Small Orbit Transfer Vehicle (OTV) for On-Orbit Satellite Servicing and Resupply*

John T. Collins, Hans F. Meissinger, Robert Bell

Microcosm, Inc.,

401 Coral Circle, El Segundo, CA 90245, (310) 726-4100

jcollins@smad.com, hansm@smad.com, rob@smad.com

Abstract. The field of on-orbit servicing of space systems has been studied extensively, and techniques for performing satellite resupply and repair functions have been developed in detail. They are covered extensively in the literature. Based on this background, Microcosm has performed design studies, partly under NASA/MSFC contract, of a small-size, 300 kg-class multi-function Orbital Transfer Vehicle (OTV) that can provide servicing and resupply functions for the International Space Station (ISS). It carries the required payload from a launch vehicle upper stage to the Station, and after berthing it supports servicing activities of the ISS crew members. The vehicle has a payload-carrying capability of 350 kg. The current design includes grappling fixtures specifically designed for ISS berthing which can be eliminated for servicing other satellites. The very strict safety requirements involving ISS access were taken into account in the servicing vehicle design. Repeated ISS servicing sorties to be performed by the OTV are of particular interest, to meet tight revisiting schedules. Extended reuse of the same OTV, once in orbit, allows substantial launch and operational cost savings. Propellant requirements for the servicing sorties are very modest, allowing an extended on-orbit life of this vehicle, with at least 3, but more likely 6 to 8 ISS revisits. The OTV discussed here can be utilized for low-cost servicing of other spacecraft as well. The paper discusses the vehicle's maneuver sequences and propellant requirements, and describes its design features and its interactions with the ISS. The OTV's total recurring cost is estimated at less than $35 Million. It would nominally be carried by a light-lift launcher, such as Microcosm's planned Sprite vehicle, at a projected cost of the order of $2.5 Million.

1. Introduction

Satellite servicing and resupply by unmanned vehicles designed for this operation has been extensively studied and discussed in the literature in recent years. The on-orbit servicing tasks would be performed by a special class of Orbital Transfer Vehicles (OTVs), designed for rendezvous, docking and interaction with target spacecraft that require either consumable resupply or replacement of defunct components that are accessible by the servicer. Of particular interest is the autonomous control of such satellites, to reduce operations costs, to broaden the range of target access, and to avoid the constraints imposed by remote control and the extensive communication requirements inherent in this operating mode.

There are many literature references covering on-orbit servicing techniques, operating modes and requirements, design concepts and cost/benefit trades. Of special interest is Ref.1, by D.M.Waltz, a handbook on satellite servicing methods, technology, design concepts and operations. Ref.2 through 6 cover various specific aspects of servicing. Ref.7. (by two of the authors of this paper) describes a small, low-cost OTV designed for multiple orbital operation functions including satellite servicing. That OTV is a much simplified version of the complex Orbital Maneuvering Vehicle (OMV) that had been under development in the 1980's for NASA/Marshall Space Flight Center (Ref.8), a program that still provides very useful data on satellite servicing technology, procedures and implementation requirements.

A study of a similar OTV to be used for resupply and servicing of the International Space Station (ISS) was performed by Microcosm, Inc. (Ref.9) in the second half of 2000 under NASA/MSFC contract, with emphasis on issues of safe access and operations at and near the Station, and the required safeguards. The MSFC program referred to is named "Alternate Access to the Space Station" (AAS).

This paper describes an OTV suitable for this purpose as well as for servicing and resupply of other spacecraft, with a capability for re-use and multiple-sorties in orbit. Major cost savings are achieved by reducing the number of repeated launches of new OTVs into orbit. The vehicle is designed to transfer cargo or servicing equipment between the launch vehicle (LV) upper stage and the ISS, with the upper stage remaining at a safe distance of 10 km from ISS, well outside the Approach Ellipse (AE) boundary. Use of this go-between vehicle equipped with the requisite ISS access and safety provisions eliminates the need of such provisions to be carried by the launch-vehicle upper stages at each ISS resupply visit. This simplifies the LV design and results in additional recurring cost savings.

Briefly, the multi-functional OTV discussed here has a dry mass of 220 kg and carries about 70 kg of propellant. It is capable of carrying a 350 kg payload to the ISS. A total of three sorties to ISS is envisioned, which could be raised by increasing the propellant mass. The total OTV recurring cost is estimated at about $30 Million. The vehicle is designed for being launched by a low-cost LV such as Microcosm's planned "Sprite", with a projected launch cost of the order of $2.5 Million. The baseline OTV design for ISS resupply is presented here along with modifications to allow low-cost servicing of other space assets.

