Astrodynamics Research and Analysis Funding

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Corresponding Author:

Nathan Strange

Jet Propulsion Laboratory / California Institute of Technology
818-393-1165, strange@jpl.nasa.gov

Co-authors:

Daniel Scheeres (University of Colorado)
Ryan Russell (Georgia Inst. of Technology)
Kathleen Howell (Purdue University)
James Longuski (Purdue University)
Victoria Coverstone (University of Illinois)
David B. Spencer (Pennsylvania State University)
Cesar Ocampo (University of Texas)
Belinda Marchand (University of Texas)
Terry Alfriend (Texas A&M)
John Junkins (Texas A&M)
Daniele Mortari (Texas A&M)
John Crassidis (University at Buffalo)
Landis Markley (NASA GSFC)
David Folta (NASA GSFC)
John Dankanich (NASA GRC)
Shyam Bhaskaran (JPL / CalTech)
Dennis Byrnes (JPL / CalTech)
Kim Reh (JPL / CalTech)
Martin Lo (JPL / CalTech)
Jon Sims (JPL/CalTech)
John C. Smith (JPL / CalTech)
Brent Buffington (JPL / CalTech)
Anastassios Petropoulos (JPL / CalTech)
Damon Landau (JPL / CalTech)
Fernando Abilleira (JPL / CalTech)
Ryan Park (JPL / CalTech)
Jeffrey Parker (JPL / CalTech)
Julie Bellerose (JAXA / JSPEC)
Stefano Campagnola (University of Southern California)
Andrew Klesh (University of Michigan)
Nitin Arora (Georgia Inst. of Technology)
Diane Craig Davis (Purdue University)
Kevin Kloster (Purdue University)
Alfred Lynam (Purdue University)
Geoff Wawrzyniak (Purdue University)

Abstract

Astrodynamics research has both enabled and greatly expanded the capabilities of numerous planetary science missions, including several current missions such as Dawn, Cassini-Huygens, and MESSENGER. However, funding for this research has been largely limited to the development and operations phases of missions. NASA funding for general research and analysis in astrodynamics would uncover new techniques prior to the formulation of new mission concepts and could motivate new classes of missions. These new techniques would not only enhance all sizes of missions, but would also expand the feasible set for new mission concepts.

Overview

Astrodynamics, the study and application of space travel, is at the core of all past, present and future space science and exploration missions. From the dawn of the space age to the present, each new mission beyond the Earth's atmosphere has relied on our engineering and scientific understanding of the design, navigation and control of space vehicle trajectories. However, just as all space missions depend on the field of astrodynamics, our ability to explore new worlds and carry out innovative scientific experiments is also *limited* by our current abilities in the field of astrodynamics. This dependence can be restated as a fundamental principle: New insights and advances in our understanding of motion in space will ultimately yield new prospects for carrying out innovative scientific measurements, increase the efficiency and extend the life of current missions, and create the ability to explore and reach new realms of the Solar System.

Past research in astrodynamics has uncovered many mission-enabling techniques such as the gravity-assists used by the Voyagers, Galileo, and Cassini spacecraft; aerobraking used by Magellan, Mars Odyssey, MRO, and other spacecraft; Lissajous and N-body orbits used by missions such as Genesis, Spitzer, and ICE; and low thrust trajectory design techniques used for the Dawn and Hayabusa missions. In Table 1 we present a series of such examples, culled from a much larger set, where an advance in astrodynamics has resulted in new or improved science return.

Despite the demonstrated benefit of this research, there has been no funding source for academic research in this field, and there has not been an effort to coordinate research with planning for future scientific exploration. Rather, the development of these techniques is typically funded as part of existing projects, projects that are formulated with only the knowledge of astrodynamics techniques used in past missions. This current process drives astrodynamics research to only consider the improvement of existing mission concepts and severely limits the ability to develop revolutionary new techniques that would enable new types of missions. We believe that new astrodynamics techniques could be better leveraged into improving our capability for Solar System exploration and science if they were available at the time of mission formulation. Development of new techniques may also create new paradigms for carrying out missions that were not considered before.

The project-focused model of funding astrodynamics research has also had deleterious effects on university astrodynamics research. The lack of a predictable funding source for research in astrodynamics for planetary and space-based missions has made it difficult to attract talented graduate students to the field, and has made it difficult to argue for the importance of the field within university engineering departments where other disciplines receive more funding from their respective industries. The lack of a coordinated funding effort from NASA has also limited NASA's ability to influence what work is done. A quick survey of the literature will find many papers on formation flying and other problems important to defense application, and no papers seeking to solve the problem of how to find feasible fast trajectory designs for Neptune orbiters (a type mission currently in need of enabling astrodynamics techniques).

