NEW MEXICO EPSCOR

PROXIMITY OPERATIONS FOR NEAR EARTH ASTEROID EXPLORATION

Grant number: NNX11AQ35A

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Progress Report: Year 1

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Proximity Operations for Near Earth Asteroid Exploration

New Mexico EPSCoR

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Research Accomplishments Measured Against the Proposed Goals and Objectives:

Goal 1: Develop strategies to plan trajectories and maneuvers of single or multiple spacecraft to enable NEA missions, including approach and orbital operations, descent, landing and surface operations, and autonomous guidance, navigation, and control capabilities.

Progress on Goal #1: Research on autonomous approach and strategies guidance, navigation, and control (GN&C) of a spacecraft rendezvousing with a tumbling target is well under way. A discrete-time scheme for guidance and control has been obtained, which will be presented in an international conference and a national conference in summer of 2012 (see list of publications). A discrete-time state estimation scheme that is robust to bounded measurement errors has also been obtained for a tumbling rigid body, and has been submitted to a conference to be held in December 2012. Work is also under way for autonomous GN&C of a formation of three spacecraft, which could be used as a sensor network for gathering data in the proximity of a NEA. In addition, research is in progress on an integrated framework for GN&C of a spacecraft during autonomous rendezvous and proximity operations near a tumbling target. Finally, work is underway to analyze the nonlinear dynamics of orbits around Types I and II triaxial ellipsoidal bodies, including finding relative equilibria, invariant manifolds, and periodic orbits, and to extend these results to arbitrarily shaped bodies. Thus far the ellipsoidal shapes have been specified by both major axes lengths and by second degree and order spherical harmonics. Figure 1 shows the orbital trajectory around a triaxial ellipsoid version of Eros as an example. A paper on this work will be submitted to the 2013 AAS Spaceflight Mechanics Conference.

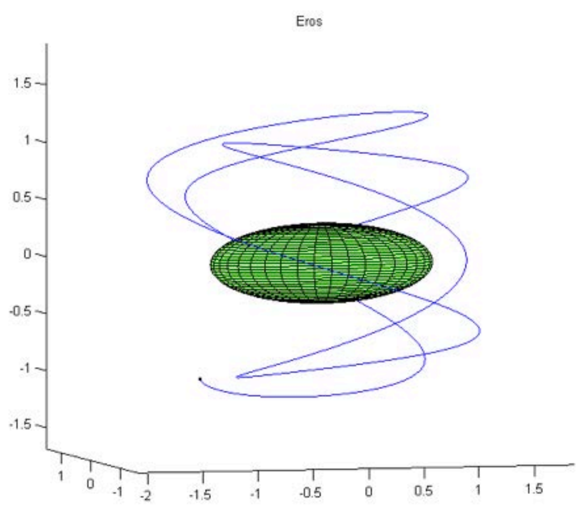

Figure 1: Simulated spacecraft orbit around NEA Eros.

In terms of orbital mechanics, the asteroid/spacecraft scenario being modeled here is referred to as a Restricted-Full Two-Body Problem (meaning one body is insignificant in both mass and shape relative to the other), and a key point is that it takes into account the effect of a large body's shape and spin rate on system dynamics. This is critical because many asteroids spin at high rates and they often have highly irregular shapes. The use of a triaxial (sometimes referred to as "scalene") ellipsoid keeps the geometry of the system simple. A full derivation of the system's equations of motion has been done by co-PI Scheeres in prior work. To perform the numerical integration required to implement computer simulations based on these equations of motion, we use a 4th & 5th order paired Runge-Kutte integrator which we have found to be as accurate in this application as a 7th & 8th order integrator but with reduced computational complexity.