Other satellites operating in low Earth-orbit (LEO) can make use of this servicing and resupply OTV, but without the safety and access features required for use in ISS servicing. Application of the OTV's repeated sortie capability would be of particular interest if several satellites in the same orbit require servicing. Use of the OTV as a go-between,

from the LVs to the satellites in question, can result in major cost savings.

2. OTV Principal Mission Objectives and Requirements

An OTV can be used either to take equipment, supplies or replacement parts to a target destination in orbit, or to perform a specific function, like replacing a defunct piece of equipment, a system component or subsystem on unmanned satellites. In supporting the operation of the ISS, the OTV can perform similar tasks or merely deliver provisions to the crew for various purposes, including repair functions.

Very few orbital servicing missions have been flown to-date, and these were performed exclusively by the Space Shuttle, such as the repeated successful refurbishment of the Hubble Space Telescope (Ref.1) starting in 1993. The complexity of the tasks performed, like the installation of optical components for correcting a defect in the telescope's primary mirror, necessitated manned operations. The high servicing cost involved was justified by the extremely high value of the HST as a space asset.

As discussed in Ref.7, the OTV can be applied to a variety of satellite or space system servicing functions all of which would make use of its basic maneuvering capability and operating flexibility. Examples of such OTV functions are listed as follows:

1. On-orbit repair and/or resupply of satellites having appropriate configurations or design features. Servicing visits to multiple co-orbiting satellites in a constellation.

2. Transfer of satellites to their intended orbit, or orbital position, from a staging point, where they are separated from their launch vehicle, e.g., if multiple satellites are being deployed, thus relieving the LV of added maneuvering requirements.

3. Retrieval of a satellite and redeployment to a different orbit.

4. Retrieval of a satellite to the Shuttle Orbiter for servicing, or for return to the ground. Also redeployment after servicing by the Shuttle. These functions had been originally considered to be performed by the Orbital Maneuvering Vehicle (OMV), referred to above.

5. Retrieving a defunct satellite and providing a deorbit impulse, followed by an equal and opposite impulse for the OTV to remain in orbit.

6. Close visual observation of another satellite or spacecraft, by circumnavigation or formation flying. This may be of interest for military or non-military purposes. A circular, rather than elliptical circumnavigation path can be established by an orbit tilted 60 degrees against the target satellite's orbit plane, as shown in Ref.7. (Even an occasional OTVcircumnavigation of the Space Station, for close visual observation, may be of interest).

These and other diverse mission objectives and operating techniques should be considered as representative of the OTV applications spectrum. For different mission objectives specific design elements will have be added to the basic vehicle design, but the vehicle's structure and primary subsystems generally remain unchanged. The required tankage capacity may be different for these mission classes, or a maximum tankage capacity, suitable for any mission objectives, may be adopted to reduce redesign requirements. Servicing and resupply of the ISS will be discussed in some detail in the following sections, with attention to the specific requirements and constraints inherent in Space Station access.

In future on-orbiting servicing of satellites, human participation should be avoided wherever possible, particularly, if the resupply or component replacement can be reduced to a routine task. In ISS servicing, manned involvement will likely remain, and generally be provided by the Station crew, with the OTV primarily performing delivery of new supplies or removal of waste and defunct equipment.

