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Autonomous Rendezvous and Docking Technologies — Status and Prospects[*]

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ABSTRACT

In general, autonomous rendezvous and docking requires that two spacecraft start at a remote distance (i.e., out of sight of each other), come together into a common orbit, rendezvous, dock, and control the new combined spacecraft in both orbit and attitude. Doing this requires developing and testing a variety of new technologies including absolute and relative autonomous navigation, autonomous rendezvous and docking hardware and software (both sensors and actuators), and autonomous control of a "new" spacecraft with different mass and inertia properties than either of the two original spacecraft. While these are very workable technologies, they do require a significant change in mindset — turning over control of thrusters to an on-board computer. While there is substantial potential for cost savings, risk reduction, and new mission modes by use of these technologies, there is a very strong reticence to allowing operational spacecraft to control their own destiny, particularly in firing thrusters for translational motion.

This paper summarizes work at Microcosm in each of the above technologies. Autonomous navigation and absolute orbit control have been demonstrated on orbit. In conjunction with Michigan Aerospace, autonomous rendezvous and docking hardware and algorithms have been demonstrated in parabolic flights and will be tested in zero-g simulations. Approaches have been proposed for more precise and robust autonomous navigation and autonomous on-orbit estimation of combined mass and inertia properties, leading to efficient orbit and attitude control of the combined spacecraft. Many of these technologies can be tested at low cost in parabolic flights, suborbital flights, and evaluation of data from existing or planned missions. Thus, a "coordinated attack" on the complete problem of fully autonomous rendezvous and docking is both feasible and potentially very low cost.

Keywords: Autonomous Spacecraft, Autonomous Navigation, Orbit Control, Rendezvous and Docking.

1.0 INTRODUCTION

There has been a tendency in the past to think of the rendezvous and docking problem as more or less synonymous with proximity operations, i.e. how do the spacecraft navigate and translate when they are very close together. This is certainly a critical element. However, there is significantly more to the problem. In general, the spacecraft must start a long distance apart, quite probably out of sight of each other. Getting closer often occurs in multiple stages, culminating in either inspection or docking activity. Once the spacecraft have docked, they may exchange fluids or other cargo, maneuver together, and ultimately separate.

While it is possible for both spacecraft to maneuver, we usually think of one active spacecraft, called the *chaser*, and one which is a passive *target*, whose principal role is to remain reasonably stable while the chaser does most of the work. The target may be either *cooperative*, with some type of beacon or target and a docking fixture if that is required or *uncooperative*, i.e., a spacecraft that has no active or passive equipment, targets, or procedures to help in the process. Targets may also be actively *hostile*, but these are beyond the scope of this summary.

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Table 1. Top-Level Mission Timeline for Autonomous Rendezvous and Docking. A passive target is assumed.

Phase	Range	Duration	Activity	Chaser Orbit Navigation	Target Orbit Navigation	Orbit Control	Targeting	Issues
I. Separate Orbits	> 10,000 km	Indefinite	Get/Compute target orbit	Assumed, AOC, ground tracking, or AutoNav	Assumed, AOC, or ground tracking	None or AOC	Min. ΔV transfer to drift orbit	Must know target orbit
II. Drift Orbit A (out of sight, out of contact)	> 2 λ_{max}	1 to 20 days	Close on target; look for target; fix orbit errors; propagate target orbit	Assumed, AOC, ground tracking, or AutoNav	Assumed, AOC, or ground tracking	Phasing control from time to time	Drift toward target and fix all other orbit errors	Duration is drift rate dependent; ability to use Earth-based or external resources
III. Drift Orbit B (in sight, in contact)	2 λ_{max} to 1 km	1 to 5 days	OD on target; stop drift maneuver; begin relative navigation	AOC or intermediate navigation	AOC or Intermediate navigation	Phasing control from time to time; stepped sequence	Target to parking orbit 1; no potential for hitting target with 4σ nav accuracy	Need for intermediate navigation; navigation accuracy and range; target passivity; collision avoidance
IV. Proximity Operations A	1 km to 100 m	1 to 5 orbits	Timing hold in parking orbit; followed by low thrust	Intermediate navigation or docking sensor navigation	Intermediate or relative navigation	Hold for timing; stepped sequence	Target to parking orbit 2	Timing hold; need for intermediate navigation; navigation accuracy and range
V. Proximity Operations B	100 m to 10 m	45 to 90 min	Low thrust profile	Docking sensor navigation	Relative navigation	Continuously adjusted drift	Target to "docking start point"	Plume impingement; collision; keeping in sensor FOV
VI. Docking	< 10 m	< 5 min	Thrust profile	Docking sensor	Docking sensor	Continuous active control	Straight to docking target	Plume impingement; collision
VII. Joint Maneuvers	Joined	Indefinite	Exchange fluid or cargo; maneuver	AutoNav	Not needed	Active control or no control	Not needed	Plume impingement; changing, possibly dynamic, mass properties
VIII. Separation and Escape	Near the target	TBD	Thrust profile	Absolute and/or relative navigation sensor	Not required	Periodic active control	Target to escape orbit	Plume impingement; collision; possibly target detection

