Visual Methods for Small Body Exploration

Task Members

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Proposal Summary

This task will develop machine vision algorithms that enable autonomous exploration and sample return from small bodies through onboard visual feature tracking and landmark recognition. These algorithms will provide estimates of spacecraft motion and position used to guide the spacecraft during autonomous landing and exploration. They will also enable hazard avoidance by providing estimates of 3-D surface topography through processing of monocular image streams. This is **continuing**, low TRL, **push** technology task. The total funds requested for this task is $500K over two years.

On-board autonomy, including precision landing and hazard avoidance, are critical enabling technologies for multiple missions. Within the Space Science Enterprise, this task is **endorsed** by Comet Nucleus Sample Return. Other relevant SSE missions are Large Asteroid Sample Return, Titan Organics and Europa Lander. This technology is also applicable in the Earth Science Enterprise in the areas of autonomous guidance sensing for pointing of fleets of spacecraft (sensor webs) and autonomous navigation to determine the real-time position between spacecraft.

Objective, Description & Benefit

Due to the small size, irregular shape and variable surface properties of small bodies, accurate position estimation and hazard avoidance are needed for safe and precise small body landing and sample return. Because of the communication delay induced by the large distances between the earth and targeted small bodies, landing on small bodies must be done autonomously using on-board sensors and algorithms. Current navigation technology does not provide the precision necessary to accurately land on small bodies, so other positioning techniques must be investigated. Optical sensors combined with autonomous machine vision algorithms offer a solution to the precise positioning problem; images can be automatically analyzed to determine the position of a spacecraft with respect to a proximal body. Since current camera resolutions enable visual positioning with errors on order of centimeters from a range of hundreds of meters, visual position estimation is accurate enough for small body landing. Simultaneous with position estimation, surface topography for hazard avoidance can be extracted from monocular image streams using motion stereo techniques. Furthermore, with few algorithmic changes, the techniques developed by this task can also be applied to the problem of precision pointing of scientific instruments and autonomous rendezvous and docking operations.

Problem Formulation

To enable this capability, multiple machine vision problems need to be investigated.

Visual Position Estimation: Although some degree of autonomous, onboard position estimation capability has been demonstrated [3][9][10], the feature tracking and landmark recognition capabilities required to enable safe small body exploration do not exist. One method for visual position estimation relies on tracking image features through a sequence of images. Image *features* are image pixels that have a high probability of being matched between two images taken from similar, but not necessarily the same, camera locations. By detecting and then tracking image features through a sequence of images, the six degree-of–freedom (DoF) relative motion of the spacecraft can be determined for each frame. This capability is useful for maintaining continuous estimates of spacecraft position, but since it does not give absolute position with respect to a body centered coordinate system, its usefulness is limited. The challenges in feature tracking are maintaining features tracks though long image streams and detecting features in comet and asteroid imagery. For motion estimation from feature tracks to be work in practice, it must be made robust to outliers and be able to estimate motion from a few feature tracks distributed unevenly across the image.

Another method for visual position estimation is landmark recognition. A *landmark* is a 3-D position on the surface of a body whose appearance is stable across moderate changes in viewing direction and illumination conditions (e.g., craters on an asteroid [5]). Landmarks are detected during 3-D modeling of the body and stored in a database. During landmark recognition, landmarks detected in an image are matched to landmarks in the database. Since the 3-D position of landmarks are known, recognizing a few landmarks in a single image is sufficient for determining the absolute position of the spacecraft relative to the body centered coordinate system. Landmark recognition is more time consuming than feature tracking, so it cannot be done at frame rate. The difficulties in landmark recognition are finding suitable models for landmarks that facilitate detection and matching landmarks to a database in an efficient manner.

These two methods of position estimation are complimentary. By combining the continuous updates of relative position from feature tracking with the occasional updates of absolute position from landmark recognition, continuous estimates of spacecraft position in absolute body centered coordinates can be obtained.