3. OTV Mission Sequence for Space Station Resupply and Service

The primary mission sequence for ISS resupply and service as defined by the MSFC Program Office includes approach and departure phases that are illustrated in part by the proximity operations shown in Figure 1. In this figure the OTV approach path is shown by solid lines, its departure and return to the initial location, for possible rendezvous with the LV upper stage that waited during the entire OTV visit to the Station (see below). Reliability and safety are key issues at all times in the approach to, and departure from the Station, and of course during all proximity operations and while attached to the ISS. The following are representative phases of the OTV transfer sequence:
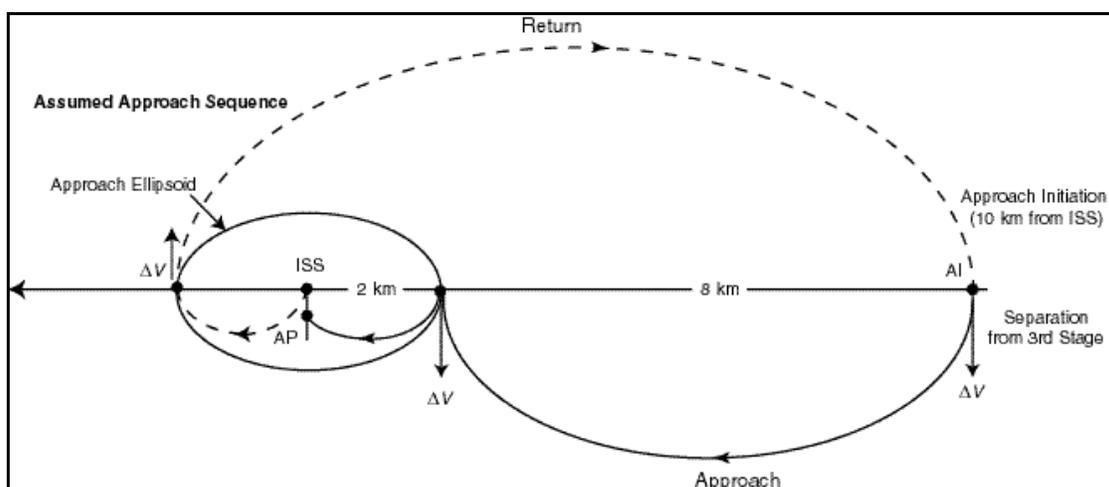
Figure 1. OTV Approach to ISS and Return Sequence

(1) Launch and delivery of the OTV with cargo canister to 185 km circular orbit. Separation from the LV 3rd Stage.

(2) Ascent by OTV carrying cargo from 185 km to 350 km ISS orbit, with an offset of about 10 km, in front of or behind the ISS, awaiting command to start the transfer and approach to ISS. Using OTV onboard propulsion capability rather than that of the launch vehicle 3rd stage is more cost effective because more total payload mass can be delivered to the ISS orbit. An offset point behind the target is preferred because the close approach from behind and below tends to be less obstructed by the Station's large structural appendages and by other visiting vehicles at their berthing locations.

(3) From the Approach Initiation Point (AI), the OTV follows an elliptical trajectory for half an orbital revolution, starting with a small vertical downward velocity impulse and ending at the boundary of the Approach Ellipsoid (AE), 2 km from the Station, an envelope defined as a last-minute contingency check point of visiting vehicles, if necessary for ISS safety.

(4) If cleared for entry into this envelope, the OTV continues its approach, along a shorter (2 km) elliptical arc, to the Aim Point (AP) about 100 m below the berthing location. The initial and final velocity impulses are directed vertically, at the start of this transfer, and nearly vertically at AP. If no wave off before entering the AE boundary is indicated, the downward delta-V at this point must be 25 percent larger than the one required for wave off at that point.

(5) The Aim Point is located at 100 m distance from ISS center of mass.

(6) The final R-Bar ascent from AP to the Grapple Point (GP), as shown in Figure 2, follows a number of shallow arcs of 10 to 15 m length. At each connection point of these arcs, a very small horizontal maneuver of less than 1 cm/sec must be performed to reach the point GP where the visiting vehicle will be grasped

by the Station's remote manipulator arm (SSRMS).
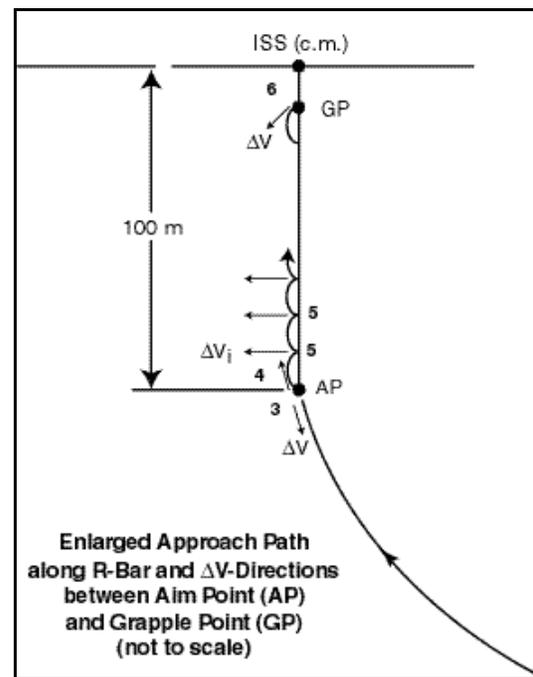
Figure 2. Details of R-Bar Final Approach Path

Details of the OTV design features used for this purpose, and for the subsequent servicing tasks are described in the next section.

