Annual Report (April 3, 2013)

The *DuAxel* Robotic Mission Architecture for Accessing and Sampling High Risk Planetary Terrains

(Keck Institute for Space Science Technical Development Program)

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1. Background

Our proposed effort is aimed at developing the technologies and prototypes needed to test and demonstrate the proposition that the *Axel* and *DuAxel* robotic rovers cannot only carry out the in-situ science capabilities of conventional rovers, but can also access extreme environments consisting of vertical drops, long crater descents, cold traps, and generally rough terrain. The proposed goal of this seed project is to develop (1) the key remaining mechanical prototypes and (2) the key autonomous control capabilities which are needed for an effective proof-of-concept demonstration of the *DuAxel* mission architecture.

2: Review of Proposed KISS Research/Development Activities.

The goal of our 2-year KISS technology development program is to complete a realistic prototype of the *DuAxel* concept and carry out realistic field tests so that we can provide the science and flight communities with a credible demonstration of this new approach to robotic exploration, thereby eliminating the perceived risks with this novel architecture. Our proposal broke down the process of developing a complete *DuAxel* proof-of-principle system into 3 major tasks:

- **Task 1: Central Module mechanical design and fabrication.** Develop and build a central module which can robustly dock with the existing *Axel* prototypes. This task, which will be carried out by undergraduate SURF students, is divided into subtasks for each of the critical mechanical components.
- **Task 2: Autonomous docking and autonomous steep terrain descent/ascent.** A complete autonomous control system for *DuAxel* is far beyond the scope and budget of this program. However, to realize a credible *DuAxel* demonstration, it is necessary to implement two critical pieces: autonomous docking and undocking, as well as autonomous tether management and path planning during steep slope operation.
- **Task 3: Field evaluations and demonstrations.** We proposed to carry out two major field tests (in addition to more frequent bench-top and JPL Mars Yard tests). The first field test, which will occur 10+ months into the program, will in part evaluate *how much* autonomy is really needed for *DuAxel* operation. The second test, (in the 23rd month), will evaluate our technical developments, demonstrate the *DuAxel* system, and generate the data needed to evaluate the viability of *DuAxel*.

These high level tasks were broken down into sub-tasks, which are summarized in the Appendix for convenicnce.

3: Progress

Below are listed the people who have been involved in this activity, as well the coordination efforts, specific accomplishments, comparisons against the original task plan, and a list of publications which have come out of this program (and have been supported by this program).

3.1. Personnel: The following people contributed to the project during this reporting period.

- **Graduate Students:**
    - **Melissa Tanner.** Melissa is 4th year graduate student in Mechanical Engineering. While Melissa has worked on some of the mechanical design aspects of the DuAxel system this year, she has primarily focused on developing new planning methods for tether management.
    - **Dorian Tsai:** Dorian was a visiting graduate student from Finland who worked with the Axel team from roughly December 2011 to August 2012 on the problem of autonomous docking.
    - **Krishna Shankar.** Krishna is a 2nd year graduate student in Mechanical Engineering. Krishna worked 100% on the project during the summer of 2012, and 30% time on the project during the October, 2012 until the present (April 2012). Krishna worked primarily on local Axel tether management planning methods that take the limitations of the tether spooling mechanism into account when planning and controlling motions.
    - **Jeff Edlund.** Jeff is a senior graduate student in Caltech's Computation and Neural Systems (CNS) program. Jeff participated, in a very important way, in the early days of Axel's development. From June 2012 through November 2012 Jeff worked ½ to 1 day per week, helping the Axel team develop Axel's on-board computing infrastructure. From December 2012 until the present, Jeff has worked 40% time on Axel, advancing the state of Axel's computing infrastructure, and developing a new stereo camera system for Axel. Upon his upcoming graduation, Jeff will work full time at JPL, and will continue to lead Axel's software and computing infrastructure effort.
- **Summer 2012 SURF students.** During the summer of 2012, KISS also funded a student-lead activity to explore new sampling tools, technologies, and techniques for Axel.
    - **Hima Hassenruck-Gudipati** was a junior mechanical engineering. She worked on percussive scooping tools for Axel. Percussive scooping is an attractive technique for Axel to obtain samples from icy soils.
    - **Yifei Huang** was a rising senior in mechanical engineering. In collaboration with Kristen Holtz, Yifei analyzed, designed, fabricated, and tested a pneumatic soil/dust sampling technology. Pneumatics sampling, which is attractive in low density atmospheres like Mars, can be used to pick up loose soil samples, as well as dust samples
    - **Nikola Georgiev** was a rising senior in mechanical engineering major. Nikola focused on developing and end-to-end Axel sampling/scooping system design that particularly considered the need to quickly seal the sample in order to retain volatile material that might be in the sample. He developed and demonstrated a complete mechanical systems to acquire, seal, and store a scooped soil sample.
    - **Kristen Holtz** was a rising junior mechanical engineering major. She collaborated with Yifei Huang to develop a pneumatic sampling concept and prototype for Axel.
- **Summer 2012 SURF student.** From the budget of this grant (not the KISS-supported student-lead activity), Diego Caporale (a rising senior in Mechanical Engineering) also worked with the KISS team during the summer of 2012. He focused particularly on new mechanisms to dock the Axel robot to the central module prototype. This was part of our proposed plan to improve the design of the DuAxel central module.

