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MISSION DESIGN AND SYSTEM REQUIREMENTS FOR A MULTIPLE-FUNCTION ORBITAL TRANSFER VEHICLE[*]

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Abstract

Functional and design concepts, and a number of promising scenarios for use of a low-cost, simple Orbital Transfer Vehicle (OTV) are presented in this paper to help provide the rationale for developing such a vehicle for near-term use in supporting and extending the mission life of valuable space assets. A principal factor in reducing development and production costs is the suitability of a basic OTV bus vehicle for many of the applications considered. Special attachments can be added, in a retrofit mode, to be used in future, more demanding service applications. Use in supporting large satellite constellations in an emergency standby mode, with one OTV being assigned to each of the constellation's orbit planes, requires numerous such vehicles in operation simultaneously. Preliminary cost estimates, a development schedule, and a list of principal maneuver performance requirements support this discussion.

1. Introduction

Orbital Transfer Vehicles (OTVs) of various types have been projected for critical support operations of the International Space Station (ISS) and other orbiting systems, including constellations of communication satellites and military spacecraft[1,2]. In general, different applications have led to different design and operation concepts for different mission objectives. This paper considers several OTV applications that can be met by developing a basic OTV bus system that is adaptable to diverse mission objectives by adding components or kits specifically required for these applications. Such an OTV would have military, non-military, and commercial applications. A current OTV development that uses primary solar-electric propulsion[3,4] is omitted from this discussion. Its range of applications is quite different from those considered here.

The potential for large development and operational cost savings is a principal driver for introducing a system concept that can be adapted to, and used in diverse applications. Also of concern is the quick response capability such a system offers to serve various operational needs, i.e., its availability on relatively short notice. The primary advantage of the proposed OTV concept is its capability to provide repeated operational sorties in orbit over an extended time period, with sufficient maneuvering capability to reach different destinations in a given orbit or nearby orbits, carrying a substantial payload mass, usually in the departure or return phase.

Applications that are of principal interest in this context include the following:

- ISS-based services, such as transferring supplies that are delivered in close vicinity by expendable launch vehicles which have no rendezvous and docking capabilities, a potential major launch cost saving. The OTV, based at the Station, can also periodically serve to deorbit waste material.
- Emergency service of capturing and deorbiting failed satellites in a constellation, to prevent a collision with other constellation members.
- Servicing satellites in a constellation that require occasional refueling or other resupply to continue their assigned mission, e.g., components that tend to have limited life such as batteries.
- Circumnavigation and close inspection of friendly, or more importantly, hostile spacecraft. If necessary, performing capture and deorbit services.

Circumnavigation at close distance, by conventional proximity operation techniques permits viewing the target object from all sides. The delta-V requirements generally are modest.

The paper describes orbital operation modes of a multiple-function OTV bus and defines its desired adaptation capabilities. Principal system design requirements and major subsystem features are defined that are compatible with the multi-functional use of the vehicle. The projected simple bus design concept offers realistic development-time savings and cost reductions. The discussion will focus on trading functional versatility versus cost, for an overall cost-effectiveness assessment. Estimates of the development time and cost for the baseline design are also presented.

Once the basic bus vehicle is developed, with design features that meet specific transportation and servicing needs, it will be ready for early application. Additional features that are envisioned in the original design concept may then be developed separately as called for by evolving additional mission support needs.

This proposed OTV concept differs considerably in its design features and operational capabilities from the Orbital Maneuvering Vehicle (OMV)[5] which had been under development for NASA in the 1980s, with TRW as the prime contractor, but was later discontinued. While some of the proposed OTV's capabilities are related to those that had been planned for the OMV, at the time, the emphasis on a much simpler bus design is a key aspect of its smaller size, its much lower-cost, and faster development schedule. As a major difference, the OTV design does not include a complete set of "on-orbit replaceable units", or ORUs, and omits extensive subsystem redundancies, both of which added greatly to the OMV's size, design complexity, and cost.

2. Operational Scenarios.

Table 1 lists the OTV's operational functions and orbit transfer requirements with an indication of the frequency and duration of sorties and the range of maneuver velocities, the principal benefits of these mission support functions, and the degree of complexity they demand. Also listed are any attachment or special equipment requirements to perform these functions. The projected time frame of using these OTV capabilities is estimated to indicate at what stage of the ongoing program development any new attachment features and support equipment have to be available.

ISS support capabilities are expected to be needed earlier than other activities on the list. The basic OTV with little or no added manipulating equipment will be suitable for this support function. It is anticipated that this support includes frequent delivery of structural and support equipment, while the construction phase is still in progress, periodic resupply of consumables, and occasional controlled deorbiting of waste material and useless or defunct pieces of hardware.

