, address high-dimensionality optimization problems (i.e., multimoons/multibody tours; low thrust, multispiral Earth orbits), improved visualization techniques including (but not limited to) 3D graphics, virtual/augmented reality, detailed terrain models, or manipulation of trajectory parameters in a 3D scene are sought.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the General Mission Analysis Tool (GMAT); Collocation Stand Alone Library and Toolkit (CSALT); Copernicus; Evolutionary Mission Trajectory Generator (EMTG); Mission Analysis Low-Thrust Optimization (MALTO); Mission Analysis, Operations, and Navigation (MONTE); and Optimal Trajectories by Implicit Simulation (OTIS), or other available software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

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**Expected TRL or TRL Range at completion of the Project**

2 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 15 Flight Vehicle Systems

**Level 2**

TX 15.2 Flight Mechanics

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Software

**Desired Deliverables Description**

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

**State of the Art and Critical Gaps**

Algorithms and software for optimizing trajectories while considering system uncertainties, spacecraft and operational constraints, and trajectory impacts on making navigational or science observations, do not currently exist. In addition, designing trajectories for complex missions, such as low-thrust cis-lunar or multibody tour missions that rely heavily on hands-on work by very experienced people. That works reasonably well for designing a single reference trajectory but not as well for exploring trade spaces or when designing thousands of trajectories for a Monte-Carlo or missed-thrust robustness analysis.

**Relevance / Science Traceability**

Relevant missions include:

- Artemis - Lunar Gateway.
- Europa Clipper.
- Lucy.
- Psyche.
- Dragonfly.
- Roman Space Telescope.
- SmallSat and CubeSat class missions, such as Lunar IceCube.

Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory.
Providing algorithms and software to speed up this process will enable missions to explore trade spaces more fully and more quickly respond to changes in the mission.

References


Scope Title

Autonomous Onboard Spacecraft Navigation, Guidance, and Control

Scope Description

NASA missions require precision landing, rendezvous, formation flying, proximity operations, noncooperative object capture, and coordinated spacecraft operations in Earth orbit, cis-lunar space, libration orbits, and deep space. These missions require a high degree of autonomy. The subtopic seeks advancements in autonomous, onboard spacecraft navigation and maneuver planning technologies for applications in Earth orbit, lunar, cis-lunar, libration, and deep space to reduce dependence on ground-based tracking, orbit determination, and maneuver planning, including:

- Onboard relative and proximity navigation (relative position, velocity and attitude, or pose), which support cooperative and collaborative space operations such as On-orbit Servicing, Assembly, and Manufacturing (OSAM).
- Advanced filtering techniques that address rendezvous and proximity operations as a multisensor, multitarget tracking problem; handle non-Gaussian uncertainty; or incorporate multiple-model estimation.
- Advanced algorithms for safe, precision landing on small bodies, planets, and moons, including real-time 3D terrain mapping, autonomous hazard detection and avoidance, and terrain relative navigation.
- Machine vision techniques to support optical/terrain relative navigation and/or spacecraft rendezvous/proximity operations in low and variable lighting conditions, including artificial intelligence/machine learning (AI/ML) algorithms.
- Onboard spacecraft trajectory planning and optimization algorithms for real-time mission resequencing, onboard targeting/retargeting, onboard computation of large divert maneuvers, primitive body/lunar proximity operations, and pinpoint landing, including robust onboard trajectory planning and optimization algorithms that account for system uncertainty (i.e., navigation errors, maneuver execution errors, etc.).
- Software that provides insight into autonomous guidance, navigation, and control system status and its decision-making for ground controllers and crew.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the Goddard Enhanced Onboard Navigation System (GEONS), Navigator NavCube, core Flight System (cFS), or other available NASA hardware and software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

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Expected TRL or TRL Range at completion of the Project

2 to 6

Primary Technology Taxonomy

Level 1

TX 17 Guidance, Navigation, and Control (GN&C)

Level 2

TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components with complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps

Currently navigation, guidance, and control functions rely heavily on the ground for tracking data, data processing, and decision making. As NASA operates farther from Earth and performs more complex operations requiring coordination between vehicles, round-trip communication time delays make it necessary to reduce reliance on Earth for navigation solutions and maneuver planning. For example, spacecraft that arrive at a planetary surface, may have limited ground inputs and no surface or orbiting navigational aids, and may require rapid navigation updates to feed autonomous trajectory guidance updates and control. NASA currently does not have the navigational, trajectory, and attitude flight control technologies that permit fully autonomous approach, proximity operations, and landing without navigation support from Earth-based resources.

Relevance / Science Traceability

Relevant missions and projects include:

- OSAM.
- LunaNet.
- Autonomous Navigation, Guidance, and Control (autoNGC).

