Development of Advanced Entry, Descent, and Landing Technologies for Future Mars Missions [1,2]

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Abstract—Future Mars missions may need the capability to land much closer to a desired target and/or advanced methods of detecting, avoiding, or tolerating landing hazards. Therefore, technologies that enable "pinpoint landing" (within tens of meters to 1 km of a target site) will be crucial to meet future mission requirements. As part of NASA Research Announcement, NRA 03-OSS-01, NASA solicited proposals for technology development needs of missions to be launched to Mars during or after the 2009 launch opportunity. Six technology areas were identified as of high priority including advanced entry, descent, and landing (EDL) technologies. In May 2004, 11 proposals with PIs from universities, industries, and NASA centers, were awarded in the area of advanced EDL by NASA for further study and development. This paper presents an overview of these developing technologies.

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1. INTRODUCTION

As part of NASA Mars Exploration Program (MEP), Mars Technology Program (MTP) has been developing advanced technologies needed for future Mars science missions, including Mars Scouts. The two principal program elements of MTP are the Focused Technology and the Base Technology Programs. The Focused Technology Program addresses technologies that are specific and critical to near-term missions, while the Base Technology Program [1]

addresses those technologies that are applicable for multiple missions and which can be characterized as longer term, higher risk, and high payoff technologies. The primary vehicle for Mars Program to acquire such technologies is to use the process of NASA Research Announcement (NRA). As part of NRA 03-OSS-01, NASA solicited proposals for technology development needs of missions to be launched to Mars during or after the 2009 launch opportunity. In particular, the following technology areas have been identified as of highest priority for this solicitation: *subsurface access, rover technology, telecommunications and navigation, planetary protection, advanced EDL, and technologies for low-cost missions*.
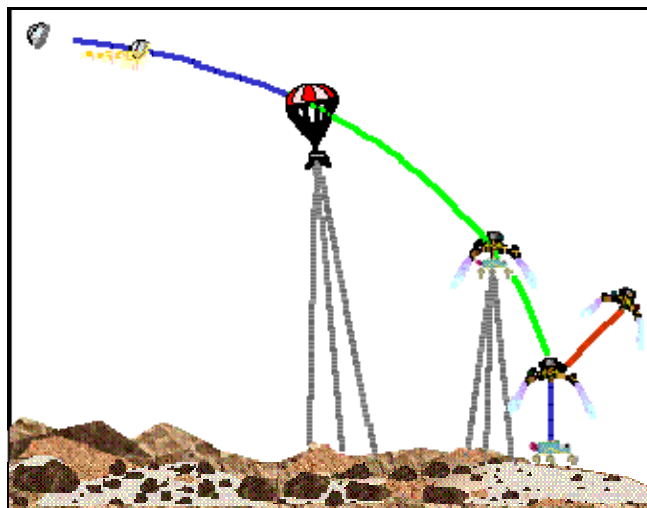

Figure 1 – A Representative Entry, Descent, and Landing Scenario

In the area of EDL, landing capabilities may be needed to enable future Mars missions to land closer to a desired target with additional capabilities to detect, avoid, or tolerate landing hazards. Therefore, "pinpoint landing" and

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advanced hazard detection capabilities will be crucial to meet future mission requirements. As the result of NASA selection process, 11 proposals from NRA 03-OSS-01 were awarded for further study and development in the area of advanced EDL.   These EDL-related technologies can be divided into the following 3 categories:

(a) *Guidance, navigation, and control (GNC) methodologies:*

- *onboard navigation algorithms utilizing the radio communication capabilities of orbital assets to achieve high navigation accuracy during the entry and descent phase*

- *advanced hypersonic entry guidance methodology capable of pinpoint delivery of parachute deployment and applicable to low, mid, and high Lift-to-Drag Ratio (L/D) lander*

- *real-time estimation algorithms using coupled vision and inertial navigation data for pin-point landing*

- *wind drift compensation system based on closed-loop parachute control*

(b) *Sensor systems:*

- *high accuracy, miniature doppler-based laser altimeter and velocimeter to aid the terminal descent and landing phase*

- *advanced phase array radar for improved hazard detection with velocimetry and altimetry functions*

- *thermal imaging system (with software) to provide future Mars lander missions the capability to recognize hazardous large rocks during descent*

(c) *Hazard detection and hazard assessment:*

- *passive imaging algorithms for hazard detection and avoidance using multiple features*

- *multiple sensors fusion algorithms for hazard avoidance*

The duration of these development ranges from 1 1/2 to 3 years.   In Section 2, we will provide an overview of these EDL technologies and describe their current status.