Research at University of Colorado has been started on developing methods and analyses to support close proximity operations about asteroids. A variety of approaches are being considered and a number of different analyses have been supported under the grant, at least in part. 1. One initial thrust focused on the development of efficient ways to automatically map out the forward sets of a spacecraft given a certain level of control authority. By developing such maps an autonomous mission planner can make informed decisions on what courses of control action will yield the best outcome. 2. A different thrust looked at the application of symplectic integration techniques to the orbiter problem. One specific area of focus is to understand how use of symplectic integration may allow for more precise qualitative phase space propagation. 3. Ballistic deployment of science packages to the surfaces of asteroids has been studied. This is a refinement of a previously developed concept for asteroid exploration. 4. A final area of work that is just starting will be to study the entire process of autonomous mission planning for motion close to an asteroid. Development of this capability could enable much more aggressive close-proximity operations with an attendant increase in science and exploration data return.

<u>Goal 2</u>: Study the impacts of communications and networking constraints within the framework of various protocols on NEA missions, and how such constraints affect and are affected by the trajectories of a constellation of spacecraft at a NEA system.

<u>Progress on Goal #2:</u> According to the work plan submitted in our proposal, no activities with respect to Goal 2 are described for Year 1. We have, however, moved forward on the first task associated with this project Goal which is described as follows in the proposal: *Begin communications and telemetry studies, and integrate communications constraints into orbital and proximity operations.* Specifically, starting with asteroid orbital simulation models originally designed by project co-PI Scheeres and implemented in Matlab by student Thomas Critz working under the direction of project technical lead Butcher, we have begun to analyze and quantify the communication tradeoffs associated with operating in the vicinity of various near-earth asteroids. Our focus thus far has been to study the communications interconnectivity between a single orbiting spacecraft and remote sensor platforms placed at various locations on the surface of the asteroid. The assumption here is that the spacecraft is required to act is a relay

for data being collected by the surface platforms so that this data can either be shared amongst the platforms for local collaborative processing or transmitted back to earth. Our initial thrust illustrate results what one might call the 'best case' communications scenario: if an unobstructed line of sight exists between a surface platform and the spacecraft, we assume that reliable communication is possible at some fixed bit rate. In a real system, line of sight is necessary for reliable communication (at all radio frequencies that are practical for space communications, at least), but it is not sufficient to guarantee error-free reception. In general, we must also consider the signal to noise ratio (SNR) of the system. Calculating the SNR requires information about the antennas and modulation hardware as well as RF background noise models (which depends not only on the antenna selection but also on the positions of the surface and space platforms). While it is our ultimate plan to incorporate all of these practical factors into our communications simulation framework, we have not yet progressed to this point. Assuming that communication is possible whenever line of sight exists, we have analyzed network availability with respect to 6 different orbital scenarios and relative to 5 different Near Earth Asteroids (NEAs). Specifically, we have considered orbits around the following asteroids: Vesta (orbits 1 & 2), Eros, Gaspra, Tempel2, and Ida. Table 1 summarizes a few of our results. In this scenario, 6 surface probes are assumed, 4 equidistant around the equator of the asteroid and 2 at each pole. The 'network stability' is the average length of time (in minutes) that a fixed set of surface probes can communicate with one another using the orbiting spacecraft as a relay while the 'average blackout time' is the time interval between communications windows with the spacecraft. The 'average net access' is the percentage of the time that surface probes have communications access to earth via the orbiting spacecraft.

Table 1. Network comparisons for various asteroids

Asteroid	Network Stability	Average Blackout Time	Average Net Access
Vesta (1)	19.27	158.3	27%
Vesta (2)	14.34	111.4	14%
Eros	23.71	173.4	27.2%
Gaspra	21.27	177.5	26.1%
Tempel2	65.81	122.8	30%
Ida	20.37	166.3	25.9%

While averaged results of the kind shown in Table 1 provide a useful overview of the various orbital scenarios, the actual design and specification of the local NEA communication system requires detailed statistics for each surface probe. From this kind of data, we can determine the data buffering requirements for both the surface probes and for the relay spacecraft (assuming specific sensor data generation rates and communication bandwidths) as well as optimal/allowable surface probe locations for a given stable orbit. An example of surface platform-specific data for the asteroid Eros orbit considered here is shown in Figure 2. In the figure, the *N* indicates the number of communications blackout intervals suffered by a given surface platform over approximately 2.5 orbital cycles. We see that there are significant variations in both the duration and number of blackout times depending upon the location of the surface platform. Note that the first four platforms are on the equator while the 5th and 6th are on the poles.

```
#1 225.585571 mins N=3

#2 131.549339 mins N=5

#3 223.684569 mins N=3

#4 203.407214 mins N=2

#5 97.426353  mins N=4

#6 159.050501 mins N=3
```

Figure 2: Average time (in minutes) without communications for each surface platform for Eros orbit.