After completing all servicing functions at the Station, the OTV follows a departure sequence, as illustrated by the dashed departure trajectory in Figure 1, and returns for rendezvous with the waiting upper stage. A typical objective of this phase is to attach a canister containing ISS waste products to the stage in order to be deorbited along with it. It will be noted that the return path shown in Figure 1 is designed to avoid any risks of possible collision.

After delivering this waste material back to the waiting LV 3rd stage for deorbiting, the OTV remains at that location, or moves further away to a co-orbiting parking position, awaiting the next engagement, when new supplies will be brought up again, perhaps several months later.

Instead of a repeated three-time OTV engagement that was assumed in the ISS servicing study, Ref.9, it may be more cost-

effective to extend its orbital life to several more servicing engagements. Also, possible OTV orbit changes to perform servicing of spacecraft other than the ISS may be of interest, but this is not further discussed here.

Regarding the sequence of short, shallow arcs in the final R-Bar approach to the grapple point (see Figure 2) and its numerical computation, a greatly simplified approximation method has been found very useful. It is based on the fact that the velocity along each arc remains very nearly constant over several minutes. This allows approximating the orbital time history of the arc sequence in Figure 2 by a set of circular segments. Their curvature radius r_c is approximated by equating the centrifugal acceleration $a_c = V^2 / r_c$ with the Coriolis acceleration $a_{cor} = 2 V$ (where is the angular rate at the orbit altitude).

As a result, parameters such as the path angle , the arc length s, the duration t_c of the segment, and the very small V to be applied at the ends of each segment, all can be readily calculated in closed form. The use of the more complex Clohessy-Wiltshire equations for this purpose is unnecessary. The approximation accuracy for arc segments of several-minutes duration is found to be better than 1 percent, which is perfectly adequate for the required trajectory analysis and control. (A more detailed discussion of this approximation and its usefulness will be presented in a separate paper, to be published by the AIAA.)

The choice of a radial departure from point AI and interim radial stop-and-go maneuvers between points AI to AP rather than horizontal

maneuvers, that would reduce the total delta-V requirements, is justified by the following considerations:

(a)   The transfer time for each of these arcs is reduced from 1 full to 1/2 revolution.

(b)   The start and end maneuvers of each arc are in the same rather than opposite direction, avoiding repeated 180-degree spacecraft reorientations that would be required in the case of horizontal transfer maneuvers.

(c)   The generally more economical horizontal start and stop maneuver mode also has the disadvantage of producing a short "looping" phase at both ends of each transfer arc, unsuitable for operation in close vicinity of the target spacecraft. This transfer mode would be preferable only under free-flight conditions, at large distances from a target.

Thruster Utilization and OTV Orientations During the Approach Phase

Figure 3 illustrates thruster utilization and vehicle orientation requirements in the selected maneuver sequence (Fig.1 and 2).The V directions at the various stages of the approach are accommodated by keeping the OTV length axis orientation vertical or nearly vertical. At departure from the AI point at 10 km distance from the Station, and at the next radial maneuver event, 2 km from the Station, the OTV is above the cargo canister it is carrying, such that the set of axial main thrusters are pointing vertically, or nearly vertically, downward (points 1,2 and 3).
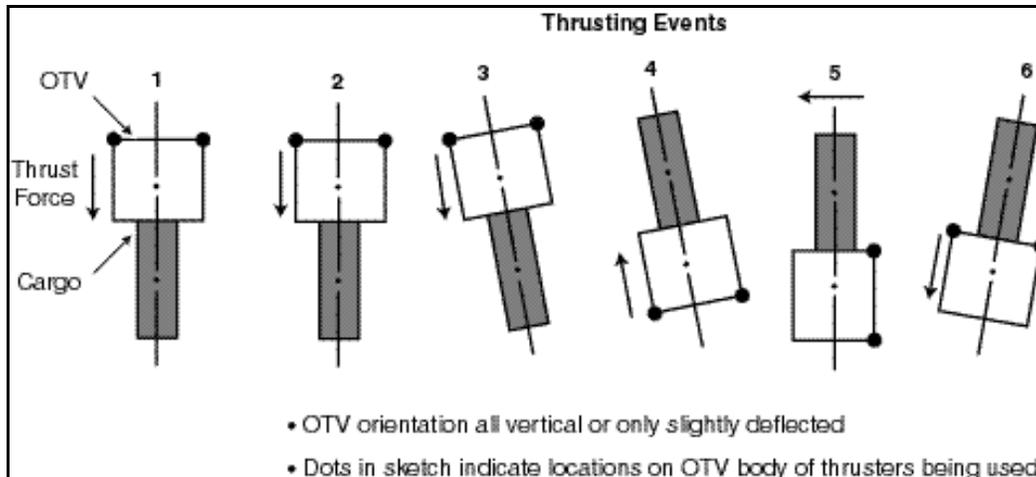
Figure 3. OTV/Cargo Body Orientations at Thrusting Events During Approach Phase

A 180-degree reorientation is required at the end of the second approach arc, the aim point AP in Fig.1 and 2, as indicated by points 3 and 4 in the orientation sequence shown in Fig.3. This permits the forward-pointing target sensors, or cameras, to be in a position to view the Station, and particularly the intended target location at the Station, during the critical final approach phase between points AP and GP shown in Fig.2.