To perform these functions, the OTV bus only needs comparatively simple handling and attachment equipment to grasp and secure the materials to be transported. Transfers will be made either to the ISS from locations nearby, where the material is placed by an expendable launch vehicle, or from the ISS, for deorbit purposes. In the latter case the Station's manipulator arm attaches the material in question to the OTV. The incoming material is retained temporarily by the upper stage that delivers it near the Station and maintains it at a fixed orientation, for easy access and grasp. Sorties from and to the Station in this case only require very little maneuver velocity, e.g., about 5 m/sec for a trip of 20 km each way. A waste-material deorbit sortie requires a much more substantial amount of maneuvering by the OTV, typically 180 m/sec each way, to assure prompt reentry and burn-up of this package, and to bring the OTV back to the Station after delivering the required deorbit impulse.

A basic capability required for these transfers is precision guidance and maneuver control, for rendezvous and acquisition of the cargo material at the point near the Station where it has been left, and the return to, and rendezvous/docking at the Station. In some cases docking may not be required if the Station's manipulator is used to capture the incoming OTV. In this and other sorties, the precision navigation and guidance task is done autonomously by the on-board computer and data processing channels (see below).

An attractive procedure for the rendezvous on return to the Station is the "R-Bar approach" (Figure 1) of the OTV in radial direction from below (or above) the Station[7,8]. Recent Space Shuttle visits to the Russian space station "Mir" have made use of this technique. It avoids using retro-thrust close to the Station and reaching zero approach velocity at a small distance (typically 10 to 20 m) below or above the Station's center-of-mass where it can be readily picked up by the manipulator arm. The technique is based on making use of the gravity gradient effect that causes the deceleration. However, it requires prompt manipulator action, since the "zero-velocity" condition is very brief, extending only over a few minutes.

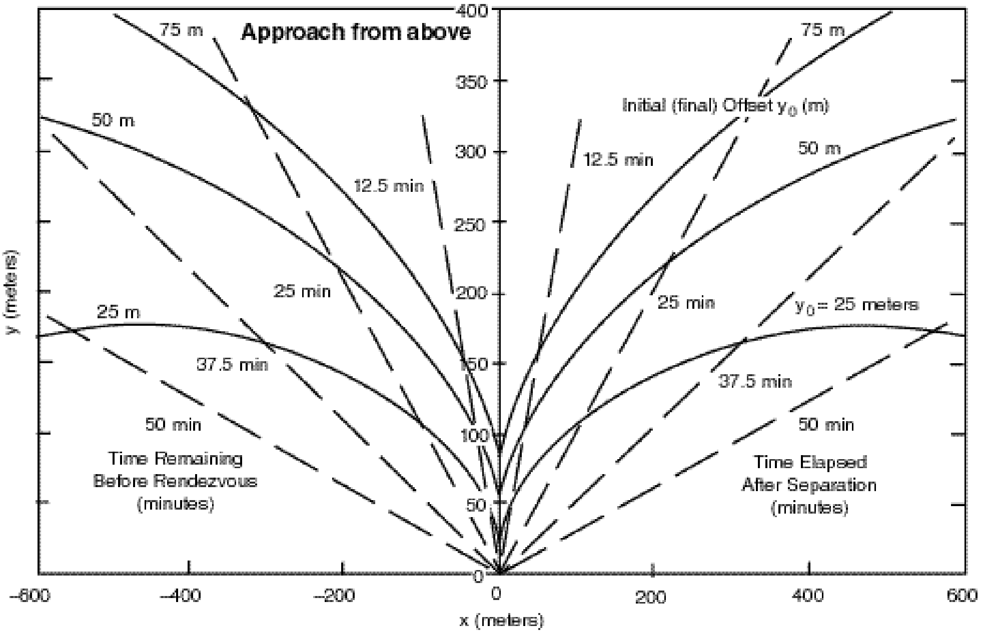


Figure 1. Zero-Velocity (R-Bar) Approach by OTV Near Space Station.

Another important ISS support function of the OTV is to perform inspection from different sides, particularly during the final assembly stage, but also whenever any configuration changes are in progress or in case of an emergency. These sorties can be performed with no added support equipment other than optical sensors that are needed in any case for close approaches to target objects. Circumnavigation is performed by the OTV moving in a slightly eccentric or circular "suborbit" that requires maneuver velocities of less than 1 m/sec to initiate and to terminate. Figure 2 shows a circular inspection path at close range. For an assumed 400 m radius circumnavigation path, a maneuver of only 0.44 m/sec each is required for both initiation and termination. (This maneuver velocity is proportional to the suborbital radius.) As shown in the figure, the suborbit is tilted against an elliptical relative trajectory with a 2:1 axis ratio in the x-y plane (i.e., the reference orbit plane), by adding an out-of plane component, in z-direction. As indicated in the figure, the maximum excursion in the z-direction is sized to produce a tilt angle of 60 degrees. The resulting circumnavigation orbit is circular with a radius equal to the semimajor axis of the reference ellipse in the x-y plane. To obtain another observation perspective only requires reversing the out-of-plane excursions by a small plane-change maneuver at one of the orbit-crossing times which occur twice per orbital revolution. The slow angular rate of the tilted circular observation orbit is slightly less

Table 1. OTV Operational Functions, Utilization and Benefits in Various Applications.