Note that the results given summarized in Table 1 are not only incomplete but they can also be somewhat misleading: for example, the results for Tempel2 would appear to be pretty good, but two of the six uniformly distributed surface probes *never* have communications access in this scenario. We can see this by considering the results shown in Figure 3. The orbital plot of Figure 4 shows clearly why this occurs.

```
#1 373.478958 mins N=3

#2 177.643287 mins N=3

#3 Always     mins N=0

#4 296.428858 mins N=3

#5 Always     mins N=0

#6 186.204409 mins N=3
```

Figure 3: Average time (in minutes) without communications for each surface platform for Tempel2 flyby.

We are currently adding sensor data generation rates and (ideal) communication channel capacities to our simulations to that we can calculate the required data buffer sizes for both the surface platforms and the spacecraft under a variety of scenarios. At the same time, we are also increasing the realism of our simulations by including SNR in the computation, using an additive (logarithmic) link budget formulation which will allow us to incorporate the effects of antenna choice/pointing error, modulation, signal processing, and noise into the calculation of communication connectivity and channel capacities.

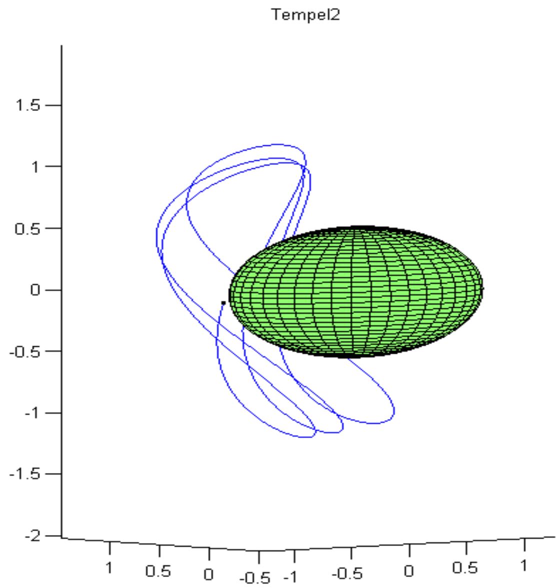

Figure 4: Tempel2 orbit. Note that the two surface probes on one side of the asteroid are never able to communicate with the spacecraft.

<u>Goal 3</u>: Improve the gravity field modeling of select NEAs through new observations and the development of numerical modeling algorithms, for the purpose of more effective proximity operation modeling and design for robotic and human NEA mission targets.

<u>Progress on Goal #3</u>: During this first year of the grant Klinglesmith has been involved in developing the ability to observe asteroids sufficiently to obtain synodic periods from the lightcurves. He has been author or co-author on 9 publications submitted the Minor Planet Bulletin. Three of the papers have been published as of June 2012 (Baker et.al.,2012; Durkee et.al., 2012, Odden et.al., 2012). A fourth one (Klinglesmith, 2012) will be published in September 2012. The remaining five papers are waiting review. All of the papers deal with determining the synodic period of asteroids. One paper (Baker et.al., 2012) also includes the determination of the absolute magnitude (H) and the opposition effect parameter (G). One paper (Warner, Klingesmith, Skiff, submitted) presents a shape determination of the asteroid 47035 (1998 WS) from the light curve inversion method developed by Warner (2011). In May of 2012, three New Mexico Undergraduate students were hired to assist with the collection of asteroid lightcurve data under the direction of Klinglesmith. They have already been involved in the submission of one light curve paper in collaboration with faculty and students from Butler University in Indianapolis, Indiana. Also, during the first year of the project the New Mexico co-Is have participated in several Skype conferences with co-I Scheeres at University of Colorado, wherein Prof. Scheeres made presentations on his past asteroid-related research and

answered many questions from the other co-Is and students. These presentations have mostly focused on the gravity modeling and orbital aspects of the asteroid environments for many different classes of asteroids, as well as on his past experiences participating in the NEAR and Hayabusa missions.

