CRAFTI: A Canadian Asteroid Mission

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Historically, planetary exploration has been performed using large, complex, and costly spacecraft that have attempted to bring a laboratory of instruments with them. Only in the early days of the American and Russian space programs were the missions less complex and more focused. The Canadian Robotic Asteroid Flyby and Tentatively Impact (CRAFTI) mission proposes to return to some of the philosophies of that era, and to bring modern microsatellite design philosophies into planetary exploration.

The CRAFTI mission is a concept study being undertaken by the University of Toronto Institute of Aerospace Studies Space Flight Laboratory (UTIAS-SFL) and the Canadian Space Society, with funding from the Canadian Space Agency and technical support from Dynacon Enterprises Limited. The study is aimed at proving that microsatellite technology can, and should, be applied to planetary exploration. The principal investigator is Dr. Kimmo Innanen of York University, and the lead engineer is Henry Spencer of UTIAS-SFL.

The target of this project is a Near Earth Asteroid suitable for a relatively slow flyby, tentatively chosen to be Toutatis during its 2008 closest approach with the Earth. Asteroids present the best target for such a mission, as they offer the greatest possible science return for relatively simple instruments and relatively low mission cost. In addition, a flyby during closest approach turns out to be a surprisingly easy mission.

The CRAFTI mission presents an opportunity to prove that microsatellite technology has come of age, not only in Earth orbiting spacecraft, but also in the realm of planetary exploration. The key to success is a careful tradeoff between available spacecraft resources and mission design, and having on board only what is absolutely necessary for the mission to succeed. This paper will highlight the tradeoffs, and examine the proposed spacecraft design and overall mission plan.

Introduction

Traditionally, planetary exploration missions cost hundreds of millions, or even billions, of dollars. For instance, the Cassini spacecraft now on its way to Saturn has an estimated total program cost of US$3.3 billion. Even NASA's Discovery program, which emphasizes lower costs, typically costs $100M or more per mission. Lunar Prospector, the first Discovery mission, was considered an outstanding bargain at approximately $63M. More recent Discovery missions have all been more expensive.

The Canadian Space Agency could afford expenditures even at the comparatively modest Discovery level only as part of a major policy initiative, which seems politically unlikely[1]. At first glance, the cost alone would seem to preclude independent Canadian planetary exploration missions. Upon closer examination, however, this is not the case.

The Microvariability and Oscillations of Stars (MOST) microsatellite [1], with a budget of approximately CDN$6M, could *almost* operate in deep space. It would need small adjustments to engineering details, plus:

- An attitude control system (ACS) less dependent on Earth's magnetic field (star sensors and thrusters instead of magnetometers and magnetorquers).
- Longer communications range (high-gain antennas and greater transmitted power).

This would complicate the design, but the cost increase would be modest. This suggests that deep space spacecraft need not be costly.

[1] CSA has recently announced a major Mars initiative, but funding is uncertain and details are unclear.

Deep Space Missions

Merely being able to operate in deep space is not sufficient to conduct a planetary mission. Also required are:

- A launch, and subsequent maneuvers, sufficient to reach the target.
- Trajectory corrections to encounter the target in the intended manner.
- Instruments capable of returning useful science data from the encounter.

These issues present somewhat more substantial problems, but not so severe that they are beyond low-cost solutions, provided the mission is chosen with care and restraint.

Small spacecraft cannot do every planetary mission. But with careful balance, planetary exploration is not beyond the reach of the microsatellite approach, and at microsatellite price tags.

There are some constraints. Planetary exploration on a microsatellite budget appears possible if:

- Spacecraft design is optimized for low-cost, available launching solutions.
- Small-scale propulsion is developed to flight readiness.
- Targets and missions are chosen with cost in mind.
- Restraint is exercised in choice and development of science instruments.
- Microsatellite philosophy is applied throughout
- existing design heritage is maximized.
- An experienced team performs the required work.
- Project work is completed at a fast pace to avoid the extra overheads of lengthy programs.

The CRAFTI Concept

Thus, the Canadian Robotic Asteroid Flyby and (Tentatively) Impact (CRAFTI) concept.