	ISS Support			**Close Sat. Inspection**	**Constell. Support**	**Individual Satellite Support**
1. Function	Resupply	Waste Dispos.	Circum Nav.	Friendly or nonfriendly	Resupply, Deorbit	Resupply, Retrieval, Refueling
2. Utilization Start	Early at A.D.*	Early at A.D.*	Early at A.D.*	Early at A.D.*	A.D. + 2 yrs	A.D. + 2 yrs
3. Sortie Frequency	High	Medium	Low	Low	Medium	Medium
4. Task Complexity**	2–3	5	2	3	7–10	5–10
5. Maneuver Velocity, m/sec (round trip)	10–20	350	1–2	20–50 dep. on distance	400–750 dep. on distance	300–500 dep. on distance
6. Attachment Kits Needed	Retention devices	Retention devices	None	None	Grasping Arms	Docking Fixt. Refueling equip.***

* A.D.—Availability Date
** On scale of 1 to 10 (10 highest)
*** Requires extensive retrofit

than 4 deg/min, depending on the orbit period at the altitude range of concern. Hovering at a point of particular interest generally is not practical.

A similar scenario, using the OTV bus for close visual or other observations of a satellite will be of interest for military or nonmilitary purposes. This needs only the basic bus vehicle carrying the requisite observation instrument(s) without any other special add-on kits. The rendezvous and circumnavigation sequence places stringent requirements on the vehicle's guidance and control capabilities. Accuracies of a few meters relative to the observation target will be essential, both for the transfer and rendezvous approach and for initiating the circumnavigation trajectory.

A discussion of proximity operations and their theory, based on Hill's equations of relative motion, that govern these excursions, is omitted here. The subject is covered extensively in the literature.[8–13]

Retrievals of the Hubble Space Telescope[14] for servicing and repair and its return to its operational orbit have been performed in recent years by the Space Shuttle, but this and other satellite retrievals for on-orbit servicing should preferably be performed by an OTV to avoid major Shuttle orbit excursions. A more demanding OTV task will be to rescue a satellite from an orbit, where it is stranded, by transferring it to its assigned operational orbit, if it does not have sufficient maneuvering capability of its own. This scenario requires the addition to the basic OTV bus of capturing arms and, generally, a greater propellant mass, i.e., additional propellant tankage, than is used in the operations previously discussed.

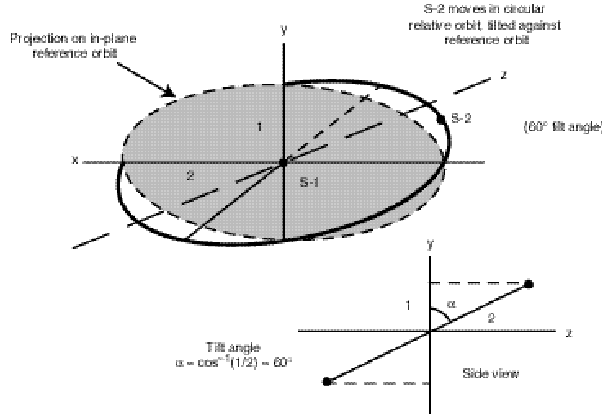
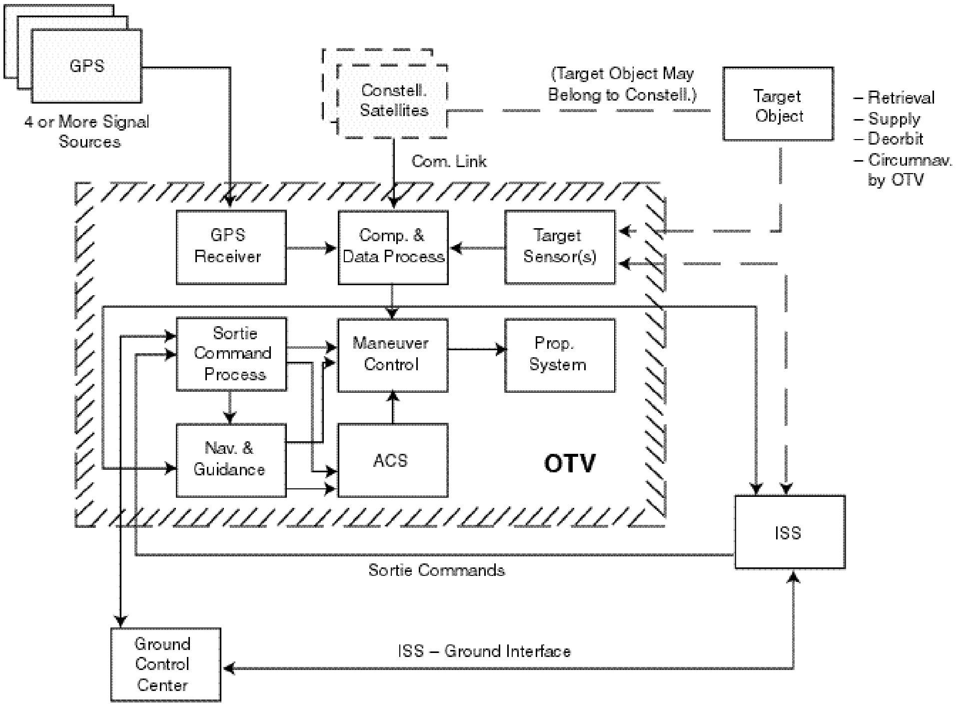