2. EDL GNC TECHNOLOGY DEVELOPMENT

2.1 Advanced Hypersonic Entry Guidance for Mars Pinpoint Landing (PI: Kenneth D. Mease, University of California at Irvine)

The objective of this task is to develop a hypersonic entry guidance algorithm that will meet the collective requirements of future Mars landing systems. A hypersonic entry guidance algorithm must deliver the lander to an acceptable parachute deployment condition, without violating thermal and structural constraints. To achieve greater landing accuracy as required for many future missions, without driving up propellant requirements, and to have access to higher elevation landing sites, pinpoint delivery accuracy (e.g., within 100 meters) is required. Although Mars landers to date have been low lift-to-drag ratio (L/D) capsules, the demands to land greater mass, larger volume payloads on the surface of Mars will require higher L/D landers. A versatile entry guidance algorithm capable of pinpoint delivery to parachute deployment and applicable to low, mid and high L/D landers is needed. A second objective of the task is to develop an aerocapture guidance algorithm.
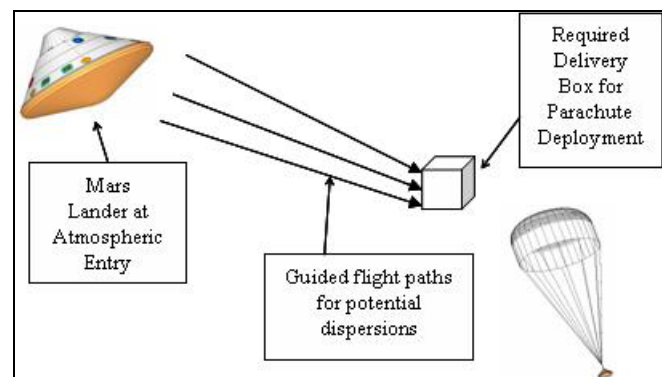

Figure 2 – Concept for Hypersonic Entry Guidance

The approach pursued in this task is to adapt, for Mars entry, the guidance algorithm "Evolved Acceleration Guidance Logic for Entry (EAGLE)", previously developed and simulation tested extensively for Earth entry. The Mars EAGLE will be developed and validated to meet the pinpoint landing requirements for low, mid and high L/D landers. The technical challenges in modifying EAGLE are to increase the delivery accuracy and to extend the applicability to low L/D. For aerocapture guidance, the trajectory planner in EAGLE will be modified to accommodate the orbital target conditions.

This is a 3-year task targeted to produce effective Mars entry and aerocapture guidance algorithms, validated by extensive, high-fidelity simulation by July 2007. In the first year of the task, EAGLE was redesigned to accommodate low L/D landers where vehicle models were identified and developed to support simulation and analysis. In addition, a medium fidelity Mars entry simulation was developed and used to evaluate the redesigned EAGLE on 500 entry cases obtained from the Mars Science Laboratory project, and the integration of EAGLE into a high-fidelity simulation program was initiated.

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2.2 *Spacecraft-to-Spacecraft EDL Navigation* *(PI: Pieter Kallemeyn, Lockheed Martin Space Systems)*

Previous Mars lander missions used unguided entry subjected to initial state uncertainties and atmospheric variations that resulted in landed delivery uncertainties of 100-200 km. Studies have shown that further improvement in entry navigation can be realized through utilization of lander-to-orbiter radiometric data before and during atmosphere entry. This task will conduct a system level study of modifications to telecommunication and flight software subsystems to improve EDL navigation through use of radiometric data between an approaching Mars lander and orbiting asset.
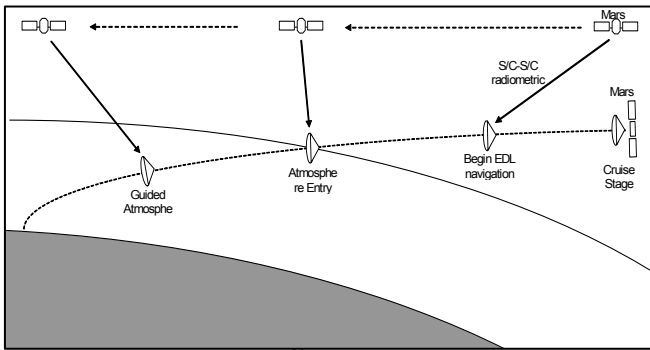