CRAFTI is a Canadian Space Agency (CSA)-sponsored concept study for an all-Canadian planetary mission on a microsatellite budget. The target cost is under CDN$20M (approximately US$13M) including launch and operations.

The spacecraft concept uses MOST technology wherever possible, developed by the MOST team at Dynacon and UTIAS-SFL. The mission involves a flyby of a near-Earth asteroid as the asteroid passes near Earth., and is implemented using two secondary payloads on Ariane 5 communications satellite launches.

To enhance mission reliability, CRAFTI proposes to revive a venerable NASA custom: launching two identical spacecraft for each mission. Building and launching a second identical spacecraft is relatively inexpensive, and it provides excellent insurance against mission loss due to component failure, operations error, or launch failure.

One question that arises, then, is given two spacecraft, what extra science can be performed if both spacecraft succeed in arriving at the target? If this occurs, one spacecraft will be tasked with the primary mission flyby, while the other spacecraft will attempt an impact. The impacting spacecraft can perform science, including imaging, at very close range, and the observations of the impact from the flyby spacecraft will yield information about the structure of the outer layers of the asteroid.

CRAFTI and MOST

The MOST project is currently demonstrating that a small astronomy satellite can be built and flown for a total cost (excluding launch) of ~CDN$6M (US $4M). Flight hardware is now under construction, and although slightly behind schedule, MOST is still on specs and on budget.

Much of the design heritage for CRAFTI comes from the MOST hardware. Many components on the MOST system, shown in Figure 1, can be reused, with modification, in a spacecraft such as CRAFTI. While new subsystems are needed, and some need to be largely redesigned (for instance, the radio subsystem), the reuse of this hardware will help make CRAFTI inexpensive.

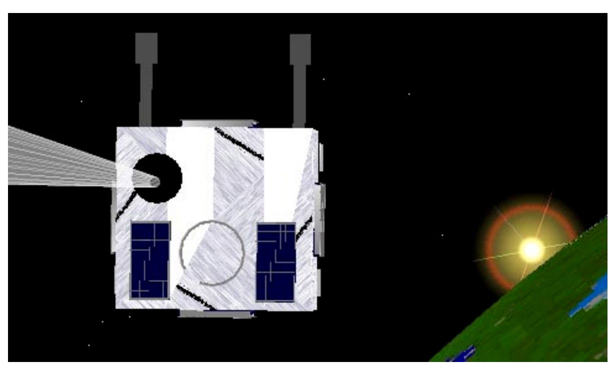

Figure 1: The MOST Spacecraft

Additionally, the experience gained by the UTIAS-SFL team in building and operating MOST and other planned microsatellite projects provides an excellent experience base for building and flying CRAFTI.

Projects have natural durations. While trying to compress them too much can lead to difficulties, as seen in some recent NASA failures, doing them at too leisurely a pace has its own problems. Brisk progress toward a prompt launch makes design easier, reduces documentation requirements, avoids problems with parts obsolescence, and improves staff morale. Most importantly, it avoids the extra costs of paying people to sit around and wait, and the subtler but even more serious costs of trying to operate a spacecraft after its development team has departed.

Launches

A dedicated launch to an interplanetary trajectory is costly, and large planetary missions are infrequent and seldom have mass to spare on secondary payloads. How, then, to launch a low-cost planetary mission?

If the spacecraft has a substantial propulsion system of its own, the difference between a high-energy Earth orbit, such as geostationary transfer orbit (GTO), and an escape trajectory is surprisingly small. It is actually easier to reach an escape trajectory than to reach geostationary orbit (GSO). Piggybacking into GTO on launches of communications satellites is almost as good as a direct interplanetary launch.

A further advantage can be had, at the expense of reduced launch opportunities, by choosing launches which are going to supersynchronous transfer orbits, with apogee above GSO. Such transfer orbits reduce apogee-burn fuel consumption for lightweight communications satellites with liquid-fuel apogee motors. An extreme example is Orion 1, whose transfer-orbit apogee was 120,000 km, approximately three times the altitude of GSO. While such extreme cases are rare, slightly supersynchronous transfer orbits are becoming common, and even a modest increase in apogee adds significant energy to the orbit and makes escape trajectories easier to reach.