3.2. Coordination: Both the JPL team members and Caltech KISS technical development team met weekly from 2-3 pm on Thursdays in the Axel lab located in JPL Building 198. During the summer 2012 period, the SURF students also attended most of the weekly Axel meetings as well. Additionally, a subset of both JPL and Caltech team members met on most Monday mornings in the Axel lab to tackle issues with the Axel hardware and software system. The team has also developed an Axel wiki to keep minutes of the weekly meetings, to maintain lists of open issues, to store documentation, and to coordinate experimental activities.

3.3. Activities: During this reporting period, we made progress on the following fronts:

3.3(a): Axel Descent Motion Planning and Tether Management System (Task 2.2). In previous work, Pablo Abad-Manterola had developed a method to plan Axel's descent down a rocky sloped terrain in such a way as to minimize the likelihood of tether entanglement. While this was a promising start, Abad-Manterola's algorithm had the unrealistic assumption that the exact geometry of the rocky, steep terrain must be known prior to the descent planning and descent execution process.

During this reporting period, graduate student Melissa Tanner has developed a significant extension of this early work tethered descent/ascent into poorly known rocky terrain, which is undoubtedly the case for any real mission. This algorithm allows for real-time updates to the terrain's geometry to be incorporated into the planning process. The algorithm also determines the best procedure to "back-up" should the vehicle reach an impass during descent. The first conference paper on Melissa's algorithm was accepted for publication and presentation at the upcoming May 2013 *International Conference on Robotics and Automation* [1].

Another important issue that we found in our early field tests was the effect of the tether reeling process on Axel's motion. In order to generate large torques needed during Axel's descent up a vertical slope, the tether spooling motor is highly geared. While this high gearing produces ample torque, it also means that the tether can only be reeled in or paid out very slowly. Since Axel must maintain a nominal tension on the tether at all times to minimize the chances for snagging, this constraint on the tether motion must be taken into account during the process of planning Axel's motions, particularly when Axel is docking (see below), or when Axel is operating on flat ground at the bottom of a descent.

Graduate student Krishna Shankar developed several new techniques to incorporate the tether's limitations on the Axel motion planning process. His work also developed a new and more realistic *motion model* for Axel. A motion model is the basis for any motion planning method, and this new model should improve the quality of our future motion planning efforts. This work has been submitted for publication [2] and presentation in the *IEEE/RSJ International Conference on Intelligent Robotics Systems (IROS 2013).*

Comparison against proposed Schedule: Task 2.2 is slightly ahead of schedule, in that we proposed to have a first version of the tether management algorithm implemented by July 15, 2013. The algorithm implementation is going well, and we expect to complete the first simulated version of the algorithm by May 1, 2013, with real-world testing in the JPL Mars Yard commencing on June 1, 2013.

3.3(b): Automated Docking (Task 2.1). Dorian Tsai completed the development and testing (in the JPL Mars Yard) of a vision guided autonomous docking system. This work has been submitted for publication and presentation [3] in the *IEEE/RSJ International Conference on Intelligent Robotics Systems (IROS 2013).*

Comparison against proposed Schedule: This work was completed in mid-August of 2012, against an original schedule of mid-September 2012. Hence, the work was completed on time, and this proposed task of the project is largely done. Over the next 6 months, Jeff Edlund will better integrate Dorian's work into the evolving Axel control architecture.