Figure 3 – EDL navigation scenario beginning at cruise stage jettison

The baseline system for this study is the Phoenix Mars lander, currently in development for a 2007 launch. This task will examine different antenna designs and develop a prototype antenna to be tested with Thermal Protection Systems (TPS) to characterize its performance before and during atmosphere entry. Plasma interference analysis will be conducted to characterize possible blackout periods over a range of entry conditions. This task will also develop a Kalman filter to utilize radiometric data during approach and entry to reduce navigation state knowledge error. Both Doppler and range measurements between the lander and an orbiter (Mars Odyssey or MRO) will be considered. The parameters derived from the antenna and filter design and the plasma environmental analysis will be added to existing EDL simulation tools to conduct a series of overall "approach-to-landing" simulations of the system.

The end product of this 1.5-year task is final report detailing the UHF antenna design, the navigation Kalman filter algorithm, and results of system-level performance assessment with different antenna designs, orbiters, and data types/spans. This final report will be available April 2006.

2.3 *Orbiting Beacon Navigation for Pin-Point Landing* *(PI: P. D. Burkhart, JPL)*

The capability to land within 1 km of a pre-defined landing site will improve safety and enable landing within roving range of sites of scientific interest while avoiding hazardous areas. The addition of beacon navigation data processing onboard the entry body in real-time will enable improvements in surface positioning error from an estimated 3 km to less than 500 m.

Beacon navigation will take advantage of the UHF link between two spacecraft (i.e. to an orbiter from an approaching lander for EDL telemetry relay) to build radiometric data, specifically the velocity between the two spacecraft along the radio beam, that are processed to determine position and velocity in real time (Figure 4). The improved onboard state knowledge provided by beacon navigation will reduce the supersonic chute deployment error to less than 1km, and ultimately improve landed position error. The Electra project has developed a radio that includes radiometric data generation and processing capability available for navigation that will be required equipment on all Mars spacecraft starting with Mars Reconnaissance Orbiter (MRO), which launched in 2005. A two-year effort including definition of the flight algorithms and validation of these algorithms in both an Electra software testbed and an Electra breadboard will advance beacon navigation to TRL 5[2][3].
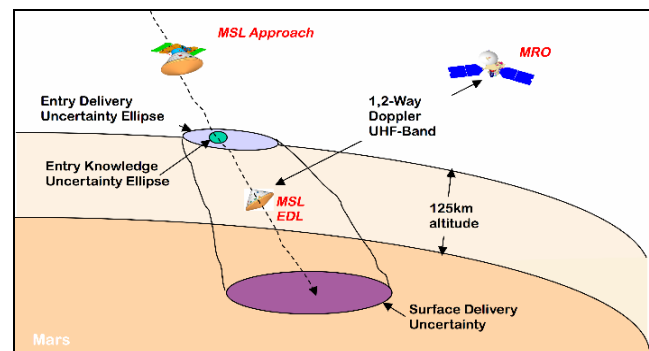

Figure 4 – Schematic of beacon navigation for EDL

The first year of this task, which recently concluded, saw completion of the following tasks. The Electra emulator has been configured, interfaces between the navigation code and the hardware I/O have been defined and sample navigation code based on an Extended Kalman Filter (EKF) compiles and executes in the emulator. This EKF leverages previous development work for EDL reconstruction. Two Electra Engineering Development Units (EDU) were developed with assembly complete and hardware checkout nearly completed. An EDL scenario with MSL and MRO has been defined for analysis and testing purposes consistent with MSL project requirements on EDL communications. Results from analysis of this scenario were used to verify the expected performance of UHF Doppler data and to define the required algorithm set needed for embedded execution on the Electra processor.