One major difficulty with launch as a secondary payload is that CRAFTI cannot control the launch date or the exact initial orbit. This is normally a problem, given the limited launch windows usual for planetary missions. However, since a spacecraft such as this has to maneuver out of orbit by itself anyway, it can launch ahead of time, and wait in a parking orbit until the right moment. Discrepancies between the desired pre-departure orbit and the results of launch can be removed at leisure during the wait.

The initial GTO is not a desirable parking orbit because of high radiation doses from passage through the Van Allen radiation belts. Some immediate orbit-raising maneuvers are necessary to reduce the total radiation dose, with the actual parking orbit perigee being significantly higher.

In short, given capable on-board propulsion, suitable cheap launch opportunities are available.

Propulsion

A planetary spacecraft needs on-board propulsion for at least three reasons:

- Reaching the desired trajectory can require major spacecraft maneuvers after launch, such as with a launch to GTO.
- En-route course corrections are mandatory, as the required trajectory accuracy is beyond that of any launcher.
- Deep-space attitude control requires thrusters, if only for momentum dumping.

Traditional chemical propulsion systems suffer from using hazardous chemicals that may not be acceptable at all for secondary payloads. Even if secondary-payload launches can be found with such a system, using it will certainly limit launch opportunities, and the handling problems and certification requirements are notorious for greatly increasing costs.

Cold-gas thruster systems are adequate for attitude control, and may suffice for course corrections, but their I_{sp} is inadequate for major maneuvers such as Earth departure.

Ion rockets and similar systems can use inert fluids, and have very high I_{sp} values, but need very large amounts of power. They also have very low thrust, which makes major maneuvers extremely tedious.

Electro-thermal propulsion [2] systems offer a compromise. They are capable of running on inert fluids. Their Isp values are high enough to be interesting and low enough to keep power requirements reasonable. Their thrust, although low compared to chemical rockets, is high enough to conduct maneuvers reasonably promptly.

Unfortunately, apart from resistojets (whose performance is not considered adequate), electro-thermal thrusters are poorly developed, especially in small sizes. Most development work has gone into larger systems.

However, some promising concepts exist, notably recent work at Pennsylvania State University on the microwave electro-thermal thruster (MET) [3,4], which uses focused microwaves to heat inert propellant. This system has been demonstrated in suitable sizes (100-200 W, thrusts of tens of milli-newtons) with acceptable performance (I_{sp} of 600-1000s, energy efficiency approximately 50%). The required power is quite significant for a microsatellite, but within the range where simple hinge-deployed solar arrays will be sufficient. The thrust is sufficient to apply a ΔV of several km/s in a time measured in months, and the I_{sp} is sufficient to keep propellant consumption within reasonable bounds for a microsatellite.

Two other candidate systems have been tentatively identified, although they are somewhat less attractive because they are not currently in active development.A thorough search might well find more.

Although further development is needed, suitable propulsion systems appear to be feasible.

Targets

What sort of mission and target would yield good science at low cost?

The Moon would superficially seem to be a good choice, being nearby and relatively easy to reach. However, it has had a lot of attention already, and much of the science that can be performed on it with simple instruments has already been done.

The planets, especially Mars, are of great scientific interest but relatively far away. This increases launch and propulsion requirements, lengthens mission duration, imposes very long communications ranges, and implies operation over a wide range of environments (e.g. thermal conditions). The planets also suffer, to a lesser extent, from the Moon's "all the simple science has been done" problem.

Asteroids, notably near-Earth asteroids, are an interesting alternative. They are poorly explored, with relatively few asteroid missions planned and many open questions which those missions are unlikely to resolve. They are a diverse collection of bodies, so even the most elaborate mission to one asteroid does not exhaust the field.

Particularly noteworthy are asteroids that come very close to Earth at certain times in their orbits. A simple flyby mission to such an asteroid can be relatively brief, and can be conducted entirely in Earth's neighborhood, with easy communications and a minimum of environmental variation.