Notes: λ_{max} is the maximum Earth central angle from the altitude of the spacecraft.
AOC is autonomous absolute orbit control (i.e., comparable to the Orbit Control Kit, OCK)
OD is orbit determination.

As summarized in Table 1, the rendezvous and docking mission can be divided into phases corresponding to the type of activity, relative distance between the two spacecraft, and source of navigation data. Each phase may require different navigation-related activities and different methods and hardware for both navigation and control for both the chaser and target vehicle. Thus, one of the challenges of autonomous rendezvous and docking is to look at the problem as a whole and find solutions that minimize the cost and complexity for the entire mission. To do this, we will look at each of the stages in the sequence, determine the information needed for navigation and control, and the potential mechanisms for achieving that.

2.0 PHASE I — SEPARATE ORBITS

Initially it is likely that the two spacecraft will be in entirely separate orbits. For example, one of them may be just launched from the surface of the Earth or another planet or arriving from interplanetary space along a hyperbolic trajectory. An inspection, repair, or disposal mission may be coming from a previous activity in a very different orbit. It is likely that the two spacecraft are out of sight and out of contact with each other. In this phase, the target must know at least approximately its own orbit and that of the target. The target orbit (and that of the chaser) can come from several possible sources:

Assumed Orbit. Since the accuracy requirements are modest, it may be possible at this stage to simply assume one or both of the orbits until such time as they get close enough for some form of communication or relative navigation. Of course, the risk is that the assumed orbit is sufficiently in error that the rendezvous fails.

Autonomous Navigation (AutoNav). Either vehicle may use autonomous navigation technology to determine its orbit. (See discussion below.) This could be GPS in low Earth orbit or true autonomous navigation in other orbits. If the target is using autonav, then the information needs to be communicated to the chaser, either directly or via the ground.

Autonomous Orbit Control. Microcosm has flight demonstrated fully autonomous orbit control using its Orbit Control Kit (OCK) software system. [Wertz, *et al.*, 2000, 2001b; Gurevich, *et al*., 2001; Conger, *et al*., 2002] The key element for rendezvous and docking is that the orbit is fully controlled to a pre-specified set of parameters. Thus, even if the spacecraft are not communicating, each will know where the other is and where it will be at all future times. This technology was flown on UoSAT-12 with results shown in Fig. 1. OCK achieved absolute orbit control to within ±1 km in low Earth orbit using less propellant than what would have been required using traditional orbit maintenance. By eliminating the need for cross-links or other communication at large distances, OCK can substantially simplify the process of autonomous rendezvous and docking.

Ground Tracking. The traditional process of orbit determination is ground tracking. While not autonomous, it can be used to initiate the process of autonomous rendezvous and docking and, in any case, is likely to serve as a back-up for most autonomous activity.

The general measurement sets available for navigation are illustrated in Fig. 2. All of these are potentially applicable to the navigation component of rendezvous and docking:

Method 1. Position and velocity at one time. Used for injection from the launch vehicle or after a large thruster firing.

Method 2. Three or more observations of direction with respect to the background stars. Traditional approach for determining the orbits of comets and asteroids.) Used for determining the relative orbit of a distant spacecraft. (See below.)

Method 3. Sequence of range and range rate measurements. This is the traditional ground tracking approach.

Method 4. Sequence of position observations. Basis for autonomous navigation using GPS observations of position.

Method 5. Sequence of observations of the inertial direction and distance to a nearby central body. Basis of most optical autonomous navigation. Provides a robust solution for AutoNav in planetary orbits.