Lateral maneuvers repeated after each small transfer arc during the R-Bar approach phase are performed by the small lateral thrusters, each maneuver requiring only a fraction of a cm/sec velocity change (Points 5 in Fig.3). It should be noted that when using the lateral thrusters mounted on the OTV hull, a small balancing thrust from pairs of the axial thrusters is required, because the vehicle's center-of-mass is located forward of the lateral thruster locations, after the relatively heavy cargo container is attached to the OTV. Further details of these configuration issues will be explained in the next section that describes the OTV design in detail.

Alternative OTV Mission Sequences.

The mission sequence shown in Figures 1 and 2 related to ISS access and servicing by the OTV is one of several alternatives that may be considered. For example, if an extended waiting time between ISS revisits is anticipated, the OTV may be parked at a greater distance than the nominal 10 km indicated in Fig.1. This allows more leeway for maneuvers to correct the slow OTV orbital decay relative to the Station. The Station itself also is subject to altitude changes, but of different magnitude during prolonged time intervals between OTV visits.

One question of concern is that of OTV disposition after the projected ISS servicing events are finished, after three or more consecutive visits. One end of the OTV servicing engagements is to perform a deorbit maneuver without saving the OTV for future use. Another scenario would allow the OTV to deorbit but preserving it for future use after reconditioning, by controlled landing at a designated landing site.

The trade between the cost of providing replacement OTVs and the cost of providing a safe return capability, involves many factors still to be evaluated. Prolonged, repeated use in orbit tends to offer many cost benefits and reduces the need for burdening the launch vehicle payload capacity with carrying the OTV mass, when it could otherwise maximize the total resupply and servicing payload mass by reducing the number of OTV launches.

Other types of OTV missions can benefit from extended OTV life on orbit and making use of repeated sorties to different targets. This would be particularly effective for servicing of satellites in a given constellation, where only repeated repositioning is required, but no orbit

altitude or even plane change maneuvers. In principle, the individual target approach sequence previously considered in the ISS servicing scenario may in part remain applicable, except the very specific, high safety and risk avoidance requirements inherent in Space Station servicing can be waived to some extent, reducing the cost of some OTV design features and mission elements. On the other hand, more autonomous control and operation required in such servicing missions need to be further investigated. In ISS servicing, the role of human operators tends to reduce autonomy requirements.

Delta-V Expenditures During Successive Mission Phases

Table 1 is a summary of the ΔV requirements of successive mission phases that are executed by the OTV in servicing the Space Station. The mission includes 3 sorties from the LV upper stage to the Station and back. The alternative of 6 ISS visits also is listed. The return trip is used to carry a waste container to the upper stage for reentry and burnup. The mission sequence also includes two OTV sorties to parking positions at co-altitude, 30 km from the Station during the intervals between ISS resupply events, as well as with orbit decay correction maneuvers during these intervals. (A 10 km orbit decay relative to the Station is assumed, but actually some larger decay may occur if the waiting time between servicing sorties is particularly long).

The mission will be terminated by the OTV performing a deorbit maneuver, for atmospheric entry and burnup. The 250 km descent from the assumed 350 km ISS altitude requires a retro maneuver of 73.5 m/sec. As an alternative, the OTV may be deorbited by the LV 3rd stage in the case of ISS servicing missions, but not if the OTV is performing other missions, with no 3rd stage being available for this function. The three servicing sorties to and from the Space Station require only 18 percent, and the assumed orbit decay corrections about 5 percent of the total maneuver expenditure. With the total delta-V requirements of only 219.3 m/sec, it is reasonable to use hydrazine monopropellant with an assumed specific impulse of 220 sec, rather than bipropellant. Table 1 lists the small propellant mass fractions used for each part of the mission sequence. The rough overall mass fraction is only 10.6 percent (just 2.9 percent more than for bipropellant).