Programmatic considerations suggest that a launch before 2006 is unlikely to be possible, and 2007 is more realistic. This is also good timing from another viewpoint: it is roughly the time of the next solar minimum, when deep-space radiation intensity will be low.

While asteroids come past Earth with some frequency, there are some additional characteristics that would make an asteroid particularly attractive:

- Large size (easier to study, easier to hit)
- A well-known orbit
- A low relative velocity as it passes Earth (resulting in a slow encounter with more time for observations)

These additional constraints greatly reduce the list of candidates. In fact, there is only one good candidate around the appropriate time: Toutatis. In late 2008, Toutatis will come within about 8 million kilometers of Earth, at a relative velocity of about 10 km/s. It is several kilometers across, and its orbit is known with great accuracy. As a bonus, both radar observations [5] and spectroscopy [6] suggest that Toutatis is a double asteroid, composed of two bodies that have hit and stuck together, giving CRAFTI a look at two asteroids for the price of one.

Trajectory Selection

Modest Earth departure velocities can reach quite large volumes of near-Earth space in relatively little time. The plot in Figure 2 shows the area of the ecliptic reachable in 90 days, starting with 1 km/s of hyperbolic excess velocity.

The Earth and Moon in the center are not to scale, although the Moon's orbit is. The trajectory plots start at Earth's sphere of influence, the distance at which the Sun's gravity begins to dominate trajectories. Toutatis is shown passing, with dates.

The actual trajectories, of course, are three-dimensional. Toutatis actually passes slightly south of the plane of the ecliptic. That changes details but not general results.

An encounter in early- to mid-November can happen less than two months after Earth departure, even at this relatively modest departure velocity. One problem, however, is that these trajectories cut across Toutatis' path at a fairly sharp angle. To minimize the relative velocity of the encounter, CRAFTI must cross Toutatis' path at a shallow angle while moving at the highest possible speed, as Toutatis is overtaking CRAFTI from behind.

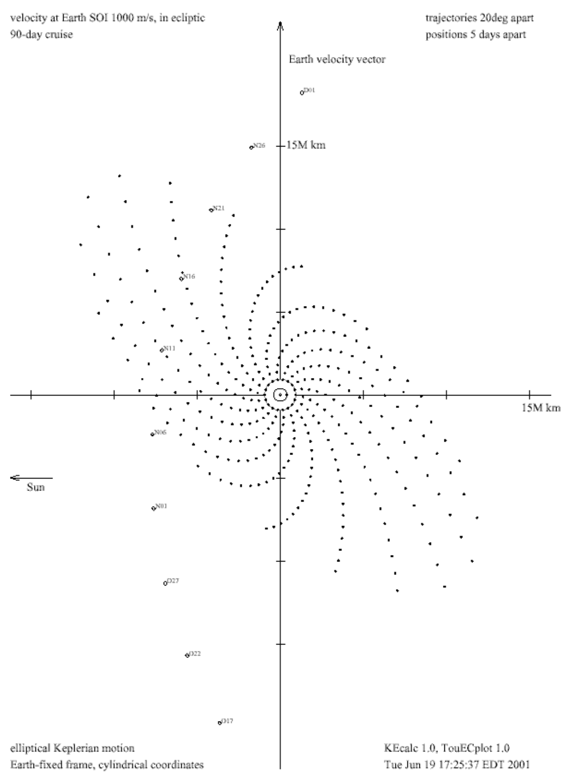

Figure 2: Reachable Volume in 90 Days

The plot in Figure 3 shows two somewhat longer trajectories that are more promising. One parallels Toutatis' path almost exactly, in mid-November, but takes about ten months to arrive and is moving relatively slowly at encounter. The other crosses slightly earlier, at a bit of an angle, but is moving faster and hence has a somewhat lower net relative velocity. Its cruise phase is only about seven months long.

Definitive trajectory selection depends on results from a more sophisticated Earth-departure analysis. These plots illustrate that there are feasible trajectories which reach Toutatis after modest cruising times, and also that there is a lot of room for optimization, depending on the exact mission priorities.