	On-orbit	Simulation
Atmosphere	Real	MSIS
F10.7	Real	Measured
Duration (days)	29	29
Performance (sec, 1σ)	± 0.12	± 0.14
Performance (km, 1σ)	± 0.9	± 1.02
No. of Burns	53	48
Maximum Burn (mm/s)	2.7	4.9
Minimum Burn (mm/s)	0.053	0.19
Mean Burn (mm/s)	1.4	1.6
Sum of Burns (mm/s)	73.3	76.3
ΔV to Restore Altitude	85 – 100 mm/s	

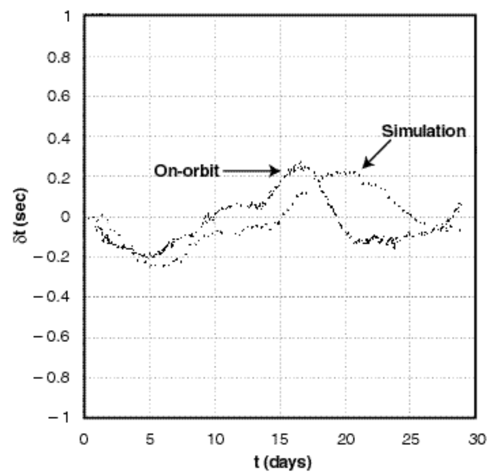

Figure 1. On-Orbit Performance of Autonomous Orbit Control flown on UoSAT-12 in 1999. The key element here is that the spacecraft follows a trajectory defined in advance and, therefore, known without any communication between the spacecraft. [Wertz, *et al*., 2000]

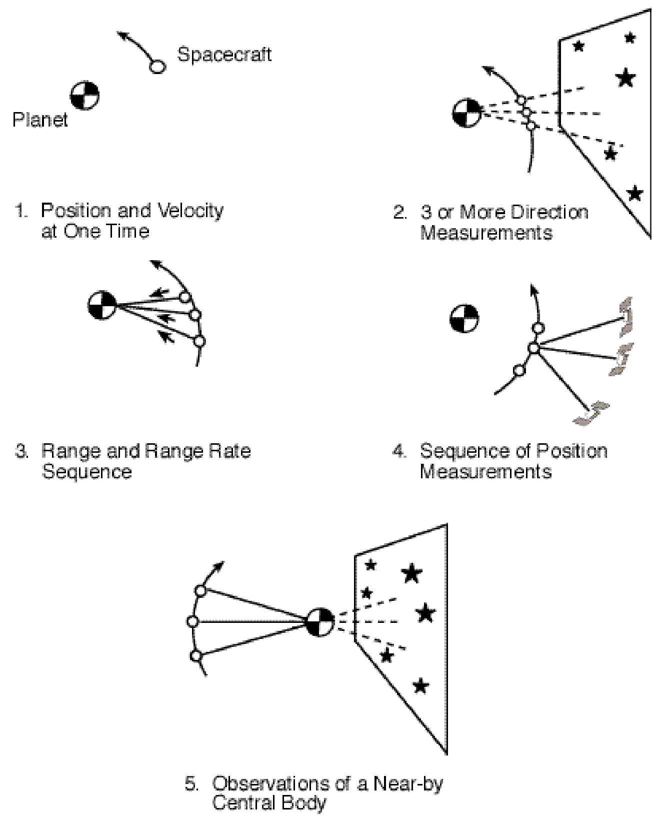

Figure 2. Basic Measurement Sets for Orbit Determination. See text for discussion. [Wertz, 2001a, pg. 106]

For AutoNav in low Earth orbit, GPS is the obvious choice. A GPS receiver provided the navigation function for the OCK demonstration on UoSAT-12. However, with modern on-board computers and sensors a wide variety of truly autonomous approaches are feasible. Approaches that have been considered are summarized by Wertz [2001a], Sec. 4.3. In 1994, Microcosm demonstrated fully autonomous navigation using the Earth, Sun, and Moon in low Earth orbit using the MANS technology [Anthony, 1992; Hosken and Wertz, 1995]. More recently, NASA's DS-1 spacecraft demonstrated autonomous navigation in interplanetary orbit [Rayman *et al.*, 1999, 2001]. MANS used the Moon and Sun as inertial references largely because they were easy to identify and unambiguous. However, modern star sensing has largely eliminated this problem. Consequently, we believe that the best current approach to AutoNav in planetary orbits is to use star and planet sensing, using method 5 in Fig. 2. This approach is exceptionally robust in low planetary orbits because the angular size of the planet provides a sensitive measure of distance and, therefore, each measurement set provides a non-singular deterministic estimate of the 3-axis position of the spacecraft in inertial space. These can then be filtered to provide noise reduction and improved accuracy with very little potential for filter divergence. Microcosm currently has a contract with JSC to access performance and feasibility of AutoNav using star and planet sensors.