During the second year, currently in progress, upgrades to

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the EKF code to complete implementation of the selected algorithm set will be performed with testing in the emulator. Once the hardware checkout of the Electra EDU is completed, compiling and test on the hardware will commence. Additional optimization of the software for execution on the Electra EDU will complete the development effort. The end product of this task will be documentation of the mathematical models required for processing UHF Doppler data for EDL, along with the software and user's guide. We will work with the Mars Exploration Program Office to ensure the availability of this technology to NASA missions regardless of the technology developer's participation in the mission. The development of this task will be completed by July, 2006.

2.4 *Adaptive On-Board Navigation for Pin-Point Landing (PI: Robert H. Bishop, University of Texas at Austin)*

The objective of the task is to develop a robust adaptive navigation methodology for actively-guided Mars EDL during hypersonic phase to acceptable parachute deploy conditions and then down to terminal phase. The adaptive navigation architecture will be capable of processing Inertial Measurement Unit (IMU) and external sensor data and produce a state estimate that is robust with respect to IMU failures and performs capably in the presence of uncertain atmospheres. Our contributions include algorithms to process IMU data (delta velocities and delta angles) recursively in a model-based filter during the upper atmospheric hypersonic phase and fusing the state information with external measurements from terminal guided phase sensors (e.g., altimeters). We are validating the navigation algorithms using MER IMU data in simulation. The navigation algorithm processing requirements will be optimized for real-time on-board processing and hosted on the Electra reconfigurable radio to demonstrate real-time operation.
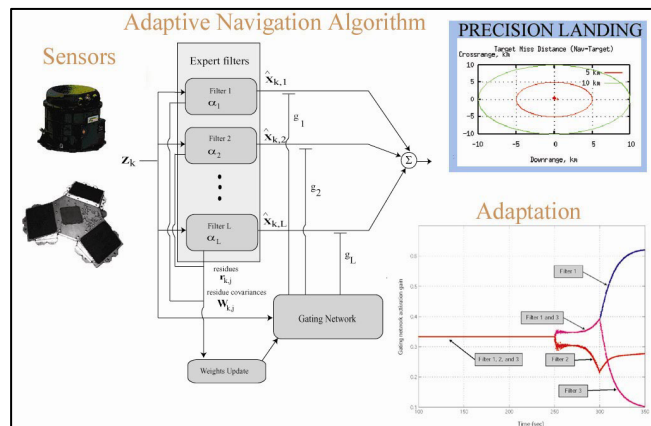

Figure 5 – Adaptive Navigation Architecture

Two competing filtering algorithms have been developed. The standard extended Kalman filter (EKF) and the sigma point Kalman filter (SPKF) are now capable of processing

IMU data provided by the MER project. A software emulator of the Electra unit is now operational and being used for initial testing of the navigation algorithms. A new multiple model hypothesis testing algorithms based on a chi-square distribution was developed and tested in EDL simulation.

The end product will be documentation of the mathematical models required for processing inertial measurement unit data fused with altimetry for EDL employing an adaptive navigation architecture based on multiple models. A software guide will be provided. The development of this task will be completed by July, 2006.

2.5 *Coupled Vision and Inertial Navigation for Pin-Point Landing (PI: Stergios Roumeliotis, University of Minnesota)*

This work focuses on precise state estimation for pinpoint landing of spacecraft. The objective of this task is to investigate and develop real-time estimation techniques for aiding inertial navigation with image-based estimates for the motion and attitude of the spacecraft. More specifically, it is designing and implementing an Extended Kalman Filter (EKF) estimator that processes inertial measurements of acceleration and rotational velocity, provided by an Inertial Measurement Unit (IMU), and images of visual features on the surface of the planet such as craters, ridges, and mountain peaks, acquired during the EDL phase.

Employing previous knowledge of their location and the ability to autonomously detect and track them through sets of images, features on the surface of a planet are categorized as: (1) Mapped Landmarks (ML) whose positions have already been determined in planet-based coordinates from satellite imagery, (2) Persistent Features (PF) which are distinct scale-invariant visual features that appear throughout sequences of images (these correspond to surface characteristics difficult to accurately model and consistently match to known features in satellite images), or (3) Opportunistic Features (OF) that appear and can be reliably tracked only between pairs of images.