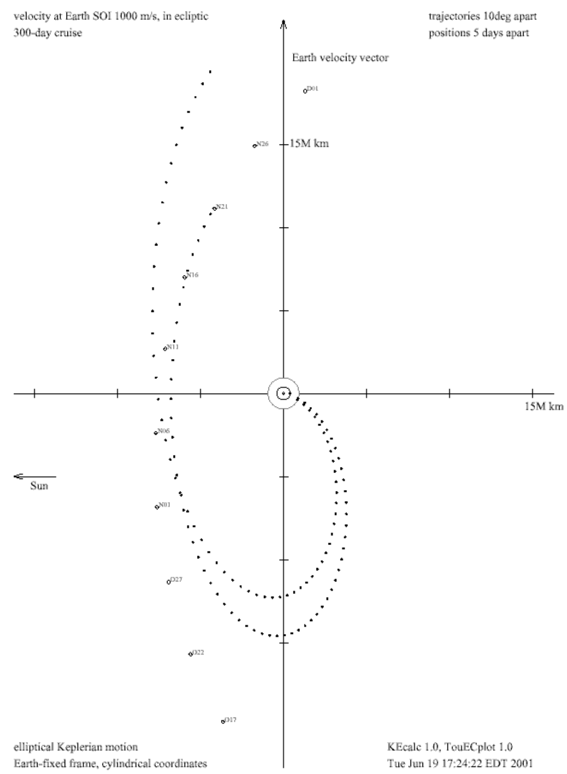

Figure 3: Sample Trajectory Plots

Required ΔV

Computing the necessary ΔV to reach these trajectories presents a problem.

The calculations are relatively simple for high-thrust propulsion, such as conventional rockets. Starting from a slightly supersynchronous GTO, and proceeding via a somewhat higher parking orbit, it actually takes less than 1 km/s of total ΔV, spread over three maneuvers, to move up to parking orbit and then to achieve a 1 km/s departure velocity.

Unfortunately, for low thrusts the situation becomes much more complex. The orbit is changing constantly, and a significant fraction of the propellant is expended inefficiently by being carried to high altitude before it is used.

Extensive simulation is the only way to obtain good results for such a complicated situation, and that has not yet been done. The tools must be developed first; low-thrust maneuver planning is a poorly developed area. Rough estimates predict a ΔV penalty factor of 2 to 3 for low-thrust departure.

While this penalty is undesirable, with the relatively high I_{sp} of electro-thermal propulsion, it does not appear to be crippling. More work is needed to determine this exactly. Indeed, a serious study of CRAFTI must include a serious effort to develop useful planning tools for low-thrust maneuvering.

Configuration

CRAFTI's configuration, shown in Figure 4, is based on a 600 mm cube, just fitting within the Ariane 5 ASAP "micro" payload envelope. The high-gain antenna is stowed on top, within a ring-shaped emergency solar array. The launch adapter ring is in the middle of the sun-ward facing side.

After separation, solar panels deploy from four of the sides, and lock into place. Body-mounted solar arrays are largely avoided due to thermal concerns. In keeping with standard microsatellite practice, there are emergency solar arrays facing in all directions, so there is no possibility of the spacecraft ever being without power, even if attitude control is temporarily lost. The ring surrounding the stowed high-gain antenna provides solar-array coverage to all sides, and small arrays on the backs of the main solar panels cover the back.

Also on separation, the high-gain-antenna is released from its stowed position, after which it gimbals on two axes around a point on its rim, for full pointing freedom over somewhat more than a hemisphere. In addition, a long dipole antenna for the radar sounder deploys from opposite faces of the spacecraft (see the Instruments discussion below). Small fixed monopoles at the corners of two of the solar panels are the emergency low-gain antennas.

The main solar arrays, when pointed directly at the Sun, provide about 250 W of power. Of this, 50 W is housekeeping power; the remainder is "large loads" power, used for the electro-thermal thrusters during maneuvering, but available to the radio system otherwise. The emergency arrays provide no large-loads power and less housekeeping power, so prolonged loss of attitude control will require shutting down non-essential systems to keep a positive power balance.

Although CRAFTI isnormally powered directly from the solar arrays, it includes a small battery system. This provides minimal survival power during eclipses in parking orbit, supplies surge power during recovery from attitude-control emergencies, and largely removes Sun-angle constraints during the most active period of the asteroid encounter.