Figure 2. Circumnavigation for Satellite Inspection (Tilted, Circular suborbit)

It is assumed that the assisted orbit transfer remains within a limited altitude range and does not involve a significant orbital plane change. An OTV assigned to support a multi-satellite constellation can be used in a rescue operation such as this. If there are a number of such planes in a constellation, as in the case of the Iridium or Teledesic communication satellite systems, one OTV may have to be assigned to each of the constellation orbit planes.

Among the OTV support tasks in a satellite con-



Note: Autonomous orbit control uses most of the functions shown.

Figure 3. Information Flow To and Within OTV (simplified schematic)

stellation is that of performing the controlled deorbit of a failed satellite. Such a satellite, if unable to respond to a deorbit command from ground control, can potentially threaten a collision with other satellites in the constellation, in particular at the points where its orbit intersects the other orbits. In a large constellation, such as Teledesic, there are literally millions of orbit crossings of each satellite with other constellation members in the course of a ten-year mission life. If the constellation consists of 12 evenly-spaced orbits with a 30-degree spacing of their ascending nodes, each orbit would have to have its own "watchdog" OTV, since the propulsive maneuver requirement to reach an adjacent orbit in an emergency would be unacceptably large.

There are several alternatives of where the OTV should be stationed, if it is kept in orbit for repeated service sorties. For ISS-related services, the OTV would preferably be stored at the Station. From here it can perform the required excursions, either to retrieve newly delivered material and consumables, to circumnavigate and inspect the Station, or to perform waste disposal. Only the latter involves a major propellant consumption for which a refueling capability would be desirable. Addition of this feature will require a more complex propulsion subsystem design with added propellant intake fixtures, distribution lines, and control and safety valves. However, this capability also is required in other OTV utilization scenarios and may have to be included as a design feature on the basic OTV bus.

The most demanding application will be the rescue and transfer of a satellite that is stranded in a useless orbit, because this generally implies a single-purpose OTV launch. The OTV in this case either would be abandoned unless it can be returned to the ground by the Space Shuttle, if its maneuvering capability is adequate to reach the Shuttle at a later time. A cost trade is essential to justify a rescue mission of this kind. It involves the value of the satellite that needs to be rescued and value of the service it is intended to provide, versus the cost of the OTV to be employed and its launch. Additional factors are a possible shared-launch opportunity and a potential OTV retrieval. The cost-effectiveness of a rescue mission of this type, including all factors involved, needs to be fully analyzed and assessed in advance.

3. Sortie Execution, Orbit and Attitude Control.

The multi-function OTV needs a versatile response capability and precise navigation, guidance, and control to carry out the various sortie modes discussed previously. In the case of ISS support services, the OTV executes a specified sortie on Station command, but performs its navigation and guidance autonomously. The maneuver sequence is based on position and velocity data relative to the Station and relative to the specified target object, and on precise information of the corresponding Earth-based (absolute) coordinates that are derived from GPS signals.

Figure 3 shows the flow of information that is used to execute the sortie, i.e., the precise maneuver sequence away from and back to the Station and during close approach to the specified target, such as a materials and supplies package delivered to the Space Station vicinity by the launch vehicle. This package and the upper stage to which it is attached are viewed by the OTV's rendezvous and docking sensor to provide for precision rendezvous and contact guidance. Guidance accuracy during the midcourse part of the sortie, based on GPS signals, is better than 10 m. Terminal guidance, based on the on-board optical sensor, is performed with accuracies in the cm-range.

In other sortie modes, i.e., for OTV excursions from a specified position on orbit, such as the standby position within a satellite constellation, the departure sequence is initiated by commands from a ground control station, together with target position data. The signal flow involved in this sortie mode also is illustrated in Figure 3. With the control station in direct radio contact only a few times per day, depending on its latitude and the constellation's (and the OTV's) orbit inclination and altitude, the sortie command must be given, typically, hours before the required departure time. The subsequent OTV maneuver sequence is controlled by its autonomous navigation and guidance channels, including the potentially prolonged orbit transfer sequence if the target satellite is in a position far removed from the standby position. This generally will require a transfer time of several orbital periods in order to conserve maneuver propellant, and is subject to trade between acceptable transfer time and propellant expenditure.

An alternative to lengthy delays in reaching the OTV directly from the ground station could be the use of relay signals via satellites in the constellation, but at a greater signal flow complexity. This option also is indicated in Figure 3. Further analysis is necessary to find the best practical command channel implementation.