Table 1: Examples of Past Benefits from Astrodynamics Research

Example Astrodynamics Techniques			**Relevance To Decadal Survey Panel Areas** (IP: Inner Planets, M: Mars, PB: Primitive Bodies, GP: Giant Planets, S: Satellites)				
Technique	**Applications**	**Impact**	**IP**	**M**	**PB**	**GP**	**S**
Aerobraking	Initially Magellan at Venus, subsequently many Mars missions	Large reduction of orbit insertion Delta-V, enabling lower mass and lower cost Mars and Venus orbiters	X	X			X
Airless body Landing and Rendezvous	Surveyor, Apollo, NEAR, Hayabusa, Rosetta	Airless body landing (e.g. at moons and small bodies) requires robust autonomy and precise navigation	X		X		X
Autonomous Navigation	Deep Space 1, STARDUST, Deep Impact	Very important to enable precise navigation in complex and unknown gravity fields found at small bodies and at some planetary satellites. Greatly improves science returns for flybys of small bodies.			X		X
Entry Descent And Landing	Viking, Huygens, Pathfinder, MER, Phoenix, others	Important for surface science at Mars, Venus, and Titan as well as for atmospheric probes at the Giant Planets	X	X		X	X
Gravity-Assist Trajectory Design	Mariner 9, Voyager, Galileo, Cassini-Huygens, NEAR, MESSENGER, New Horizons, and many more	These methods have been applied to find gravity-assist trajectories that can lower the required launch energy by a factor of 10. These techniques also enable satellite tours at the giant planets.	X		X	X	X
Lissajous and N-Body Orbit Design	ICE, Genesis, Artemis, and others. Future application to planetary satellite missions.	Enabling an entirely new methodology to be applied to the design and analysis of strongly non-Keplerian trajectories.	X	X	X	X	X
Low Thrust Trajectory Design and Optimization	DS-1, Dawn, Hayabusa. Many potential applications to future missions	We can now routinely design trajectories that rendezvous with multiple asteroids or comets. We can also find low launch energy trajectories to the outer planets.	X	X	X	X	X
Orbits in complex Gravity Fields	NEAR, Rosetta, Dawn, Hayabusa	Without these techniques it would not be possible to fly close orbits of irregular bodies such as comets and asteroids.			X		X
Stable High Inclination Orbits of Giant Planet Moons	Future orbiter missions to Europa, Ganymede, Enceladus, Triton, and other satellites	Without these techniques it would not be possible to flyby polar or near-polar orbits of giant planet satellites.					X

Potential Benefits of Astrodynamics Funding

The nature of advances in astrodynamics can be divided into two categories: incremental and fundamental. The first category is the incremental improvement of existing approaches and technologies. Such advances, such as improved trajectory optimization methods, more detailed and deeper understanding of existing phenomenon, and improved measurement and modeling precision, can all yield incremental but enabling advances in our ability to explore the Solar System.

The design of the Cassini extended mission is an example of incremental improvement to existing techniques. The initial design of the satellite tours for Galileo and of the Cassini prime mission were performed using the theory of patched conics. This approach enables the rapid generation of multiple candidate tours from which a final design can be chosen that finds the best balance in achieving a mission's science goals. For the Cassini extended mission design this approach was expanded to use trajectory arcs calculated in a higher order Saturn gravity field. This extension enabled more accurate targeting of encounters with Saturn's inner moons including Enceladus. As a result of this improvement, the extended mission design was better able to achieve diverse science goals (Buffington et al. 2008) including doubling the rate of Enceladus encounters from the prime mission (which enabled more extensive follow up investigations of the Enceladus plumes discovered during the Cassini prime mission).

The second category is fundamental advances in our understanding. These are much less predictable, yet can have extremely important and enabling outcomes. These advances can be identified using hindsight, and several are listed in Table 1. Such advances are difficult to predict as they result from new insight or the application of theory from one branch of science and mathematics to the field of spaceflight. A clear example is the application of celestial mechanics and dynamical systems theory to the rigorous understanding and automation of space mission design to the Earth-Sun and Earth-moon libration point regions of space. The roots of our current ability to design complex trajectories and missions in the Earth's neighborhood grew organically out of many different avenues. First and foremost were the initial applications of exotic orbits in the restricted 3-body problem for scientific purposes (Farquhar et al. 1977) and the use of the dynamics of the 4-body problem for capture into lunar orbit (Belbruno and Miller 1993), and the enabling design for Genesis (Howell et al. 1997). Following these applications, the rigorous study of mathematicians and astrodynamicists (summarized in Gomez, et al. 2001) over the decades after the first halo missions made fundamental connections between the abstract theory of dynamical systems and practical and applied spaceflight. These connections have yielded an expansive growth in our ability to efficiently design transfers in the larger space about the Earth-Moon system. Future applications of these connections to planetary satellite orbiters (including Earth's Moon) and other applications are waiting development and are necessary for the reliable and robust design of spacecraft transfers to any highly dynamic environment.