3.3(c): Axel Vision System (Tasks 2.3 and 2.4). While beginning the process of enabling on-board Axel image processing to support we found that Axel's current stereo vision system was woefully inadequate for the process of mapping nearby obstacles, as needed for proposed motion planning and obstacle avoidance activities of Tasks 2.3 and 2.4. There were two key issues that had to be addressed. First, because of the tether spooling mechanism in the center of the vehicle, the placement of two cameras on either side of the spooling system lead to a stereo system whose baseline was too large to provide enough overlapping cues in the near field that are needed to have accurate near field stereo, which in turn is needed to realize accurate near field obstacle and terrain mapping. Another unexpected problem was the fact that the flexing of Axel's body made it impossible to maintain a calibration between the two widely separated cameras. Additionally, we found that the field of view of the current Axel cameras did not include any view of Axel's science bays. Hence, there was no way in Axel's current configuration to visually monitor the sampling process from instruments or sampling tools deployed from the science bay.

We carried out a study to optimize the vision system of Axel to address all of these issues that we found. We concluded that a 3-camera system, consisting of two very high resolution (4 megapixel), high field of view (170^{o} cameras) with a small baseline (12 cm) placed on one side of Axel, and an original Axel camera on the other side. The side-by-side cameras will be used for near-field mapping, and also for observing scientific measurement and sampling operations in the science bays. The combination of the side-by-side cameras and the opposing camera will be used for long-distance mapping and vision.

Another components of Tasks 2.3 and 2.4 is the adaptation of the previously developed CLARAty mapping software to the Axel architecture. Under the guidance of Issa Nesnas, the entire CLARAty software package has been reorganized and adapted to the current software architecture of Axel.

Comparison against proposed Schedule: Tasks 2.3 and 2.4 are significantly behind schedule (approximately 5 months). In part, the delay is due to the unexpected need to implement a radically different vision system configuration and hardware on Axel. In part, these Tasks are also behind schedule due to lack of appropriately skilled personnel to carry out the mapping procedure. With Jeffry Edlund now spending more time on Axel, and with Melissa Tanner ahead of schedule (freeing up time for her to spend on this Task, which is relevant to her Ph.D. goals), more effort than originally scheduled will be put behind this task in the upcoming months in order to get this important task back on track.

3.3(d): Redesign of the DuAxel central module and docking system (Tasks 1.3 and 1.4). Our goal has been to redesign the DuAxel central module so that it better docks with the Axel II vehicles, and can better support field tests. Graduate student Melissa Tanner investigated changes in the Axel Caster arm geometry, performing an experimental optimization effort to determine the best trade-off between maneuverability (which drives the design to short caster arms) and energy efficiency over flat terrain (which drives the design to long caster arms). The caster arm is also an important part of the docking system. Undergraduate student Diego Caporale (during the summer of 2012) developed several new docking plate designs, and some prototypes docking plate prototypes, which were tested on Axel.

Comparison against proposed Schedule: Task 1.3 was scheduled to be carried out during Summer 2012, and was completed on schedule. Task 1.4 (central module morphology) was only partially completed during Summer 2012, and so this task is somewhat behind schedule. Tasks 1.1 and 1.2 are not scheduled until summer 2013, and are therefore still on schedule.

3.4 Publications (a copy of the publications have been attached to this report)

[1] M. Tanner, J.W. Burdick, and I.A.D. Nesnas, "On-line Motion Planning for Tethered Robots in Extreme Terrain," (to appear) *Proc. IEEE Int. Conf. on Robotics and Automation,* Karlsruhe, Germany, May, 2012.

[2] K. Shankar J.W. Burdick, and I.A.D. Nesnas, "Motion Planning and Control for a Tethered, Rimless Wheel Differential Drive Vehicle," (submitted) *IEEE/RSJ Int. Conf. on Intelligent Robotic Systems (IROS)*, Hong Kong, Nov. 2013.

[3] D. Tsai, I.A.D. Nesnas, and D. Zarzhitsky, "Autonomous Vision-Based Tether-assisted Rover Docking," (submitted) *IEEE/RSJ Int. Conf. on Intelligent Robotic Systems (IROS)*, Hong Kong, Nov. 2013.