The treatment of the visual-feature measurements within the EKF estimator differs according to their characteristics and information content. In particular, sets of at least three MLs provide measurements that support direct estimation of all degrees of freedom for the attitude of the spacecraft. Depending on the number of mapped features within the field of view of the camera, these mapped features are used to derive estimates of the state of the spacecraft, or impose constraints on combinations of them.

This form of aided inertial navigation allows for precise state estimation for most of the EDL phase, provided that the projection of the MLs is within the image plane. During the later phase of EDL, when approaching the surface of the

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planet, the role of the PFs and OFs becomes more prominent. Specifically, the position of the PFs will be included in the state vector and estimated in real-time once their images become available to the EKF. Information from subsequent observations of PFs will be used to correct for estimation errors from the noise in the inertial measurements. Finally, in order to increase robustness and achieve real-time performance, OFs will be treated separately and only the inferred estimates of spacecraft attitude displacement will be provided to the EKF estimator. Previous results in related work are being leveraged by this effort, and all algorithms are being integrated and tested on an autonomous helicopter platform. It is anticipated that this effort will result in a new class of estimation algorithms that will allow precise navigation through different phases of EDL and provide pinpoint landing capabilities by leveraging information from both inertial and visual sensors. The expected level of achieved accuracy (1 sigma) is better than 50m and 0.3 deg^o in position and orientation accuracy respectively at altitudes up to 10km with 20 matched landmarks. The computational and memory requirements for the final product will be approximately 30 to 40% of a 100MHz Power PC (PPC) 750 CPU and 30MB of memory.
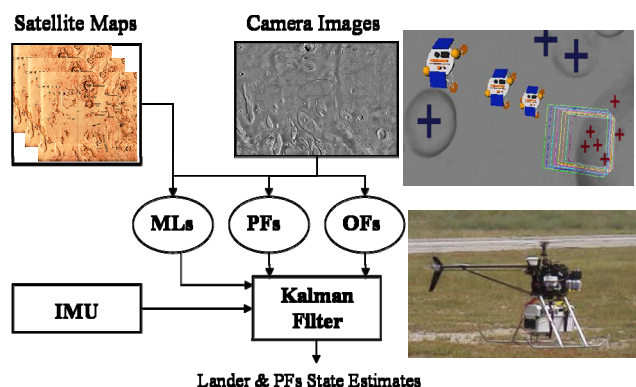

Figure 6 – Estimation block diagram

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2.6 Coupled Mars Guided Parachute Design and Flight Test (PI: John McKinney, Boeing Co.)

The objective of the Mars Guided Parachute (MGP) program is to demonstrate the technical feasibility of reducing landing site errors on Mars during descent by using parachute Wind Drift Compensation (WDC) control. The technology being developed would be used during the descent phase of the Entry, Descent, and Landing (EDL) process. This program is one component of a set of comprehensive EDL system technologies that support pinpoint landing to within tens of meters of a target landing site. This technology applies to both manned and unmanned landings on Mars.

This task was initiated August, 2004. The program involves

a Boeing led team including Irvin Aerospace, Global Solutions for Science and Learning (GSSL), Vertigo, Inc., and Oregon State University. The contract effort is being accomplished by means of four principal tasks. First, a computer simulation has been developed to predict controlled descent performance in various Martian wind environments. Second, an open-loop high altitude flight test was conducted in the 1st year to validate parachute aerodynamics at an equivalent Martian atmospheric density range. Third, a closed loop flight article will be designed and assembled utilizing winches to vary the differential riser lengths to "slip" the parachute in the desired directions. Finally, a closed-loop flight test will demonstrate fully autonomous controlled descent. At this point, all planned objectives for Year 1 have been accomplished.
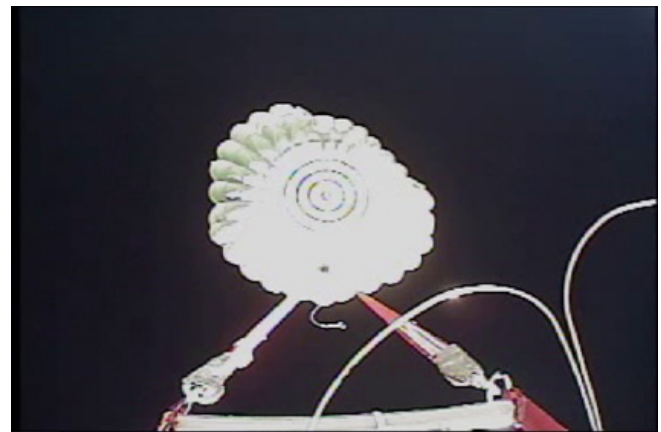