Table 1. ΔV Expenditures & Propellant Mass Fractions During Successive Mission Phases

Transfer Phase	Number of Thrust Applications	Thrust Direction*	Payload Type	ΔV per Phase (m/sec)	Total ΔV (m/sec)	Percent of Total	Propellant Mass Fraction (%)**
LV drop altitude (185 km) to ISS operational orbit (350 km)	2	H	Cargo	94.45	94.45		4.47
3 ISS Visits						43.1	
6 ISS Visits						34.1	
3rd Stage to ISS (10 km)	3	V	Cargo	5.72			
R-Bar Phase at ISS	7	V/H	Cargo	0.36			
Return to 3rd Stage	3	V	Waste	6.86	(12.94)	(10.5)	(0.6)
3 ISS Visits	39				38.82	17.7	1.8
6 ISS Visits (alternative)	78				77.64	28.0	3.6
Sortie to Parking Position (20 km from 3rd stage location)***	4	H	None	0.49			
2 sorties	8				0.98	0.4	0.045
5 sorties (alternative)	20				2.45	0.9	0.114
Orbit Decay Correction (ΔH = 10 km)	2	H	None	5.76			
2 Returns	4				11.52	5.3	0.534
5 Returns (alternative)	10				28.80	10.4	1.335
Deorbit (ΔH = 250 km)	1	H			73.50		3.41
3 ISS Visits						33.5	
6 ISS Visits						26.5	
Total Mission ΔV							
2 sorties					219.27		
6 sorties					276.84		

*H = Horizontal, V = Vertical

** Assumes monopropellant (Isp = 220 sec)

*** Parking location is 30 km from ISS, at co-altitude

In this mission, monopropellant has the advantage of being suitable for use by both the main thrusters (22 N each) and the small auxiliary thrusters (4.4 N each) without much propellant mass penalty. It simplifies the propulsion system design and saves cost.

These results support the rationale for performing a greater number of OTV servicing sorties in one mission, e.g., 6 rather than only 3, and thereby saving OTV production and launch costs: This would increase the delta-V expenditures for ISS servicing purposes from 18 to 28 percent, and similarly the share of the total propellant mass fraction. Compared with the relatively high orbit raising and deorbit ΔV requirements at the start and end of the mission, the sortie ΔV requirements are relatively small.

4. OTV Conceptual Design

The OTV designed for Alternate Access to ISS is required to autonomously dock with a cargo canister/launch vehicle 3rd stage, initiate and control its approach to the ISS, hover for Space Station Remote Manipulator System (SSRMS) grapple, and then safe itself for removal of the cargo canister by ISS astronauts. In addition to these tasks, it must be capable of autonomous failure detection and collision avoidance, it must incorporate adequate redundancies to assure safe operation near the ISS, and it must be capable of on-orbit storage for long periods of time. The vehicle design presented here incorporates the required equipment necessary to accomplish this ISS servicing mission safely and reliably.

Figures 4, 5, and 6 show the Orbit Transfer Vehicle (OTV) that will accomplish rendezvous and docking with the ISS to deliver a small

payload capsule. This OTV will also carry away a waste container for deorbit by the waiting launch vehicle 3rd stage. Our OTV design is basically a cylinder with body-mounted solar arrays. It is 0.97 m in diameter and 1.27 m in length and has a total loaded (wet) mass of 290 kg. It has a total of 24 small thrusters arranged in eight clusters of three orthogonal thrusters situated at the periphery of each end face of the vehicle. On the rear end of the vehicle, each of the four thruster clusters have one 22 N thruster and two 4.4 N thrusters. The 22 N thrusters will be used for making the larger maneuvers that the OTV will execute, such as initial orbit transfer from a 185 km launch vehicle dropoff orbit up to the Space Station orbit at 350 km, and the final OTV deorbit maneuver at end of life. The front end of the OTV has four clusters that contain three 4.4 N thrusters each. The 4.4 N thrusters will be used for fine maneuvering during rendezvous and docking (proximity operations) and for vehicle attitude control maneuvering.
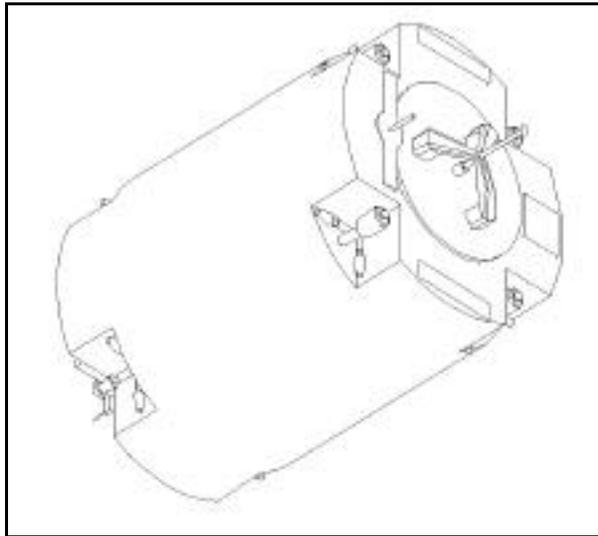
Figure 4. Orbit Transfer Vehicle Conceptual Design, Rear View

