# Annual Report (March 18, 2012)

# 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 demonstrate the *DuAxel* robotic architecture that has 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

Keeping in mind that we are approximately 4 months into this program, here are our current activities, accomplishments, failures, and challenges.

**3.1. Personnel:** The following people have joined, or will soon join the project.

- **Graduate Students:**
    - **Melissa Tanner.** Melissa is 3rd year graduate student in Mechanical Engineering. She is working on mechanical design aspects of the DuAxel central module, as well as redesign of the Axel caster arm system to make it more compatible with the future central module design. Her main thesis work will focus on automated planning for tether management.
    - **Dorian Tsai:** Dorian is a visiting graduate student (in residence for 6 months) from Finland. He is working on the automatic docking problem. He will primarily advance
    - **Krishna Shankar.** Krishna is a 1st year graduate student in Mechanical Engineering. He has started working on developing an *estimator* for Axel that will fuse together various sensors to estimate Axel's attitude on a slope. An estimator subsystem is crucial for subsystem After completing his full time M.S. course schedule in June, he will join the project full time, focusing on developing a complete estimator, as well as automated map-making.
- **Undergraduate students**
    - **Sarah Ahmed** is doing her senior undergraduate thesis on the Axel project. She is developing a prototype of an electromechanical sensor to measure the angle with which the tether exits Axe's caster arm.
- **Upcoming Undergraduate SURFs.** Pending successful completion of the SURF review process, the following undergraduates will join the team during the summer 2012 SURF period.
    - **Hima Hassenruck-Gudipati** is a junior mechanical engineering. She will work on the student-led KISS project that will develop prototypes of sampling tools to integrate into
    - **Yifei Huang** is a junior mechanical engineering major.
    - **Nikola Georgiev** is a junior mechanical engineering major.
    - **Kristen Holtz** is a junior mechanical engineering major.
    - **Ahalya Prabhakar** is a junior mechanical engineering major.

**3.2. Coordination:** Both the JPL team members and Caltech KISS technical development team meet weekly from 2-3 pm on Thursdays in the Axel lab located in JPL Building 198. Additionally, a subset of both JPL and Caltech team members meet Monday mornings in the Axel lab to tackle issues with the Axel hardware 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. Because of JPL access restrictions, the wiki can only be accessed on the JPL facility, or through an authorized VPN access.

**3.3. Activities:** During the first 4 months of activity, we have made progress on the following fronts:

**3.3.a: Automated Docking (Task 2.1).** The first key issue to be solved in automated docking is to find

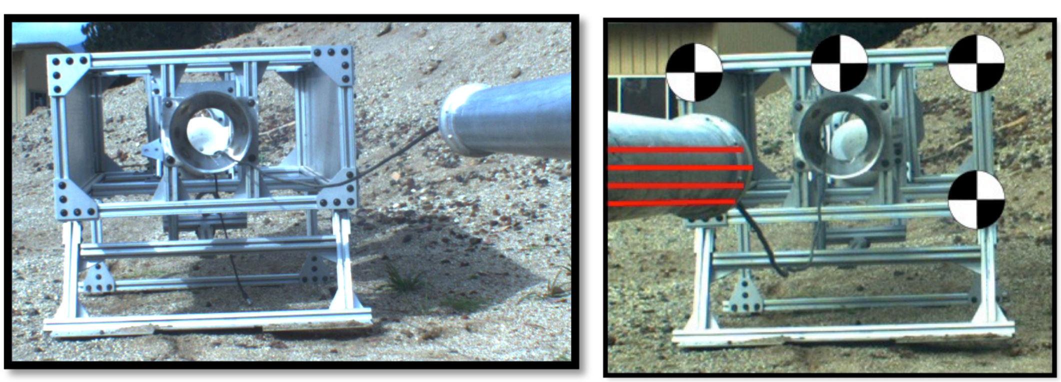

**Figure 1:** (a) view of Central Module from left on-board Axel camera. (b) preliminary evaluation of docking targets.

and then localize the docking fixture. The next issue is to control the Axel rover (by coordinating the wheel and tether motions) so that it can successfully guide it's caster arm into the docking tube, and make a firm connection with the docking plate. After performing an extensive literature review, to solve the first issue we are using some simple docking targets placed on the docking face of Axel's central module. By finding and localizing these targets using the on-board Axel cameras, the docking Axel can better estimate the location of the docking fixture and docking tube relative to its current position. Figure 1(a) shows a view from Axel's left on-board camera, showing the docking face and docking tube. Figure 1(b) shows a preliminary test involving some simple markers in an asymmetric pattern on the front face of the Axel module. At least under normal sun-light conditions, it is possible to find these targets. We are currently progressing on several fronts:

- Optimal target pattern, size, and location on the docking face
- Visually-guided servoing of Axel to place the caster arm in the docking tube

**Comparison against proposed Schedule:** We were about 7 weeks behind the original schedule on the literature review process, but we have now caught up to originally proposed schedule to complete the docking theory and software implementation by May, 2012. The delay largely arose from getting a graduate student in place to carry out this work.

**3.3(b): Redesign of Axel Caster Arm (Task 1.3).** While our goal is to redesign the DuAxel central module, and not to redesign the Axel II module, we have investigated changes in the Axel Caster arm geometry. By shortening and redesigning the Axel caster arm, we can simplify the design of the central module with which Axel docks. We have built several new Axel caster arms, and are in the process of testing them in the JPL Mars yard.

**Comparison against proposed Schedule:** These tasks were originally proposed to be carried out by SURF students during the summer of 2012. Hence, we are ahead of schedule on this task, and we believe that this preliminary work will allow us to keep the originally proposed schedule during this first year.

**3.3(c): Implementation of on-board Axel Descent Motion Planning and Tether Management System (Task 2.2).** Melissa Tanner has thoroughly read and understand Pablo Abad-Manterola's thesis, and has conceptualized the first steps to adapting this algorithm to an on-line situation where Axel's on-board cameras will provide updated information on the types of obstacles encountered during a descent.

**Comparison against proposed Schedule:** This task is currently right on schedule, but may fall behind in the next few months due to Melissa's need to prepare and manage the large number of undergraduate students who will work on Axel in Summer 2012.

**3.3(d): Develop a visual mapping system (Tasks 2.3).** We have made very little progress on this task, as the graduate student (Eric Wolff) originally expected to join this effort decided to join another research group. When Krishna Shankar joins the group full time in June, this will help us start to get back on schedule in this area.

## 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.** n, 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.