If we once have the orbits of the two spacecraft, what remains is to calculate the orbit transfer burn that will put the put the chaser into the same orbit as the target. Microcosm has previously developed the software for autonomous orbit transfer on internal R&D. Typical results of this transfer analysis are shown in Fig. 3. The result is similar to the usual "porkchop" plots used for interplanetary transfer analysis, except that it may be reasonable to allow the chaser or target or both to go several orbits in order to find a low-energy opportunity.

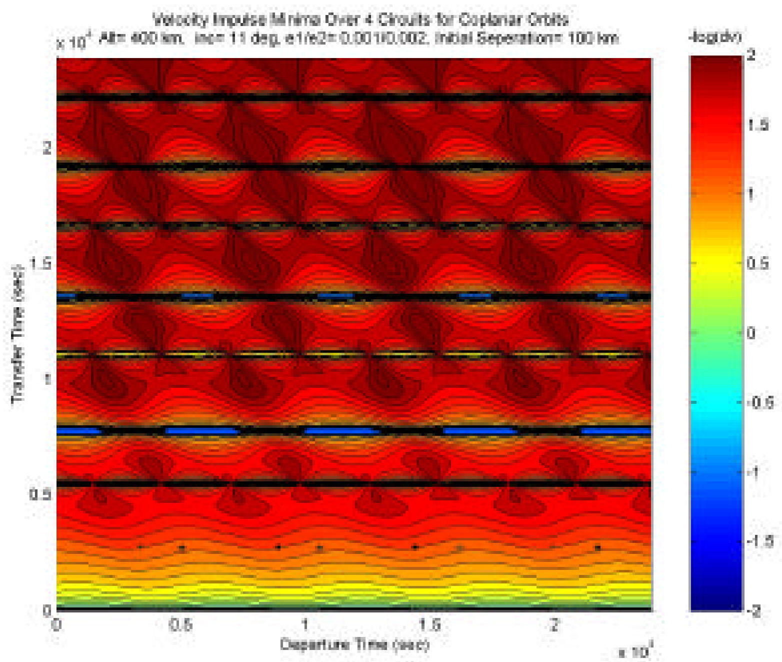

Figure 3. Autonomous Orbit Transfer. The process involves selecting the best choice from among a number of discrete, well-defined options.

3.0 PHASE II — DRIFT ORBIT A (OUT OF SIGHT, OUT OF CONTACT)

In general, the chaser will transfer into the orbit of the target spacecraft well away from the target and drift toward it. If the chaser is approaching from below, it will typically transfer to a location below and behind the target. This *drift orbit* leaves the chaser slowly closing with the target in a similar, but lower, orbit. Transferring to a drift orbit has several advantages. It avoids any possibility of collision with the target. By aiming short, it ensures that the next correction burn will be in the same direction as the first transfer burn and, therefore, avoids wasting propellant by making burns in opposite directions. It also allows time for orbit determination following the transfer burn and for any corrective burn to adjust the drift rate.

This can be a challenging phase for autonomous operations. The chaser and the target will be out of sight and out of direct contract if the angular separation between them as seen from the center of the planet is greater than $2\lambda_{max}$, where

$$\cos \lambda_{max} = R_p / (R_p + H) \tag{1}$$

Here R_p is the radius of the central planet, H is the altitude of both the chaser and target above the planet, and λ_{max} is the angular radius of the spacecraft's true horizon as seen from the center of the planet. Equation (1) represents the general requirement that two spacecraft can see each other if and only if they can see at least one point on the ground in common. (See, for example, Wertz [2001a], pg. 507–8.)