Goal 4: Contribute to and promote the development of research infrastructure in New Mexico in areas of strategic importance to the NASA mission while assessing and leveraging the many existing core capabilities relative to NASA in the state.
Progress on Goal #4: PI Butcher is developing a state-of-the-art orbital mechanics 3D visualization laboratory which is funded by his recent grant from AFOSR (see below). This laboratory will be used for the current project as well as serving as an outreach tool for visiting K-12 students at New Mexico State University.

Goal 5: Improve the capability of New Mexico to gain support from sources outside the NASA EPSCoR program in space and aerospace related STEM-related research.
Progress on Goal #5: The team has a number of publications in press and in review (see list below for details). These publications will support the team for follow-up research funding, in particular, for development of a credible IGERT proposal. During the first year Sanyal and Butcher submitted a proposal that was funded by the National Science Foundation ($278,158) for a three-year project "Robust State and Uncertainty Estimation for Unmanned Systems in the Presence of External Uncertainties." Co-I Butcher obtained another related three year grant "Libration Point Orbit Utilization for Tactical Advantage in Communications, Surveillance, and Risk Mitigation" ($451,360) funded by AFOSR shortly before the present project was awarded. Co-I Scheeres submitted a proposal to NASA's NSTRF program, which he was recently awarded. This is for work in autonomous mission planning and will fund his student David Surovik, who was initially funded on this project. Due to this, a different CU Ph.D. student, Simon Tardivel, will be brought into the current project while Surovik's work will still be tied to the basic project goals.

Goal 6: Develop partnerships between NASA research assets and New Mexico academic institutions, federal laboratories, and industry.
Progress on Goal #6: During the first year of the project collaborations have been strengthened at NASA JPL and at AFRL in Albuquerque, NM. In particular, co-I Sanyal obtained a ASEE-funded summer faculty fellowship to spend the 2012 summer period working with our AFRL collaborators (Lovell and Jah). In addition, both Butcher and Sanyal have made presentations during the past year to AFRL staff that have visited NMSU, and Butcher is making two trips to AFRL this summer to give presentations and meet with Jah and Lovell, as well as other AFRL staff.

Goal 7: Contribute to New Mexico's overall research infrastructure, science and technology capabilities, higher education, and/or economic development.
Progress on Goal #7: The graduate (M.S. and Ph.D.) programs in aerospace engineering at NMSU (the only aerospace program in the jurisdiction) recently admitted its first students and began offering graduate level courses. As part of this program, three graduate courses in astronautics were added to the curriculum: AE 562 Astrodynamics was taught for the first time

in Fall 2011 by Butcher, AE 561 Spacecraft Attitude Dynamics and Controls was taught in Spring 2012 by Sanyal, and AE 565 Statistical Orbit Determination will be taught for the first time in Fall 2012 by Butcher. These courses are helping developing a solid graduate program in astronautics at NMSU which will help to train students involved in the current project.

Goal 8: Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) to improve the environment for STEM education in New Mexico.
Progress on Goal #8: Recently PI Hynes presented preliminary results from the project to the Astronomical Society of Las Cruces (ASLC). Also, co-I Butcher communicated with the ASLC president about getting involved in the club's free outreach activities which include star parties and beginning astronomy classes.

Systemic change as evidenced by:

Improvements in jurisdiction research and development infrastructure: See progress on Goal #4 above.