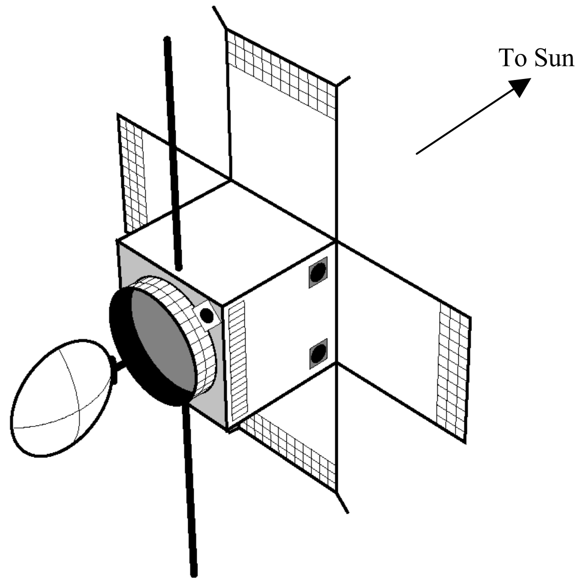

Figure 4: The CRAFTI Spacecraft

Two electro-thermal thrusters are located at opposite corners of the cube (the viewpoint of the figure looks almost exactly into one of them). They have a small amount of gimbaling to permit aiming them exactly through the center of mass. There are two of them, partly for redundancy, and partly to permit thrusting in most directions while still keeping the solar arrays pointed roughly at the Sun (which is also why they are located somewhat off the nominal Sun axis). The thrusters normally run directly from the solar arrays; they use battery power only in emergencies.

The star tracker and the camera look out in the same direction, behind one of the solar arrays (which doubles as a sunshade for them). The star tracker has a relatively wide field of view, and can serve as a "finder scope" for the camera, which has a 1-2° field of view for detailed images at a substantial flyby distance.

The main body is wrapped in multi-layer insulation (MLI) and thermally isolated from the environment as much as possible. The need to retain temperature control despite cycling of large loads, notably the electro-thermal thrusters and the high-power transmitters, dictates some small measure of active temperature control. Tentatively, there are thermostatically controlled louvers on selected parts of the body.

In the baseline design, a large spherical propellant tank, a bladder tank holding 50-60 kg of (tentatively) isopropyl alcohol, dominates the interior of the spacecraft. Everything else is fitted into edges and corners. This is orthodox but awkward.

An interesting alternative approach is to feed the thrusters from a much smaller bladder tank that is occasionally refilled from low-pressure main tanks (which use surface-tension screens to control their contents) by a small electric pump. This would give much greater freedom of interior layout, since the low-pressure tanks need not be spheres (and perhaps could form a major part of the spacecraft structure). The required flow rates are so low that the pump (plus a redundant spare) would not be heavy, although the added mechanical complexity is a concern.

Either way, the tankage is slightly oversized, so that final pre-launch propellant loading can load extra propellant to use up all remaining mass margins.

Communications

CRAFTI clearly requires a high-gain antenna for Earth communications. Assuming a 0.5m dish (which fits comfortably within the Ariane 5 ASAP volume), and an X-band transmitter that can use the 200 W of large-load power, a data rate of about 5 Kbps at encounter is achievable. This assumes the availability of a 15m antenna on Earth.

The most obvious Earth communications facility to use is NASA's Deep Space Network. Unfortunately, DSN is already overcommitted and the situation is steadily getting worse..

United Space Network [7] sells commercial access to a network of 15m dishes. They currently are used primarily for LEO satellites, but deep-space use presents no great problems.

An alternative, if CRAFTI has need of only one ground station, is to add electronics to an existing Canadian antenna. The Algonquin Park radio observatory has a 46m antenna that is lightly used and might be suitable. Another possibility is the 15m Kennedy Array antenna owned by the CSA David Florida Labs (DFL). This antenna is not as big, and it needs mechanical refurbishing as well as new electronics, but it has no other commitments to meet, and it is much closer to high-speed network communications.