If the two spacecraft are out of sight of each other, then they will not be able to do relative navigation and, even if they can both do absolute navigation, will not be able to communicate directly with each other. Thus, we are in a similar circumstance as we are in Phase I, only somewhat worse. The initial estimate of the chaser's own orbit comes from knowing its orbit before the transfer burn and an estimate of the burn parameters. This will need to be refined over time with one of the approaches described in Phase I. Unless there is an update from the ground, there is no new information available about the target, and the chaser must continue to use the assumed orbit for the target from prior to the burn. (Of course, so long as the target is not maneuvering, its position accuracy will simply continue to decay slowly and is not directly effected by the chaser's activity.) Relatively little can be done, except to continue to drift toward the assumed location of the target. If the target is using autonomous orbit control, then its location is well known and there is no targeting problem. If there is the potential for large initial errors or for a Phase II of significant duration, then the use of autonomous orbit control by the target becomes more important.

4.0 PHASE III — DRIFT ORBIT B (IN SIGHT, IN CONTACT)

As discussed above, $2\lambda_{max}$ represents the fundamental horizon for direct spacecraft-to-spacecraft viewing and communication. It is possible, but unlikely, that the spacecraft will be within this range for the entire mission. In any case, once the chaser has gotten within this distance of the target, they can potentially see each other and communicate directly for the first time. As shown in Fig. 4, this horizon distance is typically between 3,000 and 10,000 km for spacecraft in low Earth orbit.

If the target spacecraft is cooperative and has its own navigation system, such as GPS or AutoNav, then it can communicate its position to the chaser. Alternatively, if the chaser can see the target move as a point of light against the background stars, then relative autonomous navigation is possible. If its approximate position is known, picking out the target can be done by watching for "stars" that move relative to the rest of the star field. Computations for the approximate brightness of the target are given by Wertz [2001a], Sec. 11.6. The process for doing relative AutoNav is the same as that used for many years in classical astronomy to determine the orbits of comets and asteroids by watching their motion with respect to the background stars. (This is Method 2 on Fig. 2.) Microcosm is currently under contract with NASA JSC to determine the approximate relative navigation accuracy that can be achieved using typical spacecraft star sensors.

During Drift Orbit B the chaser continues to close on the target, possibly by simply drifting, or, more likely, by a series of ever smaller thruster firings. Throughout this phase, fuel usage is important. As the spacecraft get close together accurate relative navigation and collision avoidance become important. At the end of the drift orbit, the spacecraft may go into a hold, or parking orbit, at a distance of about 100 m to 1 km to provide the correct timing, geometry, and lighting conditions for the final proximity operations and docking.

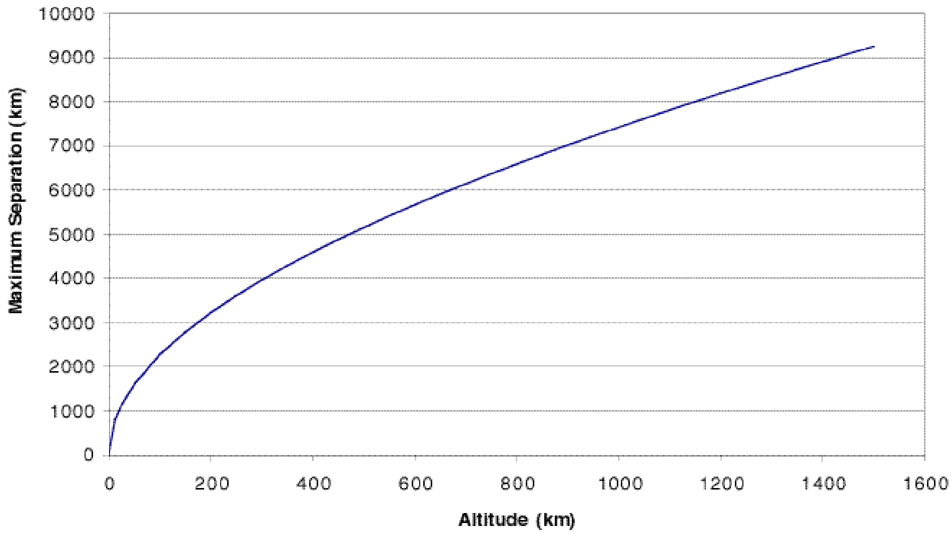

Figure 4. Maximum Separation Between Spacecraft that are Mutually Visible. Within this distance, there is the possibility of seeing the other spacecraft and direct communication.