Increased financial commitment from the jurisdiction, industry, and participating institutions: None

Response of activities to NASA and jurisdiction priorities: None

Reordered jurisdiction and/or institutional priorities: None

Examples of successful technology transfer to the private sector: None

Extent to which collaborations with jurisdiction agencies, industry, research and academic institutions, and NASA have evolved.
In the area of spacecraft navigation about small bodies, the NMSU researchers have interacted at the Spaceflight Mechanics Conference with Drs. Shyam Bhaskaran and Roby Wilson of NASA/JPL. It has also been recommended to interact with Dr. Lee Bryant of NASA/JSC which will be pursued during the second project year. Prof. Scheeres has maintained his close interactions with several additional NASA and industry colleagues. In addition, Dr. Sanyal was awarded the Summer Faculty Fellowship to spend summer 2012 at the Air Force Research Laboratory (AFRL) working with collaborators Lovell and Jah on issues tangentially related to the project. Dr. Butcher also recently visited AFRL and gave a talk on spacecraft delayed feedback attitude control and estimation, and he expects to return to AFRL later in the summer for another visit. Also, both NMSU and CU are participating institutions in the FAA COE on Commercial Space Transportation.

Discussion of interaction between and cooperation with the jurisdiction's Space Grant Consortium.

New Mexico Space Grant continues to provide funding to Dr. Amit Sanyal, including for curriculum development in aerospace engineering at the undergraduate level. (This resulted in his teaching Spacecraft Attitude Dynamics and Controls in the Spring 2012 semester.)

Research success of individual investigators as measured by:

Articles submitted to or published in refereed journals

Baker, R.E., Pilcher,F., Klinglesmith III, D.A. (2012), "Rotation Period and H-G parameters determination for 1188 Gothlandia", *Minor Planet bul.*, **39**, 60-63

Durkee, R.I. Klinglesmith III, D.A.,Warren, C., Briggs, J.W. (2012), "The rotational period of 1406 Komppa", *Minor Planet Bul.* **39**, 25

Klinglesmith III, D. A., "Asteroid lightcurve analysis at the Etscorn Campus Observatory for January and Feburary 2012", *Minor Planet Bul.* ,***39***

Klinglesmith III, D.A., Ferrero, A., Odden, C., Strabla, L., Quadri, U., Girelli, R., "Light Curve for 8345 Ulmerspatz", accepted for publication in *"Minor Planet Bulletin*", January 2013

Klinglesmith III, D.A., Risley, E., Turk, J., Vargas, A., Han, X. L., Heffner, O.R., Kidd, A.W., Magnetta, J., Rastede, F. W., "The Short Period Asteroid, 8077 Hoyle", Submitted *"Minor Planet Bulletin"*

Odden, C., Martinez, L., Klinglesmith, D. A., Warren, C. (2012), "Lightcurve Analysis of 3080 Moisseiev",*Minor Planet Bul.*, **39,** 93

Pilcher, F., Briggs, J.B., Franco, L., Inasaridze, R.Y., Krugly, Y.N., Molotov, I.E., Klinglesmith III, D.A., Pollock, J., Pravec, P., "Rotation Period Determination for 5143 Heracles", submitted *"Minor Planet Bulletin"*

Pilcher, F., Benishek, V., Briggs, J.W., Ferrero, A., Klinglesmith III, D. A., Warren, C., "Eight Months of Lightcurves of 1036 Ganymed", submitted *"Minor Planet Bulletin"*

Warner, B.D., Klinglesmith III, D. A., Skiff, B. A., "Light Curve inversion for 47035 (1998 WS)", submitted "Minor Planet Bulletin"

Nazari, M., Samiei, E., Butcher, E. A., and Schaub, H., "Attitude Stabilization using Nonlinear Delayed Actuator Control with an Inverse Dynamics Approach," *Journal of Guidance, Control, and Dynamics,* submitted.

S. Tardivel and D.J. Scheeres. "Ballistic Deployment of Science Packages on Binary Asteroids," submitted to *Journal of Guidance, Control and Dynamics*.