In Figure 4, the OTV is viewed from the side that docks with the ISS Payload/ORU Accommodation (POA) location. The Power Data Grapple Fixture (PDGF) is shown mounted on this end and will serve as the attachment point between the OTV and the POA on the Space Station. This PDGF will allow

the OTV to receive power and data directly from the Space Station during the critical payload canister removal operation by the SSRMS if necessary. The figure also shows two Sandia Laser Ranging sensors (two rectangular shaped objects near top and bottom edge) and a MSFC Video Guidance Sensor (VGS) sensor (square object to the right of the PDGF). The sensors are recessed into the body of the OTV to allow for sufficient clearance for the OTV to be placed on the POA.
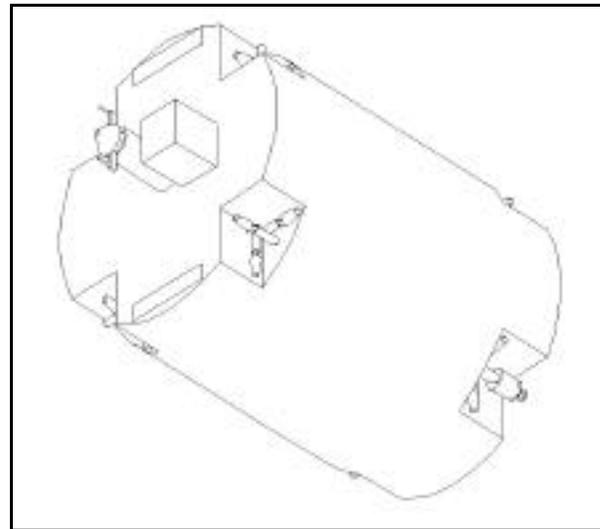
Figure 5. Orbit Transfer Vehicle Conceptual Design, Front View

Figure 5 shows the front end of the OTV that has a Michigan Aerospace docking probe mounted to it. This is the side that docks with the cargo canister during rendezvous with the launch vehicle 3rd stage, and where the payload will separate from the OTV after the OTV is docked on the POA. Also, when a waste canister is to be removed from the ISS, it will be placed back on the OTV using the Michigan Aerospace docking system to mate with the OTV. The cargo canister and the waste canister are one-in-the-same and has the Michigan Aerospace docking cone mounted on both ends. Also shown in the figure are two Sandia Laser Ranging sensors (two rectangular shaped objects near top and bottom edge) and a MSFC VGS sensor (cubical object to the right of the docking probe). Figure 6 shows end and side views of the OTV.
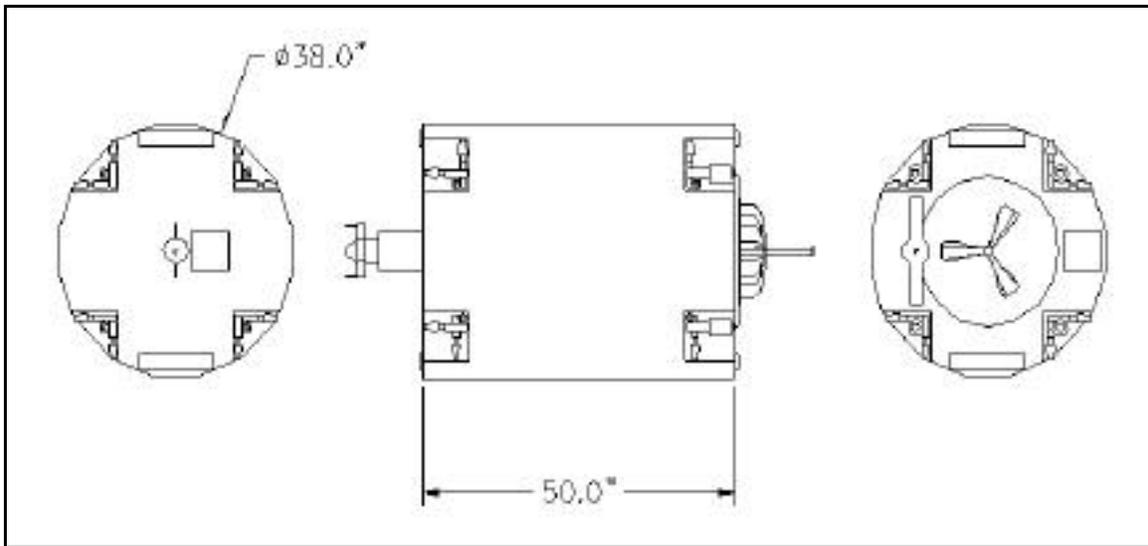
Figure 6. Orbit Transfer Vehicle Side and End