These complex, deep space missions require a high degree of autonomy. The technology produced in this subtopic enables these kinds of missions by reducing or eliminating reliance on the ground for navigation and maneuver planning. The subtopic aims to reduce the burden of routine navigational support and communications requirements on network services, increase operational agility, and enable near real-time replanning and
opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

References


Scope Title

Conjunction Assessment Risk Analysis (CARA)

Scope Description

The U.S. Space Surveillance Network currently tracks more than 22,000 objects larger than 10 cm, and the number of objects in orbit is steadily increasing, which causes an increasing threat to spacecraft in the near-Earth environment. The NASA CARA team is responsible for protecting NASA assets by submitting owner/operator trajectory information on the protected spacecraft, including predicted maneuvers, to the 18th Space Control Squadron (SPCS) at Vandenberg Space Force Base in California. The trajectories are screened against the catalog of space objects, and information about predicted close approaches between NASA satellites and other space objects is sent back to CARA. CARA then determines the risk posed by those events and works with the spacecraft owner/operator to develop an appropriate mitigation strategy. The ability to perform risk assessment more accurately and rapidly will improve space safety for all near-Earth operations and cislunar (Earth + 2 million kilometers) operations.

Because CARA does not produce ephemeris data for the NASA-protected assets or the catalogued objects, the orbit determination aspect of the problem is not of interest in this call. Additionally, CARA does not control the screening process and is therefore not looking for solutions in that area. Only the conjunction assessment (CA) risk assessment aspect is within the scope of this call.

This subtopic seeks innovative technologies to improve the risk assessment process, including the following specific areas (see Reference 1 for the 2020 NASA Technology Taxonomy (TX) areas TX05.6.4, TX10.1.4, TX10.1.5, and TX10.1.6):

1. The Probability of Collision (Pc) is the standard metric for assessing collision likelihood. Its use has substantial advantages over the previous practice of using stand-off distances. The Pc considers the uncertainties in the predicted state estimates at the time of closest approach (TCA) so it provides a probabilistic statement of risk. A number of concerns with the use of the Pc, however, have been identified, including “diluted” probability (see Reference 2) and “false confidence” (see Reference 3). While it is believed that use of the Pc is a responsible approach, there is always interest in alternative risk assessment techniques and parameters that may confer certain advantages. Special consideration will be directed to approaches that explicitly avoid extreme conservatism but instead enable the CARA mission statement of taking “prudent measures, at reasonable cost, to improve safety of flight, without imposing an undue burden on mission operations” and the balancing required to improve safety while allowing largely unencumbered space mission operations.
2. It is appropriate to take explicit cognizance of all the uncertainties in the inputs to the Pc calculation in order to emerge with a range or Probability Density Function (PDF) of possible collision probabilities, or some other parameter that takes account of these uncertainties in some way. Approaches to characterizing the uncertainties in the hard-body radius and object covariances are logical (see Reference 4), although NASA is open to entirely different constructs and approaches while keeping in mind that CARA cannot
control the orbit determination process and cannot change the state estimation/propagation and uncertainty representation paradigm.

3. The number of conjunction events is expected to continually increase with the increase of resident space objects from large constellations, the ability to track smaller objects, the increasing numbers of CubeSat/SmallSats, and the proliferation of space debris. New or improved techniques are sought to increase the speed of risk analysis of conjunction events that also retain the ability to screen the planned trajectory via the 18 SPCS process. A semiautomatic approach for risk analysis could involve preliminary analysis on the severity levels of a given conjunction as a form of triage. Given the information available in a Conjunction Data Message (CDM) and the historical information of a given space object, new or improved techniques or algorithms using for predicting event severity in either a singular event or an ensemble risk assessment for contiguous close approaches for several events including those using artificial intelligence (AI) or machine learning (ML) are sought.

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See section 1.6 for additional details on TAV requirements.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Level 2

TX 05.6 Networking and Ground Based Orbital Debris Tracking and Management

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan toward Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps

CARA has identified the following challenges to which we are actively looking for solutions: efficient ways to perform conjunction analysis and assessments such as methods for bundling events and performing ensemble risk assessment, middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions), improved CA event risk evolution prediction, ML/AI applied to CA risk assessment parameters and/or event evolution. The decision space for collision avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques for CA.
Relevance / Science Traceability

This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth, cislunar, and lunar environments. The ability to perform CARA more accurately will improve space safety for all near-Earth operations, improve operational support by providing more accurate and longer-term predictions, and reduce propellant usage for collision avoidance maneuvers.

References

1. 2020 NASA Technology Taxonomy: 2020_nasa_technology_taxonomy_lowres.pdf
13. Consultative Committee for Space Data Systems (CCSDS) Recommended Standard for Conjunction Data Messages: https://public.ccsds.org/Pubs/508x0b1e2c1.pdf