5.0 PHASE IV — PROXIMITY OPERATIONS A

In this phase, the chaser begins using a relative navigation sensor or, possibly, the docking sensor in conjunction with very small thruster firings to begin the approach to the target. This will be a planned sequence of thruster burns with sufficient time for navigation solutions between thruster firings. Proximity operations have been the subject of a great deal of work and, of course, have been successfully carried out on a great many manned missions. A brief summary of this process and Hill's equations, which are ordinarily used for analyzing the motion is given by Meissinger [2001]. The two most common methods of approach are horizontally along the spacecraft velocity vector (called *V bar*) and vertically along the radial vector (called *R bar*). In both cases, the process is well understood and has been implemented in space many times. No further development is needed in this regime, although it is critical that the appropriate sensor or sensors be available to transition from the distant relative navigation of Phase III to the rendezvous and docking sensor used in Phase V.

6.0 PHASE V — PROXIMITY OPERATIONS B

The chaser begins this phase at a distance of typically 10 m to 100 m from the target. The sequence of events depends on whether the chaser will actually proceed to dock with the target or simply look at or circumnavigate the target, called an *inspection mission*. These cases are best treated separately as described below.

When the two spacecraft are very close, the nature of the propulsive activity changes significantly. In earlier phases, the goal was to use as little propellant as possible. Here the more important goals are (1) to maintain the proper relative position and attitude profile and (2) to avoid plume impingement on the target. Plume impingement is a particularly serious problem. It can damage or destroy sensitive optics, disturb thermal blankets and coatings, and impart very large disturbance torques. The plume is likely to hit deployables and appendages such as the end of the solar array that can be a long way from the center of mass. With the long moment arm, even small forces can provide significant torque that can disturb or even tumble the target vehicle. This, in turn, can cause either thruster firings or a direct collision that could damage either or both spacecraft. When expanding into a vacuum, the thruster plume will have a component 90 deg or more from the line of thrust. Thus, it is particularly important to design proximity operations taking plume impingement into account.

Inspection Missions. In this case the chaser will not actually close and dock with the target, but will remain a small distance away and examine the target, either for the purpose of intelligence or possibly damage assessment. It may be appropriate to "hover" over one location on the target or to circumnavigate the target to examine all sides. If the chaser is directly in front of or behind the target, i.e., offset in the in-track direction, then it can remain there with no expenditure of propellant. Any other "hovering" position with respect to the target will require a continuing propellant usage. It is convenient to think of this as overcoming the micro-gravity forces between any two nearby objects in space. These continuous-thrust formations are described by Wertz [2001a], Sec. 10.2.4, and the non-thrusting relative motion is described in Sec. 10.2.1.

Docking Missions. When the ultimate goal is to dock the two spacecraft, the chaser proceeds ever closer to the target, matching both position and attitude. Typically, this will be done with V bar or R bar approaches, as described above, using a series of very small thruster firings or a slow continuous drift of the chaser toward the target due to small differences in the orbital elements. This phase will make use of a docking sensor to provide relative position and attitude data and very short correction thruster firings with great care taken to avoid plume impingement. Docking maneuvers have been done with crewed missions since the early days of the space program. Therefore, the only substantial challenge for current programs is to do the rendezvous and docking fully autonomously and possibly out of contact with any ground station. This would be the case, for example, with rendezvous and docking about any distant planet where the round trip communications delay is too long to permit meaningful ground control. Microcosm is testing the automated pre-docking proximity operations procedures in a Phase II SBIR with AFR, including sensor and algorithm testing in the NRL docking simulation facility currently scheduled for late spring, 2003.

7.0 PHASE VI — DOCKING

As with proximity operations, spacecraft docking has been done with crewed missions for many years with well-defined procedures and successful results. However, there is now a potential need to do this fully autonomously with small, robotic spacecraft. Michigan Aerospace Corp. has developed a docking adapter for small spacecraft that was recently successfully demonstrated on a series of KC-135 zero-gravity flights, as shown in Fig. 5 [Pavlich, *et al*., 2003; Tchoryk, *et al*. 2003]. The key element of docking is to have a compliant capture mechanism that can accommodate small differences in position, attitude, and velocity, capture the target spacecraft, and bring them together in a hard dock that effectively creates a new, rigid, single spacecraft from the two separate spacecraft.

Figure 5. KC-135 Zero-Gravity Testing of a Small Spacecraft Docking Adapter Developed by Michigan.