Appendix: Review of Original DuAxel Tasks and Schedule

The tasks presented in the original proposal are summarized below. Greater detail and motivation for each task can be found in the proposal.

Task 1: Central Module mechanical design and fabrication. This task aims to build a robust *central module* prototype suitable for field testing, is broken into subtasks which focus on each of the central module's key mechanisms.

- **Task 1.1: Leg Deployment mechanism.** This task will look at both passive (i.e., driven solely by forces generated via tether tension) vs. active (i.e., using additional actuators embedded in the CM) deployment mechanism designs.
- **Task 1.2: Central Module anchoring strategies.** This task will focus on designing, building, and demonstrating active anchoring and de-anchoring mechanisms
- **Task 1.3: Docking and tether anchoring mechanisms.** The main focus of this task is to totally redesign the docking fixture mechanism to improve its robustness on various terrains and to reduce the forces needed to maintain a solid docking engagement of *Axel* with the CM during navigation.
- **Task 1.4: Central Module morphology and structural design.** This task will consider the overall optimal shape of the central module

Task 2: Autonomous docking and autonomous tether management on steep terrain.

- **Task 2.1** will develop and test an image-guided procedure to autonomously dock *Axel II* with the central module using a combination of *Axel*'s on-board cameras and the central module's stereo mast.
- **Task 2.2**, during the second program year, a prototype of planning algorithm which plans the path of a single *Axel* rover to descend a slope so as to minimize the likelihood of tether entanglement on obstacles, etc. during the descent and ascent process. This algorithm will assume that a visually obtained 3-dimensional model of the slope is available (see below). Task 2.2 assumes that terrain map has been constructed prior to the planning process. In a real mission, such data would be synthesized from both high resolution orbiter images (if available) and visual images from *DuAxel*'s stereo mast. For our developments and field tests, we will simulate this process by using a 3-dimensional laser scan of the field test site to simulate orbiter data.
- **Task 2.3** will develop a visual mapping system which synthesizes the 3-dimensional laser scan data of a test-site with images obtained from *DuAxel's* onboard cameras to construct a 3-dimensional terrain map of *DuAxel*'s vicinity and the slope to be explored. Such a map would simulate the kind of data available which would be available to a *DuAxel* prior to the decent of an *Axel* into an extreme terrain.
- **Task 2.4** (2^{nd} program year) will extend the mapping system of Task 2.3 to update the terrain model using images captured by *Axel*'s onboard cameras as it descends.

Task 3: Field Evaluations and Demonstrations. The first field test will take place in the Vulcan Materials rock quarry located in S. California. This test has two aims: to assess our progress toward the end of the first project year, and to refine our understanding of how much autonomy is really needed to operate *DuAxel* in a mission-like scenario.

The second field test will likely take place in the same Arizona desert location as that of the final *Axel II* RNTD tests. This 3-day test will evaluate the results of each of the tasks outlined above by operating the integrated *DuAxel* platform in navigation, exploration, and docking/undocking modes at the field test site. We expect this field-test to gather sufficient data so that an initial evaluation of the *DuAxel* architecture. The summary of this data can be presented to the space exploration community to judge if this concept demonstrates enough merit for further development.

Originally Proposed Schedule

The schedule below assumed an October 1, 2011 project start date. The actual project start was November 15, 2011.

Task 1: Central Module Mechanical Design and Fabrication. Since this task will be carried out by undergraduates working through the SURF program, the schedule for each of this task's four subtasks are largely dictated by the SURF program schedule. Tasks 1.1 and 1.2 will be carried out during the summer of 2012. Task 1.3 and 1.4 will be carried out in the summer of 2013. Each of the tasks will follow a similar schedule, as they all involve the conceptualization, design, and evaluation of a mechanical subsystem prototype. The approximate schedule for each summer is given below. Note that the portion of the schedule for testing the student's prototypes is designed to coincide with the proposed field tests.