In addition to the communications to the ground, CRAFTI includes an inter-spacecraft “crosslink” to support the secondary (impact) mission. Given the modest data rate to the ground, clearly most of the asteroid encounter data must be recorded on board, and trickled back to the ground later. However, the impactor spacecraft cannot do this, since it will not survive the encounter. Its data must be forwarded to the flyby spacecraft for recording there. The data rate is dependent largely on the amount of data generated by the impactor’s science instruments. Data rates of 250 Kbps or more can easily be accommodated.

To reduce the dedicated equipment needed for what is, after all, a secondary mission, the impactor spacecraft uses its high-gain antenna and its main radios for the crosslink. Once the encounter begins, all communications between Earth and the impactor spacecraft are relayed via the flyby spacecraft. The flyby spacecraft uses its backup set of radios, and its low-gain antennas, for the crosslink, since its high-gain antenna and primary radios are in use for the Earth link. (It would not be difficult or costly to include a dedicated medium-gain antenna for the flyby end of the crosslink, but it appears to be unnecessary.)

Attitude Control System

CRAFTI's attitude-control system is derived from that of MOST (which brings precision pointing to microsatellites for the first time), with some improvements dictated by mission requirements.

Primary attitude actuation is by reaction wheels, specifically somewhat larger variants of Dynacon's current MicroWheel. Their momentum capacity needs to be roughly 1 N-m-s to handle the closest approach of the flyby, during which the spacecraft has to turn relatively rapidly (as rapidly as 6°/sec) to track an asteroid passing it at several kilometers per second. Three wheels, plus a fourth for redundancy, handle all attitude control except for the need for occasional momentum dumping.

Primary attitude sensing uses the low-precision rate sensors in the reaction wheels, plus a star tracker as a precise absolute reference. Coarse Sun sensors facing in all directions, and possibly a simple medium-resolution Sun sensor on the sun-ward side, aid initial attitude acquisition. Depending on star-tracker characteristics, it may be necessary to include fiber-optic gyros for the encounter period, when the spacecraft isrotating more or less continuously for target tracking and may need better pointing stability than the reaction-wheel rate sensors can provide.

In the absence of a cold-gas or chemical thruster system, momentum dumping presents challenges. It may be possible, power requirements permitting, to dump momentum around two axes by tilting the spacecraft somewhat, offsetting solar light-pressure thrust away from the center of mass. Without movable surfaces, this approach cannot affect angular momentum around the Sun axis, and it requires attitude stability, so it cannot be used for initial or contingency detumbling. These limitations relegate light-pressure momentum dumping to a secondary role, although at the very least, it will be used to minimize net light-pressure torque during periods of quiet cruise.

The electro-thermal thrusters need limited gimbaling for trim (to point their thrust accurately through the current center of mass) anyway, so deliberate thruster mis-trimming is the primary method of momentum dumping. The limited number of thrusters, limited gimbaling, and constrained spacecraft pointing can require a sequence of two or more burns to bring the wheels back to their nominal operating point, but this seems manageable. Similarly, initial or contingency detumbling can require firing the thrusters on battery power, in short bursts separated by recharging periods, but this too appears workable... if a trifle slow. Given clever software and careful light-pressure trimming, it will typically be possible to do momentum dumping as part of normal maneuvers, so propellant consumption for it will be minimal.

Instruments

Instrument development can be very expensive. The camera systems alone on the Voyagers cost more than entire Discovery-class missions. However, with restraint, simple instruments can be built inexpensively. The ~US$4M budget of MOST includes development of a 15 cm telescope with a cooled focal plane, a pair of high-resolution imaging sensors, specialized optics, and low-noise readout electronics. The entire assembly weighs 13.4 kg and requires 7 W of power.

Low-cost instrument development requires adhering to the microsatellite philosophy: work within the state of the art, rather than pushing it, and consider reductions of capabilities when cost growth threatens. Limiting the number of instruments is also helpful, since clashes between multiple instruments frequently increase costs.

More generally, limiting instrument costs requires choosing a target and mission design that permits simple instruments to do leading edge science. There are science objectives that simply cannot be satisfied, at present, with low-cost instruments. Low-cost mission planning must recognize them and avoid them.