8.0 PHASE VII — JOINT MANEUVERS

In terms of orbit and attitude dynamics, the two docked spacecraft now represent a single, new *combined spacecraft* with moments of inertia and center of mass significantly different than either of the spacecraft separately. In addition, if there is cargo or fluid transfer between spacecraft, then the mass properties will be a function of time. For small spacecraft, these relative changes can be quite large and can significantly impact the dynamic performance of the combined vehicle. The Cassini mission has refined the spacecraft moments of interia based on the measured response to thruster firings. [Wertz and Lee, 2001; Lee and Wertz, 2002] Microcosm and Michigan Aerospace have proposed using this technique with a defined series of small "calibration firings" to measure the mass properties of the combined spacecraft. Thus, the two spacecraft will undergo a hard dock, fire thrusters to determine on-board the new mass properties based on responses measured by on-board gyros, and then undertake whatever orbit or attitude adjust maneuvers are needed. This allows the combined spacecraft to maneuver safely and efficiently in any manner needed to meet mission requirements. Dynamic determination of mass properties could be easily tested via either KC-135 flights or, for example, the Spheres experiment that will be flying shortly on the Space Station. [Miller, *et al.*, 2000]

Because the spacecraft are now docked, relative navigation is no longer relevant. However, absolute navigation using any of the previously discussed techniques may be needed, depending on the mission requirements. Plume impingement remains a serious concern because thrusters from either of the spacecraft may face appendages from the other and could cause serious control anomalies or tumbling.

9.0 PHASE VIII — SEPARATION AND ESCAPE

The final phase of the rendezvous and docking process is the undocking, separation, and ultimate escape of the two spacecraft. Either or both spacecraft may proceed with other mission activities, such as continued normal operations after having been refueled. Either of the two may also be left in a graveyard orbit or allowed to decay and re-enter. The functions in this phase remain essentially the same as for the proximity rendezvous activity, except that it may be the target spacecraft, rather than the chaser, that does the maneuvering. In any case, relative navigation and thruster firings designed to avoid plume impingement are required during the early phase. In addition, the spacecraft must separate sufficiently to ensure collision avoidance when they return to the same vicinity after one orbit. While there is significant mission planning to be done, no new technology development is required for this phase of the mission.

10.0 CONCLUSIONS

Fully autonomous rendezvous and docking requires developing and testing a variety of new technologies, including absolute and relative autonomous navigation, autonomous rendezvous and docking hardware and software (both sensors and actuators), and autonomous control of a "new" spacecraft with different mass and inertia properties than either of the two original spacecraft. The development status of the key elements is as follows:

- **Absolute autonomous navigation using GPS.** In use on many operational missions, but only applicable in low Earth orbit. Can also be used for relative navigation using either differences in absolute locations or differential GPS to eliminate the largest systematic errors.

- **Absolute autonomous navigation without GPS**. Demonstrated on the Technology for Autonomous Operational Survivability (TAOS) mission using the Earth, Sun, and Moon. A more modern, accurate, and robust approach would use a planet and star sensor combination. Analysis is underway on expected accuracies. Sensing hardware exists and has flown many times. On-orbit accuracy verification would be needed prior to operational implementation.

- **Relative optical navigation**. Technology is the same as that used for determining the orbits of comets and asteroids. Accuracy validation and on-orbit demonstration is needed.

- **Close-In rendezvous and docking sensors**. Several alternative sensors exist. Some will require additional testing or on-orbit validation.

- **Fully autonomous rendezvous and docking algorithms.** The algorithms themselves can follow well-tested approaches used in crewed flight for many years. Will require some additional testing or on-orbit validation for autonomous operations. Can be done via a docking simulator, parabolic flight-testing, or on-orbit tests.

- **Rendezvous and docking mechanisms.** Several alternative docking adapters exist. Some will require additional testing or on-orbit validation.

- **Dynamic determination of mass properties.** Has been partially demonstrated on Cassini. Additional testing and validation can be done on orbit or using parabolic zero-g flights.

While these are very workable technologies, they do require a significant change in mindset — turning over control of thrusters to an on-board computer. While there is substantial potential for cost savings, risk reduction, and new mission modes by use of these technologies, there is a very strong reticence to allowing operational spacecraft to control their own thruster firings.