Figure7 – Modified Beagle 2 parachute in glide mode

The planned Open-Loop gliding parachute test was conducted on April 21, 2005. A view looking at the inflated, gliding parachute is shown in Figure 7. The 6-DOF simulation has been developed and runs are being accomplished to duplicate results of the drop test. Configuration options have been identified to reflect and respond to what was learned from the Open Loop test and a specific course of action will be implemented. Results of the program will be documented and delivered in a final report at the completion of efforts which is planned for January, 2007.

3. EDL SENSOR TECHNOLOGY DEVELOPMENT

3.1 A Miniature Coherent Velocimeter and Altimeter (MCVA) for Terminal Descent Control (PI: Daniel Chang, JPL)

The objective of this task is to apply state-of-the-art integrated-optic components to the development of a sensor that specifically addresses many of the shortcomings of existing radars for the terminal guidance of soft-landers.

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MCVA will provide cm/s-accuracy velocity and meter-accuracy position measurements at 10-100Hz update rates. The emphasis of this proposal has been to take advantage of component technologies to minimize the sensor's power and mass footprint while maximizing the ease of designing an EDL system around it. For example, a novel measurement technique- Binary-Frequency Shift Keyed Pseudorandom Noise ranging (BFSK-PN) will be developed, but only because this permits the use of a single, low power waveguide electro-optic modulator for simultaneous Doppler frequency biasing and range-code modulation.
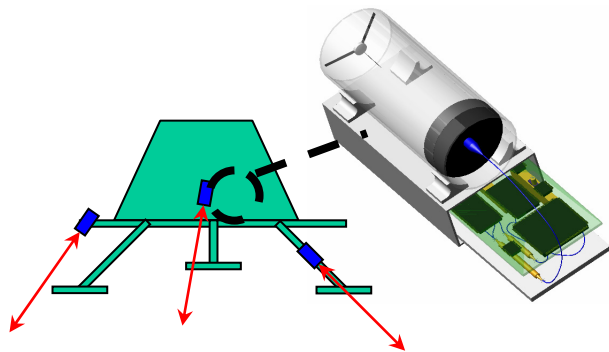

Figure 8 – Miniature Velocimeter and Altimeter

The task is divided into three phases. Phase 1 is feasibility demonstration in a laboratory environment which was completed in. March 2005. The prototype sensor which integrates electronics, optics, and telescope in a single package, but with velocimeter-functions only is expected to be completed in January, 2006.

3.2 Rock Hazard Avoidance System (ROHAS) (PI: Karl Blasius, Raytheon Santa Barbara Remote Sensing)

ROHAS is intended to further the development of a navigation aid to support a controlled landing, with terminal navigation corrections, to a rock hazard-free location close to the nominal landing site. There are two subtasks:

- Miniature thermal IR camera core developed to breadboard demonstration maturity (TRL 4), including a flight-like digital signal processing board
- Hazard data processing algorithms developed to a similar level of maturity and demonstrated using simulated landing images

The anticipated end products are demonstrations of TRL 4 maturity for the camera core breadboard and the hazard detection-mapping algorithms.

The expected completion dates are March 2006 for the

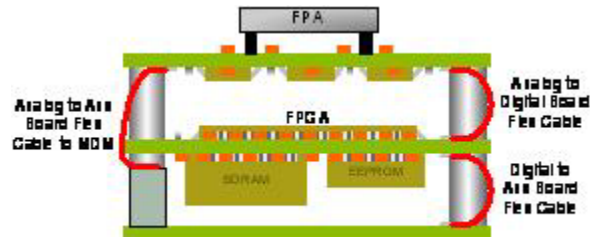camera core breadboard demo and September 2006 for the algorithms demo.