Autonomous orbit determination and control, considered essential for this mission class, has been under development for some years. Several programs at Microcosm, Inc. are specifically concerned with this technology advance, and the first flight application of autonomous orbit control is currently in progress on UoSAT-12, a satellite flown by Surrey Satellite Technology Limited (SSTL) in the UK.

Table 2 lists program elements in the OTV on-board computer and data handling channels that are used to control the flight and maneuver sequence autonomously, from the start of the sortie to arrival at the designated target and in reverse. Principal parts of the program to be used by the OTV's on-board control channels are: (1) address codes for the designated target, the point of origin from where the sortie is taken and to which it is to return, and possibly intermediate points to pass en route; (2) data handling routines for the received GPS signals, to derive relative positions with respect to the departure point and the target; (3) algorithms for determining required maneuvers in direction and magnitude, and their timing, leading to target rendezvous; and (4) a format for data transmittal to the ground control station (including the appropriate time slots, based on the current position relative to the ground station location). The autonomous guidance maneuver commands derived by the on-board software are then used to perform spacecraft orientation changes that precede the firing of the delta-V thrusters in the proper time sequence.

These factors indicate that computer and data handling requirements to support both the commanded and autonomous navigation and guidance processes are comprehensive and fairly complex. They provide the foundation on which the OTV functional capabilities are based. Also, considerable flexibility is required in adapting these program features to the various specific OTV service scenarios.

Table 2. Program Elements of On-board Computing and Data Processing Channels.

Program Steps	Data Source	Processing Function	Output Data	Addressed To
1. Target Data Processing	Sortie command from (a) ISS, (b) ground sta.	Accepts & processes transfer traject. data	Maneuver sequence depart/return	Sortie control channels
2. GPS Data Processing	GPS signals (4 or more sources)	Determine own position and velocity rel. to target	Current orbit data	Maneuver req. update
3. Autonomous Nav/Guidance Data Evaluation	Output of #1 and #2	Uses nav/guid. algorithms Determines Maneuver	Maneuver command signals	Maneuver control channels
4. Autonomous Maneuver Preparation	Outputs of #1, #2 and #3	Determines Delta-V req.	Maneuv. control data	Maneuv. control channels
5. Maneuver Execution	Output of #4	Determ. Maneuv. Commands (ACS and orbit control)	Maneuv. Data & timing	Thrust control valves
6. Maneuver Verification Sequence	Output of #2 to 5	Compares traj. data with commanded changes	Updated traject. info.	Status data to commun. channels
7. Data Transmission to Ground/ISS	Output of #3 to 6	Prepares updated status info	Current status	Status data to ground/ISS

4. OTV Conceptual Design Features.

The following design features are essential to be included in a conceptual basic OTV bus:

- A structure large enough to house all subsystems and which can be fitted with docking and cargo-holding fixtures.
- Subsystems including power supply (solar array and batteries), communication, computer and data handling, attitude control, and propulsion.
- The propulsion subsystem uses storable bipropellants (hydrazine, nitrogen-tetroxide), includes 4 primary thrusters and 12 secondary (vernier) mono-propellant hydrazine thrusters.
- Computer and data handling/storage system, with capabilities as described in Section 3.
- The communication subsystem includes omni-antennas for receiving GPS signals and signals from nearby sources, e.g., the Space Station, plus a directional antenna for ground communication and contact with other distant sources.

Some of the subsystem elements critical to mission success require redundancy. In principle, the basic OTV is much simpler in design and smaller than the old Orbital Maneuvering Vehicle (OMV)[5], and therefore very much less costly (see cost estimates given in Section 5). This is essential to the mission concept that includes applications where the OTV would be used only once and cannot be retrieved for reuse.

The configuration, somewhat reminiscent of the OMV, although considerably more compact (Figure 4) is shown to be "disk-shaped", i.e., with a 3.0 m diameter and 0.85 m length. This has several advantages compared with a narrower, cylindrical body of greater length. They include: (1) a large enough area to place solar cell panels on the "aft" side where the four main engines are mounted, thus avoiding the need for a deployable solar array; (2) a flat configuration suitable for launch as a piggy-back payload on most launch vehicles that would offer such opportunities, or for launching a stack of several OTVs (it also would make the most economical use of cargo bay space if launched by the Space Shuttle); and (3) the disk shape also more readily accommodates the attachment of a large diameter payload.

Docking with a target satellite, or cargo attachment, will take place on the OTV front face, opposite the side where the solar panels and main engines are mounted. The engines, rated at 100 lb_f (450 Newton) thrust level each, usually are being fired in pairs, with redundancy provided by the second pair. With the largest OTV-plus-cargo mass, all four engines would be used to shorten the thrust period. Thrust vector control capability is provided by gimbal-mounting each of the four engines. This accommodates any center-of-mass offsets, from the OTV body's centerline, which will be particularly important with diverse types of payload vehicles or supply packages that are to be attached to the OTV. An exact alignment of the combined c.m. of the OTV-plus-payload with the OTV center line usually cannot be expected. One example is the grasping of a failed satellite for deorbiting purposes.