Approaches have been proposed for more precise and robust autonomous navigation and autonomous on-orbit estimation of combined mass and inertia properties, leading to efficient orbit and attitude control of the combined spacecraft. Many of these technologies can be tested at low cost in parabolic flights, suborbital flights, low-cost on-orbit testing, and evaluation of data from existing or planned missions. At this time, a “coordinated attack” on the complete problem of fully autonomous rendezvous and docking is both feasible and potentially very low cost.

REFERENCES

Anthony, J., 1992, “Autonomous Space Navigation Experiment.” Paper No. AIAA 92-1710, presented at the AIAA Space Programs and Technologies Conference, Huntsville, AL, March 24–26.

Conger, R., F. Gurevich, and J. R. Wertz, 2002, “Autonomous On-Board Orbit Control.” Paper No. AIAA 2002-1976, presented at the 20th AIAAA International Communications Satellite Systems Conference, Montreal, Canada, May 13–15.

Gurevich, G., and J. R. Wertz, 2001, “Autonomous On-Board Orbit Control: Flight Results and Cost Reduction.” Presented at the JHU/APL Symposium on Autonomous Ground Systems for 2001 and Beyond, April 25–27.

Hosken, R., and J. R. Wertz, 1995. “Microcosm Autonomous Navigation System On-Orbit Operation.” Paper No. AAS 95-074, presented at the 18th Annual AAS Guidance and Control Conference, Keystone, CO, Feb. 1–5.

Lee, A. and J. A. Wertz, 2002, “In-Flight Estimation of the Cassini Spacecraft’s Inertia Tensor.” *J. of Spacecraft and Rockets*, 39:1, pg. 153–5, Jan.–Feb., 2002.

Meissinger, H., 2001, “Hill’s Equations and Rendezvous,” Sec. 10.2.3 in *Mission Geometry; Orbit and Constellation Design and Managemen*t by J. R. Wertz, Dordrecht, The Netherlands and El Segundo, CA: Kluwer Academic and Microcosm Press.

Miller, D., A Saenz-Otero, and J. A. Wertz, et al., 2000, “SPHERES: A Testbed for Long Duration Formation Flying In Micro-Gravity Conditions.” Presented at the AIAA/AAS Space Flight Mechanics Meeting, Jan. 2000.

Pavlich, J., P. Tchoryk, A. Hays, and G. Wassik, 2003, "KC-135 Zero-G Testing of a Micro-Satellite Docking Mechanism." SPIE AeroSense Symposium, Space Systems Technology and Operations Conference, Orlando, FL, April 24.

Rayman, M., P. Varghese, D. Lehman, and L. Livesay, 1999. "Results from the Deep Space 1 Technology Validation Mission." Paper No. IAA-99-IAA.11.2.01, presented at the 50 International Astronautical Congress, Amsterdam, the Netherlands, Oct. 4–8, 1999. Also *Acta Astronautica*, v. 47, pp. 475, 2000.

Rayman, M., P. Varghese, 2001. "The Deep Space 1 Extended Mission." *Acta Astronautica*, v. 48, No. 5–12, pp. 693–705, 2001.

Tchoryk, P., A. Hays, and J. Pavlich, 2003, "A Docking Solution for On-Orbit Satellite Servicing: Part of the Responsive Space Equation.Æ Paper No. AIAA LA Section/SSTC 2003-2001. AIAA LA Section/SSTC Responsive Space Conference, Redondo Beach, CA, April 1–3.

Wertz, J. A. and A. Lee, 2001, "In-Flight Estimation of the Cassini Spacecraft's Inertia Tensor." Presented at the AIAA/AAS Space Flight Mechanics Meeting, Feb. 2001.

Wertz, J. R., J. Cloots, J. Collins, S. Dawson, G. Gurevich, B. Sato, and L. J. Hansen, 2000, "Autonomous Orbit Control: Initial Flight Results from UoSAT-12." Paper No. AAS 00-071, presented at the 23rd Annual AAS Guidance and Control Conference, Feb. 2–6.

Wertz, J. R., 2001a, *Mission Geometry; Orbit and Constellation Design and Management.* Dordrecht, The Netherlands and El Segundo, CA: Kluwer Academic and Microcosm Press.

Wertz, J. R. and G. Gurevich, 2001b, "Applications of Autonomous On-Board Orbit Control." Paper No. AAS 01-238, presented at the 11th AAS/AIAA Space Flight Mechanics Meeting, Santa Barbara, CA, Feb. 11–15.