Recent advances in computer hardware and software engineering techniques hold promise as another source for future breakthroughs in this category. In particular, the solutions of many computationally intensive combinatorial problems in astrodynamics (e.g. tour design) are becoming feasible to solve with the extraordinary new hardware and memory capabilities of modern computers. The infusion of astrodynamics research with new advanced software engineering techniques could lead to dramatic improvements in the feasible set of science missions.

A speculative example of a possible future topic of research that could have significant impact would be coupled navigation and mission design. Current approaches to designing trajectories decouple the process of navigation (i.e., actually "flying" the spacecraft while correcting for errors and uncertainties) and mission design (charting the course of the spacecraft). This decoupling is acceptable in relatively benign dynamical environments such as inter-planetary flight or planetary orbiters, but is no longer acceptable in highly dynamic environments such as low-altitude planetary satellite orbiters, such as the Europa Orbiter mission. Intensive gravitational tours, such as the Cassini trajectory at Saturn, are on the edge of this decoupled process, and require a large team of navigators and mission designers to constantly iterate new solutions due to small navigation dispersions. This approach entirely results from the classical and somewhat arbitrary academic separation of these two fields. There are many possible approaches to improving this problem, but all of them would require a deeper understanding of spacecraft trajectories as being "uncertainty distributions." Making such connections are feasible (Scheeres et al. 2006) and could enable a transformative understanding of how to design trajectories that simultaneously satisfy scientific goals and which are safely "navigable" in strongly dynamic systems. This understanding could be leveraged into either lowering the operations costs or to increase the science capability of future missions.

Recommendations

Finally, we propose a unified research program that includes Astrodynamics as part of its larger charter. A research program dedicated to studying the dynamics of motion in space across all temporal and spatial scales (e.g. including the fields of Solar System dynamics, astrophysical dynamics, astrodynamics, etc.) would also encourage interdisciplinary collaboration across the disparate sub-communities that study motion in space from an engineering and from an astronomical point of view.

We call for a new program to support fundamental research in this field. An added investment of $500K - $750K per year (perhaps 10-15 grants per year) would create an energetic response and lead to robust growth and development of new methods of analysis and simulation in astrodynamics and would encourage interdisciplinary engagement with related fields that study the dynamics of the Solar System. Assuming 3-year grants, the total program size once in a steady state would be on the order of $1.5-2.2M.

The goals for this program would be:

I. Foster an interdisciplinary community that grapples with dynamics across science and engineering disciplines, charged with applying their understanding to problems related to the motion and interaction of natural and artificial bodies.

II. Maintain NASA and NSF's traditional support of applied dynamical astronomy research through such programs as Astrophysical Theory, Planetary Geology & Geophysics, Outer Planets Research, Astrobiology, and others.

III. Institute a funding pathway for migration of research between the different dynamics sub-communities, including the development of Astrodynamics-related issues of benefit to Solar System dynamical astronomy, such as space situational awareness, mission design, trajectory navigation, and the exploitation of natural dynamics for space missions and observatories.

Desired Outcomes

A successful implementation of this program will have a number of important outcomes, including:

- Maintenance and growth of an interconnected research and academic community in the broad fields of Astrodynamics and Astrophysical and Celestial Dynamics that can serve the larger community of Solar System Astronomy.
- Development of a theoretical background and foundation for tying together the disparate advances across the spectrum of research in planetary dynamics into a more unified understanding of how the Solar System evolves from the largest to the smallest scales.
- Creation of healthy academic communities which can produce world-class researchers in the field of Astrodynamics and Solar System dynamics, enabling the United States to be the preeminent contributor to theoretical advancements in these fields.
- Discovery of new physical processes and their rigorous physical understanding, which could have application to many other areas of science and technology.
- Enhancing existing mission concepts to increase science return and reduce cost and risk.
- Enabling new high-value space science missions that were previously undiscovered or considered infeasible.

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