An advantage of using gimbaling rather than differential engine throttling for thrust vector control to accommodate c.m. offsets is the redundancy available by using alternate engine pairs, when a lower thrust level is intended, or otherwise, by falling back on only using two out of four engines when nominally four engines would be used. This redundancy would not be available if thrust vector control by differential throttling were employed instead of gimbaling.

The design drawing, Figure 4, shows the 12 vernier engines, in clusters of three, in four locations around the OTV body. They are used when approaching a target to provide retro thrust, and also for other minor orbit corrections. As discussed before, the R-Bar approach limits the use of retrothrusters. Control torques for body reorientation are produced primarily by control moment gyros rather than the vernier engines.

The four propellant tanks of 68-cm (27-inch) diameter basically determine the depth (or "length") of the OTV disk structure. Its 3.0 m diameter provides an unobstructed flat area of about 5.0 m^2 for mounting the solar cell panels with a power output of 500 W (before degradation effects). With battery recharge requirements (at 75 percent efficiency), the net day/night power level is between 250 and 280 W, taking degradation into account, which is adequate to cover the moderate power requirements of the system. This assumes full solar illumination in the daytime, with the body generally oriented toward the sun. During thrust phases, the Sun-orientation may have to be interrupted, but they tend to be of reasonably short duration, at most between 5 and 10 minutes, even for applications with large delta-V requirements and a large payload mass.

Table 3. Representative Delta-V Maneuver Requirements and Propellant Mass for Several OTV Sortie Modes*

Sortie Mode	Delta-V Required (one way) m/sec	Propellant Mass (depends on payload mass, round trip) kg	
		P/L Mass	Prop. Mass
1. Consumables Resupply for ISS** (from 250 km to 350 km altitude)	58	500 1,000 1,500	48 57 67
2. ISS Waste Disposal (from 350 km to 50 km altitude)	177	500 1,000 1,500	139 166 194
3. Constellation Satellite Retrieval (from 300 km to 700 km altitude)	222	500 1,000 1,500	174 210 246
4. Failed Constellation Sat. Controlled Deboost (from 700 km to 50 km altitude)	370	500 1,000 1,500	270 322 374

* Assumptions in calculation:
OTV dry mass 180 kg. Initial propellant mass 800 kg. Storable hypergolic bipropellants (N_2H_4, N_2O_4) with Isp = 300 sec. (Data given are for first sortie, starting with full tanks).

** ISS—International Space Station

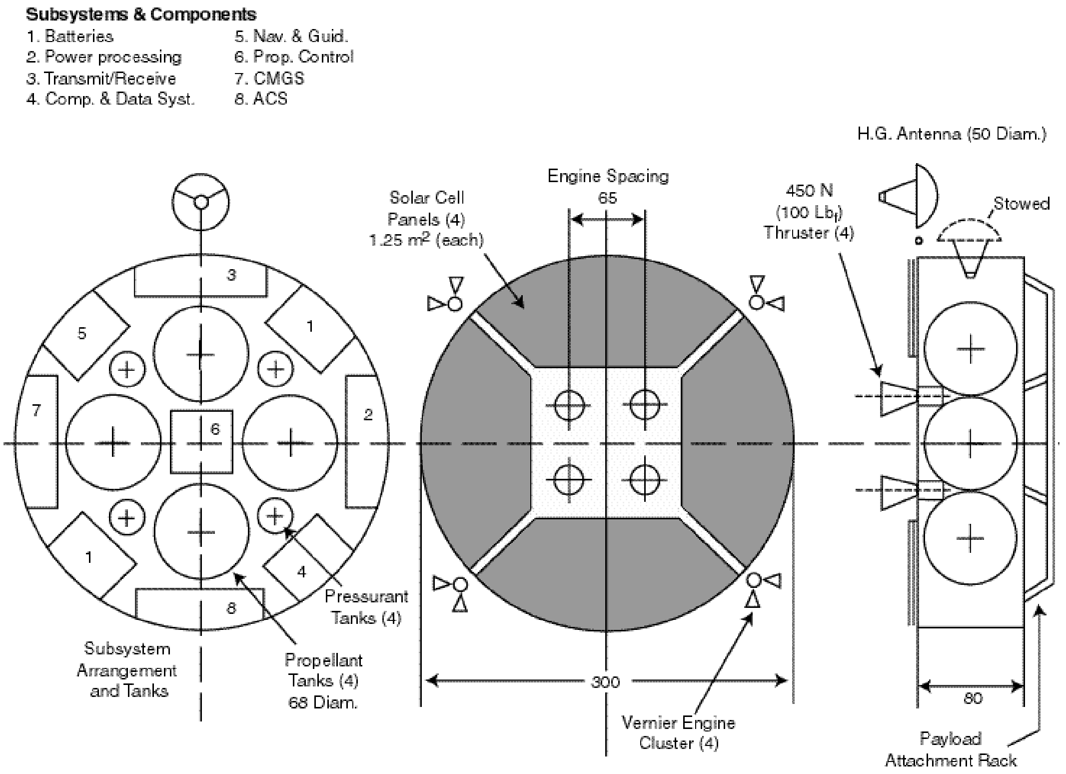


Figure 4. Conceptual OTV Configuration (dimensions in cm).