Motion Stereo Vision: Using image-based motion estimation and stereo vision techniques, it is possible to generate dense topographic maps of a small body surface from monocular image streams. First image-based motion estimation [2] is applied to determine the spacecraft motion between each frame. Next, each image is rectified to a fixed plane and stereo vision techniques are used to match image pixels to obtain pixel level depth estimates. The accuracy of surfaces reconstructed using motion stereo is directly related to the accuracy of motion estimation. Consequently, techniques to feedback surface reconstruction information to motion estimation are needed to enable accurate surface reconstruction. Another difficulty in motion stereo is dealing in a consistent manner with image regions that cannot be matched reliably due to lack of image texture. In this case, some form of interpolation must be used to guarantee the generation of dense depth maps. Given surfaces generated from motion stereo, terrain hazards can be detected and illumination and viewing direction invariant landmarks for absolute position estimation can be extracted.

Hazard Avoidance: Hazard avoidance includes detecting hazards and then planning paths that avoid the hazards. Hazards can be characterized as high-level (e.g., rocks, cliffs) or low level descriptions (e.g., surface slope and roughness), High-level hazards are detected by segmenting hazard from the background while low level descriptions are computed at each pixel in an image. The difficulty with high level hazard detection is defining the appropriate model for objects that allows for efficient hazard detection and also accurate localization of hazards. The difficulty with low level hazard detection is deciding what combination of low-level hazards create a hazard for the spacecraft. Avoiding hazards once they are detected is similar to obstacle avoidance for ground vehicles [5], except that these techniques must be extended to the six dimensional space of spacecraft movements.

On-board image-based navigation will be applied to autonomous vehicles where computational resources, power and mass are all constrained; the solutions proposed must keep these constraints in mind. Computational efficiency must be a driving force behind algorithm development and proposed hardware systems must keep mass and power to a minimum.

Proposed Ideas and Uniqueness

The following concepts will be developed to solve the small body navigation problems described above:

Autonomous Visual Position Estimation from Comet and Asteroid Imagery During Descent and Orbit: Current missions require optical navigation for orbit determination and instrument pointing during close fly-bys of small bodies and moons of the outer planets. This is implemented by ground-based image processing to extract centroids of small reference targets like asteroids and moons. For the Near Earth Asteroid Rendezvous (NEAR) mission, orbit determination around asteroid Eros will use manual designation of known landmark features on the surface of the asteroid [8]. Limited automation will be introduced in the New Millennium DS-1 mission by implementing onboard centroiding of reference asteroids for autonomous navigation in small body fly-bys [10]. Proposed missions to explore comets and asteroids will not be able to rely on such techniques, because safe, precise navigation will require accurate knowledge of complex surface topography and because the round-trip light time will not allow this to be done on the ground. Therefore, we are developing algorithms that will provide autonomous, accurate, and robust six degree-of-freedom position estimation near a proximal small body.

The visual positioning problem we are investigating spans three axes: comet vs. asteroid, orbit vs. descent, and motion estimation vs. position estimation. In FY98 we investigated motion estimation for comet descent. In FY99, we are investigating motion and position estimation during comet orbit and asteroid orbital position estimation. In FY00 and FY01, we will fill out the axes by developing techniques for asteroid motion estimation during descent and orbit, and comet and asteroid position estimation from descent imagery. We started with position estimation from orbit because it is simpler than position estimation from descent; during descent, landmarks and the scene being imaged change scale, which adds another dimension to the landmark models and matching data structures.

Monocular Motion Stereo Vision: Stereo imaging has been studied extensively, and well known techniques for reconstructing dense surfaces from stereo images exist [8]. Unfortunately, stereo imaging cannot be applied to the small body exploration problem, except near to the surface, because at high altitude the camera baseline required for structure recovery is too large for typical spacecraft structures. On the other hand monocular motion stereo, reconstructing scene structure from a stream of images produced by a single camera, can be used instead of stereo vision at any distance from the small body surface. Unfortunately, motion stereo techniques are not as well established because of the added complexity of computing motion as well as scene structure.