- June 15-June 30. Conceptualization phase in which the SURFer: (1) meets with JPL/Caltech *Axel* team members to be briefed on history and the requirements of the subsystem design; (2) researches background material relevant to the design problem.
- July 1-July 15. Conceptual prototypes and/or computer models of the component design are developed, with mock-ups made as necessary.
- July 15: Preliminary Design Review (PDR) with Prof. Burdick, Dr. Nesnas, and relevant *Axel* team members.
- July 15-August 10. Refinement of the mechanical design based on the PDR review, and fabrication of the first mechanical prototype.
- August 11-August 20. Integration of the prototype with the *DuAxel* experimental platform, and preliminary in-situ evaluation (in the JPL Mars Yard, and as part of the annual field tests).
- August 21-30. Refinement and refabrication of components as dictated by the in-situ evaluation. Preparation of documentation of all project components.

Task 2: Autonomous Control System Development.

- **Task 2.1: visually guided docking algorithm.**
    - Oct. 1, 2011-Dec. 31, 2012 . Literature review and conceptualization phase of algorithm
    - Jan. 1, 2012 –May 1, 2012. Implementation and testing of preliminary approach.
    - May 1, 2012. Preliminary evaluation of the docking algorithm in the JPL Mars Yard, and presentation to the JPL/Caltech *Axel* Team.
    - May 2, 2012-Aug. 15, 2012. Redevelopment and refinement of docking approach.
    - Aug 15, 2012. Retest of docking algorithm in JPL Mars Yard, in preparation for annual field test.
    - August 15-Sept 31, 2012. Evaluation of algorithm at Field Test #1, documentation of of lessons learned, critical evaluation of shortcomings found in Field Test #1.
- **Task 2.2: *Axel* Descent Motion Planning .**
    - Oct. 1, 2012-Nov. 15, 2012. Review of Abad-Manterola's thesis work.
    - Nov. 16, 2012 –Feb. 1, 2013. Conceptualization of how to adapt the Abad-Manterola algorithm to the data format produced by Task 2.3.
    - Feb. 1, 2013. Presentation of proposed approach to the JPL/Caltech *Axel* Team.
    - Feb. 2, 2013-July. 15, 2013. Algorithm Implementation.
    - July 15-20, 2013. Test algorithm in JPL Mars Yard, and in JPL Arroyo if possible.

- July 21-Aug. 20, 2013. Improve algorithm and prepare for Field Test #2
- Aug 20-Sept. 31, 2013. Evalute performance at Field Test #2, and document results.

- **Task 2.3: 3-dimensional mapping using visual images**
  - Oct. 1, 2011-Nov. 15, 2011. Meet with Dr. Issa Nesnas and become familiar with the JPL CLARAty system.
  - Nov. 16, 2011 –Feb. 1, 2012. Conceptualization of how to adapt CLARAty to the map making problem.
  - Feb. 1, 2012. Presentation of proposed approach to the JPL/Caltech *Axel* Team.
  - Feb. 2-Aug. 15, 2012. Implement and incrementally test the algorithm on stored image data base.
  - Aug 15-25, 2012. Live test in Mars yard.
  - August 25-Sept 31, 2012. Evaluation of algorithm at Field Test #1, documentation of of lessons learned, critical evaluation of shortcomings found in Field Test #1.
- **Task 2.4: Improve 3-dimensional mapping to incorporate incoming Axel images.**
  - Oct. 1, 2012-Nov. 15, 2012. Develop camera models and image fusion framework to integrate onboard camera images.
  - Nov. 16, 2012 onward. Test and incrementally improve the mapping system in the JPL Mars Yard.

Task 3: Field Evaluation and Demonstration. Design and evaluation of a mechanical subsystem prototype. The approximate schedule for each summer is given below.

- **Field Test #1:** August 28/28, 2012. **Milestones:** The *DuAxel* prototype will attempt at least 8 docking/undocking cycles on different cliff edges in a rock quarry located near Lancaster, CA. An undocked *Axel* will attempt at least 4 roundtrip exploration ascents/descents on steep terrain (e.g,, see Fig. 12) , covering at least 150 meters round trip, and over at least two separate slopes. At least two of these explorations will
- **Field Test #2:** August 28-September 2, 2013. The *DuAxel* platform will be exercised over 3 days in the Arizona desert. **Milestones:** *DuAxel* will attempt at least 12 complete navigation-undocking-exploration-redocking cycles on a variety of terrains and slopes. At least one 300 meter exploration phase will be attempted, and at least one 500 meter navigation mode excursion will be carried out.