Table 3 lists typical propellant requirements per sortie for several OTV scenarios, including those related to several Space Station servicing tasks. Payload masses ranging from 500 to 1500 kg are assumed to be carried on only one leg of these round trips. A total bipropellant capacity of 800 kg generally can support from 5 to 20 sorties of the kind assumed here, according to the data in Table 3. In some applications, the OTV tanks may be off-loaded to reduce the launch mass. Table 4 gives a preliminary mass breakdown of the basic OTV bus. The dry mass is approximately 180 kg, including a 20 percent growth margin. Also listed are retention attachments required for some of the transfer tasks. Propellant expenditure varies greatly with the application to which the vehicle is assigned. For Space-Station-based missions and cargo masses of the order of 1000 kg, representative propellant consumptions range from 60 to 200 kg per sortie.

Table 4. Preliminary Mass Breakdown of OTV (in kg)

Structure	30	(plus retention fixtures, 15*)
ACS	10	
Prop. Dry mass	30	
C & DS	15	
Comm.	15	
Power	35	
	135	(150*)
20% Margin	28	(30*)
Total	**163**	(180*)

5. Estimated Cost and Development Schedule.

The spacecraft development and 1st unit costs will be calculated from the mass breakdown in Table 4, using a small satellite space mission cost model presented in Chapter 20 of Reference 16. The cost breakdown is summarized in Table 5.

Table 5. Total System Cost Estimate Less Launch Cost

Program Element	Cost (FY00$K)
Spacecraft (development plus 1st unit)	18,011
Flight Software (10,000 lines of C)	2,175
Integration, Assembly, & Test	2,503
Program Level Costs	4,124
Ground Support Equipment	1,189
Launch & Orbital Operations Support	1,099
Total Cost Not Including Contractor Fee or Launch	29,101
Contractor Fee (10%)	2,910
Total Cost Not Including Launch	32,011

We propose a short development schedule, which has the prototype OTV being built and ready to ship to the launch site within 26 months of the program start date (see Figure 5). Based on several small satellite programs conducted in the last 10 years, we feel that this schedule is quite reasonable, especially in light of the fact that no specialized payload element is required. The key cost-driver of the non-recurring spacecraft development cost will be creating autonomous rendezvous control laws for the various OTV applications discussed previously. The spacecraft hardware is basically off-the-shelf technology which is space-proven, with the exception of any mission-specific docking and cargo holding fixtures.

Pre-Phase A will consist of defining the basic mission architecture, laying out the OTV performance goals and metrics, proposing a preliminary spacecraft design, investigating risk mitigation approaches, evaluating the key performance/cost/risk trade-offs, and selecting a launch opportunity. Phase A will entail detailed spacecraft design, autonomous rendezvous simulation development/refinement to initiate control law formulation for the key modes to be demonstrated, and refining the performance/cost/risk trades. Phase B will finalize autonomous rendezvous control algorithms and initiate rendezvous control software and general onboard software development. Also in Phase B, hardware- and software-in-the-loop testbed validation will be carried out for major spacecraft subsystems. Phase C/D will primarily involve building the spacecraft, setting up the chosen ground station with appropriate software and any required additional hardware for processing telemetry data. (We assume use of an existing ground facility with minor modifications.) Phase C/D will also include the final integration, assembly, and test of the spacecraft. Phase E comprises launch and orbital operations for the mission, with a nominal mission life of 30 to 60 months. The total program will last 56 to 86 months.

Figure 5. Proposed OTV Mission Schedule for 1st Flight Unit

6. OTV Utilization Trade vs. Availability and Cost.

Considering the substantial cost of developing and building the OTV as well as the question of its earliest availability for diverse mission applications, it is important to perform a comprehensive assessment of its utility and value in solving operational and survival problems of critically needed and expensive space assets. Such problems would have to remain unresolved if some of the support and service functions that the OTV can provide are unavailable. The assessment requires a multi-faceted trade study of how much is gained by using OTV services, and in what time frame, versus the cost of developing and using the OTV. This also includes the operational cost of continued use in orbit, as well as the cost of "one-shot" missions that would require OTV service under conditions where it cannot be retrieved for subsequent further applications.

An important consideration is the cost reduction per unit inherent in using a conceptually simple OTV bus design of reasonably small size and minimum complexity. This basic OTV will be produced serially, several units at a time. It should have sufficient adaptability to utilize attachment kits that would be developed for specific purposes such as grasping and transporting failed or defunct satellites for controlled deorbiting. The basic function always will be autonomous maneuvering, regardless of the required delta-V maneuver magnitude.