Figure 9 – ROHAS miniature thermal IR camera core

3.3 Next Generation Radar for Improved Hazard Detection, Velocimetry, and Altimetry (PI: Gregory Sadowy, JPL)

Safe, precise landing on planetary bodies requires knowledge of altitude and velocity, and may require active detection and avoidance of hazardous terrain. Radar offers a superior solution to both problems due to its ability to operate at any time of day, through dust and engine plumes, and ability to detect velocity coherently. While previous efforts have focused on providing near term solutions to the safe landing problem, the high accuracy requirements in velocity and position estimation will require the design of advanced radar velocimeters and radar imagers for missions beyond the next decade.

Figure10 – G-band radar for hazard detection, velocimetry, and altimetry

The objective of this task is to make advances in the design of a G-band radar velocimeter and altimeter with a center frequency at or around 160 GHz. Such a system is capable of achieving sub-10 cm/s accuracy, and a G-band imager is capable of sub-0.5 degree resolution over a 28 degree field of view. The focus of the task is to develop power and low noise amplifiers, signal distribution methods, and antenna arrays that enable the construction of these next generation sensors [4]. It is anticipated that the task will complete its key development by July of 2007.

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4. HAZARD DETECTION AND ASSESSMENT TECHNOLOGY DEVELOPMENT

4.1 *Passively Imaged, Multi-Cue, Hazard Detection for Safe Landing (PI: Yang Cheng, JPL)*

The objective of this task is to develop a passive-imaging-based, multi-cue HDA system for Mars and other lander missions. This is the first passively imaged HDA system that will seamlessly integrate multiple algorithms (crater detection, slope estimation, rock detection and texture analysis) and multiple cues (crater morphology, rock distribution, shadows) to detect a variety of landing hazards (craters, steep slopes, discontinuities and rocks) in real time.
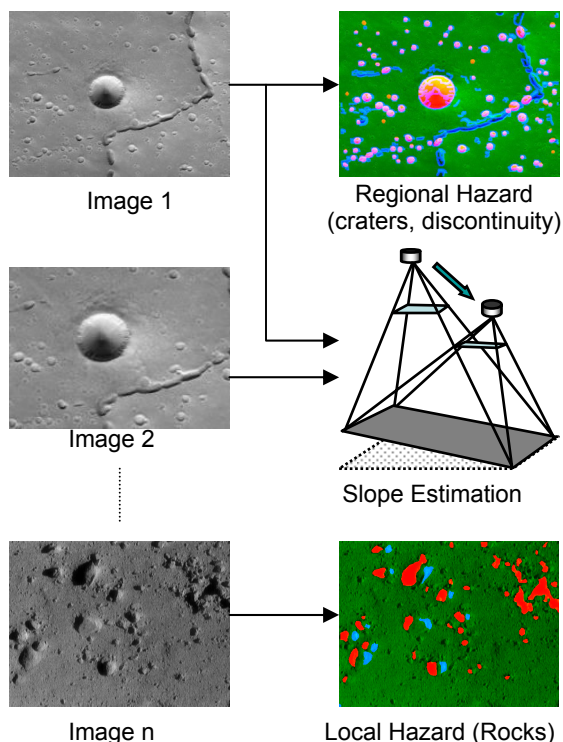

Figure 11—Multi-cue hazard detection system

Two key algorithms of this system have been developed so far which are:

- A new spacecraft motion and slope estimation algorithm. This new algorithm can accurately and rapidly estimate the spacecraft motion as well as the surface slope by using two descent images (Figure 11)**.**

- A new rock detection algorithm**.** This new algorithm detect, extract and model rock shadows and estimate their height and size by using known sun elevation and azimuth as well as shadow model.

It is expected that a passive image based comprehensive

hazard detection system will be delivered at the end of this task (July/2007). The system will be able to operate under Mars EDL constraints for computing power, speed, and hazard detection robustness. The system will be able to update various hazards detection between 0.2 to 1 Hz and its hazard detection rate is better than 90% and the selected landing site is better than 99% safe. The final Technology Readiness Level (TRL) level will be 5. The proposed system will be applicable to numerous Mars and other planetary body missions, such as low cost scout, pinpoint landing mission, Mars Sample Return, and lunar lander mission [5].