We have techniques for estimating motion between images through feature tracking that also produces scene depth at each tracked feature. Using this coarse scene structure and the provided motion estimate, this year we are developing motion stereo algorithms for reconstruction of a comet surface from orbital imagery. Next year we will investigate reconstruction of scene structure from descent imagery; this is a more difficult problem because the focus of expansion creates a singularity for structure recovery. In addition we will develop techniques for motion stereo from asteroid imagery; since asteroids are less textured than comet imagery, interpolation techniques will have to be employed to guarantee dense structure recovery.

Hazard Detection and Avoidance: Hazard detection and avoidance depend on the mission scenario and the design of the spacecraft. As a baseline we will use the ST4/Champollion spacecraft and mission scenario when designing our algorithms. In their scenario, large slopes, rough surfaces, crevasses and boulders are present hazards to the spacecraft. Our hazard detection algorithms will start by characterizing the surface being imaged in terms of surface slope and roughness using the dense surface reconstructed using motion stereo. Crevasses and boulders will be characterized as scene regions bordered by extreme slopes. Next, constraints on maximum roughness and slope will be used to detect parts of the scene to be avoided, and given these constraints, algorithms will be developed that guide the spacecraft to a safe target patch on the surface while avoiding unsafe parts. As the spacecraft moves, information about hazards will improve and new hazards will be detected and avoided. This type of 3-D hazard avoidance has not been explored, yet it is a necessary capability for small body exploration missions.

The table below summarizes the capabilities that will be advanced, from the current state of the art, by this task.

CAPABILITIES	Current	FY 2000	FY 2001
Trajectory DoF	3 DoF orbit	3 DoF descent	Full 6 DoF exploration
Applicable surfaces types	1 (comet)	1 (asteroid)	2 (comet & asteroid)

State of the Art with Metrics & Justification

By the end of this task, the state of the art in vision-based navigation for small body exploration will be extended in many directions. First, an integrated set of algorithms for 6 degree of freedom motion and position estimation for comets and asteroids during descent and landing has never been developed. Second, these algorithms will perform completely autonomously. These algorithms will also provide techniques for dense surface reconstruction from monocular image streams that enable hazard avoidance and 3-D mapping for in-situ science. Finally, these algorithms are based on a single camera; this has positive implications in terms of power, cost and mass for any spacecraft utilizing these techniques. This task started with conceptualization of these ideas (TRL 1) and will end with a proof-of-concept experiment using realistic data (TRL 3).

Detailed Technical Approach to Advance NASA TRL

<u>FY00 Milestone:</u> Demonstrate comet absolute position estimation from descent. Demonstrate asteroid motion estimation from orbit. In FY00, we will concentrate on two problems: motion estimation from orbital asteroid imagery and comet absolute position estimation during descent. Asteroid orbital motion estimation will be achieved by tracking craters through a sequence of images using crater detection and feature tracking software developed previously in this task. Comet absolute position estimation during descent requires generation of dense depth maps from descent imagery and algorithms for matching of these depth maps to a model of the comet surface generated from orbit. The year will end with a demonstration of asteroid position and motion estimation using data collected during the NEAR rendezvous with Eros (pending availability). Comet absolute position estimation during orbit will be demonstrated using imagery acquired in the lab of a comet analog.. Quantitative of motion and position estimation will be achieved by comparing estimated trajectories to ground truth collected by external means.

FY01 Milestone: Demonstrate hazard avoidance during descent to comets and asteroids. Demonstrate motion and position estimation for descent and orbit of comets and asteroids. In FY01, we finish algorithm development for vision-based small body navigation. First, the capability to track asteroids with scale change caused by descent imagery will be developed. Next, techniques for crater matching previously developed will be used to estimate absolute position. For hazard avoidance, slope and roughness of the surface being imaged will be computed using accurate depth maps reconstructed using previously developed depth map generation techniques. Next, the guidance techniques that bring the spacecraft to a safe landing site will be developed. The year will end with a demonstration of complete motion and position estimation for descent and orbit of comets and asteroids using real laboratory images or spacecraft images taken during recent small body rendezvous.