There is a question of whether in-orbit refueling is to be performed, or alternatively, the addition of a tankage module for extra propellant capacity would be necessary. Both of these alternatives would add complexity and impose considerable extra cost to the basic design. What would be required is the addition of extra propellant handling and control, extra propellant lines and valves, etc. and design features to assure operational safety. Connecting of the propellant lines after docking and controlling the propellant flow under strict safety rules are among the more complex handling sequences to be performed in any spacecraft resupply task. For Space-Station-based OTV uses, the refueling task would be less demanding than performing it in free flight, e.g., by rendezvous with a tanker. An alternative to refueling would be to have slightly different OTV bus sizes with propellant tank capacities that would fit different on-orbit satellite support requirements.

This and other cost-versus-utility trade issues are summarized in Table 6. Included are entries such as OTV utilization frequency, support for several mission classes, such as watch-dog functions for a satellite constellation, and cost factors. Also of concern is the frequency of replacing an on-orbit stationed OTV to assure continued availability of services. A major factor is the combined cost of the OTV being assigned to a specific application and that of the launch vehicle being used. Piggy-back launch of the relatively small vehicle will be an important cost-saving option, as well as the possibility of several OTVs being carried by a single launch vehicle.

7. Conclusions and Summary.

The foregoing conceptual description of operational scenarios, functional requirements, design factors, utility, versatility, and development cost estimates of a moderate-size Orbital Transfer Vehicle (OTV), together with a discussion of cost/effectiveness trades, supports arguments for starting its development as soon as possible, for near-term availability in a number of important support missions, especially for ISS and the numerous commercial communications constellations (e.g., Iridium, GlobalStar, Teledesic, Ellipso). The principal design and functional characteristics are quite different from, and much less stringent than those of the earlier Orbital Maneuvering Vehicle (OMV) which had been under development for NASA during the middle and late 1980s. The OTV serves primarily as a low-cost transportation stage with significant autonomous maneuvering, rendezvous and docking capabilities, but with much less sophisticated and advanced servicing features, and none of the costly redundancy and on-orbit replaceable units that were considered essential to the OMV’s functional role. Its estimated moderate development and production costs reflect the design concept

Table 6. Major Trade Issues in OTV Design, Utilization and Cost.

Trade Issues	Complexity	Add-on Features	Utility/Benefits	Cost Factors
A. Design Issues				
1. Basic OTV Bus	Lowest	None	· Suitable for many applications · Serial production · Early availability	Lowest devel. and product. costs
2. Configuration: Short Length ("Disk" shape)	—	—	· More adaptable to shared launch options (piggy back) · Solar panels placed on OTV body · Easier thruster control with c.m. misalignment	Can save launch cost Saves development cost
3. Medium Propellant Capacity on Basic OTV Bus (ca. 800 kg)	Lowest	None	· Fits many mission types · Off-load if appropriate	Can save launch cost
4. Added Refueling Capability	More complex prop. module (prop. distrib. and control)		· Needed for some mission types · Refueling of or by OTV	Considerable design, develop. cost increase
5. Autonomous Guid., Nav., & Control Capability	Incr. on-board comp. and data processing capability		· Essential in most mission types · Remote GN & C is often impractical	Extra design & development cost but greatly reduces ops. cost.
B. Utilization and Operating Issues				
1. Many Basic OTV Bus Mission Applications	Lowest	None	· Earliest available · Needed in ISS ops. (resupply, waste disposal, circumnav.)	Lowest mission cost
2. Growth in Mission Complexity	More complex mission profiles, added equipment		· Overall benefit of expanded OTV role	Add-on kits less costly than new OTV model
3. Support of Sat. Constellations	Greater ops. complexity. Use of multiple OTV functions a main issue.		· Sat. refueling & resupply · Enhances constell. safety. (Deorbits defunct sats.)	Greater deployment cost. Many OTVs in use simultaneously
4. OTV Stationed in Orbit vs. more Frequent Launch, Retrieval by STS	Operational complexity trade. Depends on scenario.		· Offers rapid response · Only practical for some mission types	Saves launch cost. But extra OTVs may be needed.

of a basically simple bus vehicle that can be adapted to a variety of servicing and transportation tasks by adding special-purpose attachments for which the vehicle configuration would be designed from the outset.

On this basis, the basic OTV bus can be produced serially, which further reduces manufacturing and assembly cost, and can be made available to numerous mission applications on an accelerated schedule. As an example, its use to support satellite constellations in a standby position, in each of the constellation's orbit planes, becomes economically attractive, to perform refueling services and, if necessary, to dispose of failed satellites by a controlled deorbit procedure.

Examples of the cost versus utility and functional capability trades are discussed in Section 6. Additional study with more well-established cost data and mission operation plans is suggested to further assess and definitize the role to which the OTV would be assigned. It also will be important to determine additional applications, ranked as to their respective urgency and cost-saving potential by protecting and/or prolonging the orbital life of both valuable military and nonmilitary space assets. This also should take into account program objectives not available in the literature at this time.

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