An optical imaging system is a must. It will likely be necessary for approach navigation, and much good, basic science can be accomplished with it. Preliminary analysis indicates that a substantial telescope like MOST's is unnecessary: a simple lens system, probably available commercially, would suffice.

To keep the spacecraft simple and limit costs, the number of instruments must be limited. Yet it seems attractive to try to do something more than just imaging, preferably something novel. Existing asteroid missions are almost all surface science missions, yielding little or no information about the interior, where major mysteries remain. Thus, an instrument for examining the internal structure of an asteroid can break significant new ground.

To this end, a simple radar sounder will be included on CRAFTI to provide a depth profile and show whether the asteroid has a layered or otherwise heterogeneous internal structure. Preliminary analysis indicates that such an instrument isnot difficult to build or particularly power-intensive. It does, however, require either a relatively close flyby (within 100 km) or use from the impactor spacecraft, since radar effectiveness deteriorates very rapidly with distance.

Conclusions

The CRAFTI concept study has identified no fundamental obstacles to flying a planetary-exploration mission at microsatellite prices. Some problems remain, notably finishing development of a suitable propulsion system, but these problems do not appear to be limiting.

Such small missions cannot address all possible objectives, and they will need careful mission planning, based firmly on fitting within a small budget. But many interesting questions of planetary science can be addressed this way. Indeed, many of them could be addressed better this way, because occasional large spacecraft can be replaced by more frequent smaller ones. This avoids the complex operational compromises of large spacecraft with many conflicting instrument requirements, and allows later spacecraft to benefit from experience gained from earlier ones.

CRAFTI appears to be a good first mission of this type. It is feasible, and if full-scale study work is started now[2], it is possible to fly it in time to meet an excellent target: Toutatis in 2008.

Acknowledgements

The CRAFTI concept study was funded by the CSA, and conducted largely by volunteers from the Canadian

[2] A grant proposal for just such a study has been submitted to CSA.

Space Society and students from the University of Toronto Institute for Aerospace Studies. Dr. Kimmo Innanen of York University's Department of Physics and Astronomy was the study's Principal Investigator. The first author, Henry Spencer, is CRAFTI's chief designer. Dynacon Enterprises Limited (prime contractor for MOST) and the UTIAS Space Flight Laboratory (MOST's major subcontractor) provided mentoring and technical support.

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Biographies

Henry Spencer is a freelance software engineer, space historian, and space technologist. He was head of mission planning for the Canadian Solar Sail Project, and is now Software Architect for MOST. He was one of the founders of the Canadian Space Society and is now on its governing board.

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Alex Beattie is a communications engineer with the Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies (UTIAS) in Canada. He is currently in charge of integrating the communication subsystem and ground stations for the MOST microsatellite. He is also currently completing a degree at the Masters level at UTIAS.

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Dr. Robert Zee is co-founder and manager of the Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies (UTIAS) in Canada. He presently leads a team of professional engineers and graduate students in developing micro and nano-satellites for space science, technology research, and education. The first such microsatellite is MOST, Canada's first space telescope for the Canadian Space Agency. Dr. Zee has worked with AMSAT and AeroAstro to help design the MOST microsatellite and cultivate an integrated small team approach at UTIAS for future missions.

In 1991, Dr. Zee joined Spar Aerospace Limited (now MD Robotics) to work on the Space Station Remote Manipulator System in the Controls Analysis and Design Group. There he helped to review the Artificial Vision Function Supported Tracking Mode and analyzed the null-space motion of the seven-jointed Space Station Canadarm. In 1992, he joined Allied Signal Aerospace Company to work on the electrical design and analysis of environmental control units for the McDonnell Douglas C-17A and Boeing 777 aircraft. In 1996, Dr. Zee was project manager and senior control systems designer at the University of Toronto for the Dynamics, Identification, and Control Experiment (DICE), a space shuttle middeck experiment to study the control of flexible space structures.

Dr. Zee's current interests lie in defining collaborative low-cost space missions, and the exploitation of the latest nanotechnologies and Micro Electro Mechanical Systems (MEMS) for use in space.