Final Product: The final product of this task will be a set of algorithms for comet and asteroid absolute position and relative motion estimation for orbit and descent. Algorithms for hazard avoidance during comet and asteroid descent will also be delivered. The algorithms will be tested in a proof of concept demonstration, and consequently will be at TRL 3.

Customer Relevance and Endorsement

The task is being proposed in the Thinking Space Systems Thrust of the Cross Enterprise Technology Development Program (UPN 632). Within the Thinking Space Systems Thrust, this technology lies in the areas of Autonomous Execution and Control and the sub-area of Autonomous GN&C. It is also relevant to the area of Intelligent Assistants and sub-areas Data Fusion and Computer Vision Based Methods.

Within the Space Science Enterprise, the primary user of this technology will be small body missions. A future science mission that can benefit greatly from this mission is Comet Nucleus Sample Return (CNSR). A requirement of CNSR is precision guidance and landing with hazard avoidance to three pre-determined sites on a comet nucleus. The technology being developed in this task enables this capability, and a **letter of endorsement** by Jackie Green, the CNSR Pre-project Manager, is enclosed with this proposal. Other relevant future missions within the Building Blocks and Chemical Origins Campaign in the Solar System Exploration Theme are Large Asteroid Sample Return, Asteroid Tomography and Multi-Asteroid Trojans Flyby Missions. Within the Prebiotic Chemistry in the Outer Solar System Campaign. this technology is applicable to hazard avoidance during landing for the Europa Lander Mission and 3-D surface mapping by aerobots during the Titan Organics Explorer mission. According to the Solar System Exploration Theme Overview by R. Gershman on March 2^{nd}, 1999, on-board autonomy including landing and hazard avoidance are critical enabling technologies for multiple missions, and these technologies are not being researched and developed adequately to meet mission needs.

This technology is also applicable to requirements expressed by other enterprises in the areas of autonomous pointing of scientific instruments, rendezvous and docking, and distributed spacecraft control. In particular the Earth Science Enterprise has need for autonomous guidance sensing for pointing of fleets of spacecraft (sensor webs) and autonomous navigation to determine the real-time position between spacecraft. The Human Exploration and Development of Space Enterprise has need for tools to support human operations in space. This task can provide the fundamental techniques for automatic relative position estimation for to aid humans during rendezvous and docking operations.

Team Qualifications

Dr. Andrew E. Johnson: Manager of two CETDP technology tasks (FY99). ST4/Champollion flight project member. 8 years of experience in 3-D computer vision and autonomous navigation.

Dr. Larry Matthies: Supervisor of JPL Machine Vision Group. Task manager of Army and DARPA funded autonomous robot tasks. 20 years of experience in autonomous navigation, obstacle detection and stereo vision.

Dr. Yang Cheng: 6 years experience in computer vision and photogrammetry. Developed first conformal mapping algorithm for small bodies.

References

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Dr. Peter Norvig
NASA /Ames Research Center
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Dear Dr. Norvig:

I am the Pre-project Manager of Comet Nucleus Sample Return (CNSR), a follow-on mission to ST4/Champollion. A key element of the CNSR mission, is the acquisition of material samples from three pre-selected sites on the surface of a comet nucleus. To target and land accurately at the selected sites, estimates of body relative motion and position are required for autonomous navigation of the spacecraft in the dynamic comet environment. Current missions (DS1,ST4) use optical sensors and machine vision algorithms for autonomous vision-based navigation. It is our intention to build on the advances made by these missions. However, due to the large amount of small body exploration necessary to complete the CNSR mission, more capable autonomous vision-based navigation techniques are needed than are currently available.

I was pleased to learn about the technology task "Visual Methods for Small Body Exploration" being proposed to the Thinking Systems Thrust Area of the Cross Enterprise Technology Development Program. This task is studying ways to estimate spacecraft motion and position around small bodies using image-based methods. If this technology demonstrates a promising solution to autonomous small body navigation, then we will definitely consider infusing the developed technology into CNSR.

Sincerely,

Jacklyn R. Green, Ph.D.
Comet Nucleus Sample Return
Pre-Project Manager