Talks, presentations, or abstracts at professional meetings

A. Sanyal, L. Holguin, and S. P. Viswanathan, ``Guidance and Control for Spacecraft Autonomous Chasing and Close Proximity Maneuvers," to be presented at 2012 IFAC Symposium on Robust Control Design, June 20-22, 2012, Aalborg, Denmark.

L. Holguin, A. Sanyal and S. P. Viswanathan, ``Guidance and Control for Spacecraft Autonomous Rendezvous and Proximity Maneuvers using a Geometric Mechanics Framework," to be presented at AIAA Guidance, Navigation and Control Conference, August 13-16, 2012, Minneapolis, MN.

S. P. Viswanathan, A. Sanyal and L. Holguin, ``Dynamics and Control of a Six Degrees of Freedom Ground Simulator for Autonomous Rendezvous and Proximity Operations of Spacecraft," to be presented at AIAA Guidance, Navigation and Control Conference, August 13-16, 2012, Minneapolis, MN.

J. Bohn and A. Sanyal, ``Unscented State Estimation for Rigid Body Motion on SE(3)," submitted to 51st IEEE Conference on Decision and Control, December 10-13, 2012, Maui, HI.

Nazari, M., Butcher, E. A., and Hall, C.D., "On the Stability Investigation of Single- and Dual-Spin Spacecraft," to be presented at 2012 AIAA Guidance, Navigation, and Control Conference, Minneapolis, MN, Aug. 13-16, 2012.

Samiei, E., Nazari, M., Butcher, E. A., and Schaub, H., "Delayed Feedback Attitude Control using Neural Networks and Lyapunov-Krasovskii Functionals," 22nd AIAA/AAS Space Flight Mechanics Meeting, Jan. 29-Feb. 2, 2012, Charleston, SC.

Nazari, M., Samiei, E., Butcher, E. A., and Schaub, H., "Attitude Stabilization using Nonlinear Delayed Actuator Control with an Inverse Dynamics Approach," 22nd AIAA/AAS Space Flight Mechanics Meeting, Jan. 29-Feb. 2, 2012, Charleston, SC.

C.D. Creusere, E. Nelson, T. Critz, and E. Butcher, "Analysis of communication interconnectedness in the proximity of near-earth asteroids," to appear in the *International Telemetering Conference Proceedings*, October 2012.

Erik Komendera, Daniel Scheeres and Elizabeth Bradley, "Intelligent Computation of Reachability Sets for Space Missions," Accepted for presentation at the IAAI conference on Artificial Intelligence, Toronto, CA, July 22-26, 2012.

Erik Komendera, Elizabeth Bradley and Daniel Scheeres, "Efficiently Locating Impact and Escape Scenarios in Spacecraft Reachability Sets," to be presented at 2012 AIAA Astrodynamics Specialists Conference, Minneapolis, MN, Aug. 13-16, 2012.

Articles submitted to NASA venues

None

Patents and patent applications

None

Follow-on grant proposals submitted/funded including funding amounts

Amit Sanyal and Eric Butcher, *Robust State and Uncertainty Estimation for Unmanned Systems in the Presence of External Uncertainties*, NSF, $278,158, Sep. 1, 2011-Aug. 30, 2014.

Amit Sanyal and Ou Ma, *A Special Robot and Mobile Platform for Experimental Research on Space Robotics Technology*, AFOSR (DURIP), not funded.

Daniel Scheeres, proposal to NASA NSTRF program on autonomous NEA mission planning, awarded.

Participants

Faculty

Dr. Eric A. Butcher, New Mexico State University
Dr. Amit K. Sanyal, New Mexico State University
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Dr. Daniel J. Scheeres, University of Colorado Boulder
Dr. Daniel A. Klinglesmith III, New Mexico Institute of Mining and Technology

Post-doctoral, graduate, and undergraduate students supported from EPSCoR funds

Dr. Daero Lee, postdoc, New Mexico State University
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Janek Turk, undergraduate, Mexico Institute of Mining and Technology
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Students working on aspects of current project who are supported through other sources

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