4.2 *Multi-Sensor Hazard Assessment and Safe Site Selection (PI: Homayoun Seraji, JPL)*

The goal of this task is to develop and demonstrate the enabling technologies needed for autonomous safe spacecraft landing on a planetary surface using on-board terrain sensors (e.g. radar, camera, lidar). The landing site selection will be based on site safety, science return, and engineering constraints (e.g. fuel). A novel tiered sensor fusion methodology for real-time terrain assessment is proposed which uses a combination of active and passive sensors, specifically, radar, camera, and lidar, which operate in three tiers according to their inherent ranges of operation. Low-level terrain features (e.g. slope, roughness) and high-level terrain features (e.g. hills, craters) are integrated using principles of reasoning under uncertainty.

Three methodologies to infer landing safety: *Fuzzy Reasoning, Probabilistic Reasoning*, and *Evidential Reasoning*. The safe landing predictions from each fusion engine are consolidated in a subsequent decision fusion stage aimed at combining the strengths of each fusion methodology. Finally, we present and discuss results from simulated spacecraft descents [6]
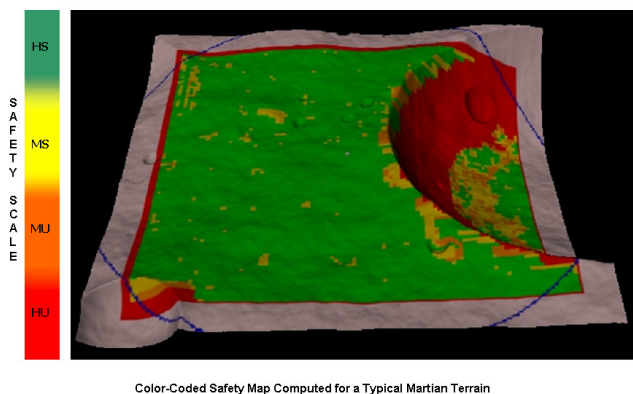

Color-Coded Safety Map Computed for a Typical Martian Terrain

Figure 12 – Safety mapping resulting from multiple sensor data fusion

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The end-product of this task will include a complete end-to-end dynamic simulation environment demonstrating a spacecraft with on-board sensors in the terminal descent phase approaching and landing on a planetary surface. Complete documentation and software of all the algorithms developed within the task will be delivered to MTP. In addition, a comparative statistical analysis of using multiple sensors versus a single sensor for safe landing in different regions of Mars using actual Mars data obtained from Mars Orbiter Camera (MOC), Mars Orbiter Laser Altimeter (MOLA), and MER will also be carried out. It is expected the task will be completed by July, 2007.

5. CONCLUSION

Mars Technology Program has been developing advanced technologies needed for future Mars missions. Base Technology Program Element of Mars Technology Program addresses technologies that are applicable for multiple missions and can be characterized as longer term, higher risk, and high payoff technologies. These technologies are acquired primarily via competed NASA NRA process. This paper presented an overview and status of technology development efforts within MTP in the area of Advanced EDL. These technologies are scheduled to be completed by July 2007. At the end of the development, most of these technologies will achieve TRL 4~5 and require further development prior to technology infusion to a mission.

ACKNOWLEDGMENT

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BIOGRAPHY

Dr. Cheng-Chih (Chester) Chu received the M.S. degree in Electrical Engineering and Ph.D. degree in Control Science from University of Minnesota, Minneapolis, MN, in 1981 and 1985, respectively. His research interests include robust control, system identification, and flexible structure control problems. His current research focuses primarily on the development of robust attitude estimation algorithms, autonomous GNC technology, feature tracking, formation flying control, autonomous rendezvous, and simulation software tool development. Dr. Chu is a member of IEEE and AIAA. He has published over 40 articles in the areas and robust control, system identification, control of flexible structures, image processing, and feature tracking. He is presently the program manager for Mars Base Technology Program at JPL.