The overall mass budget of the OTV is shown in Table 2 below. There is significant redundancy built into the OTV, in strict adherence with the guidelines for Space Station "visiting vehicles" as outlined in the following reference documents:

- "Interface Definition Document (IDD) for International Space Station (ISS) Visiting Vehicles (VVs)," SSP 50235, International Space Station Program Office, Feb. 2000.

- "Guide for Visiting Vehicles to the International Space Station (ISS)," Mission Operations Directorate, Flight Design and Dynamics Division, Feb. 2000.

Details on each subsystem and the choices behind the selection of hardware are discussed below.

Propulsion

The OTV mono-propellant hydrazine budget is sized to do an initial ascent to ISS altitude (350 km) from a 185km launch vehicle drop-off altitude and perform from 3 to 6 sorties (full round-trips from the AI point to the ISS). Finally, there is enough residual propellant for station keeping activities. The spent OTV can either perform one final burn to deorbit itself or it can be deorbited by a launch vehicle 3rd stage after final delivery of a waste capsule to the third stage.

As discussed earlier, the OTV has a total of 24 thrusters: four 22 N thrusters and twenty 4.4 N thrusters.

The propellant tank is a modified version of a commercial tank that is rated to $2 \times$ MEOP (Maximum Expected Operating Pressure). The tank has a very large ullage volume in order to reduce the feed pressure variation to the thrusters between beginning and end of life. This is required in a blow-down system. A regulated system may be more efficient, and will be evaluated in future design studies.

The current OTV was designed with the possibility of on-orbit refueling in mind. Extra valves were added to the propulsion system to enable on-orbit refueling if such an option is deemed viable by the time the resupply missions begin.

Table 2. OTV Subsystem Mass and Power Breakdown

Component	Mass (kg)	Power (W)	Potential Vendor
Propulsion	**88.1**	**214.48**	
Propellant	67.54	N/A	
MR-50T Thrusters	2.72	114.92	Primex
MR-111C Thrusters	6.60	54.56	Primex
Valves	1.92	45.0	Moog/Valcor
Propellant Tank	8.62	N/A	PSI Pressure Systems
Plumbing & Fittings	0.70	N/A	
Communications	**20.48**	**66.0**	
TDRSS Transponders	8.16	39.0	Motorola
UHF Transponders	10.21	27.0	Motorola
Antennas	2.11	N/A	
GN&C	**7.29**	**36.4**	
GPS Receivers	0.90	6.40	Rockwell Collins
IMUs	1.40	10.0	Litton Industries
Star Trackers	4.99	20.0	Ball Aerospace
C&DH	**22.5**	**22.5**	Litton Amecom
Remote Sensing	**26.14**	**121.0**	
MSFC Video Guidance Sensor	18.14	85.0	NASA MSFC
Sandia Scannerless Range Imager	8.0	36.0	Dept. of Energy
Power Systems	**21.77**	**2257.19***	
Batteries	17.28	2073.60*	Eagle-Picher
Solar Array	4.49	183.59	TECSTAR
Docking & Grapple Fixtures	**49.85**	**11.0**	
Michigan Aerospace Docking Probe	13.56	11.0	Michigan Aerospace
Power Data Grapple Fixture	36.29	N/A	GFE
Structure	**25.0**	**N/A**	
Monocoque Shell	9.27	N/A	
Support, Etc.	15.73	N/A	
Thermal	**2.5**	**N/A**	
Margin	**26.67**	**N/A**	
Totals	**Mass (kg)**		
OTV Total Mass	290.30		
OTV Dry Mass	222.76		
Mass Margin	26.67		
		Power Req. (W)	**Battery Life(hr)**
Berthed Mode Power		22.5	82.9
Coast Mode Power		100.72	18.5
Docking Mode Power		268.20	6.96

*Refers to total power output capability, not to required power for this subsystem. The power system employs 3 batteries (24 cells) for double redundancy, which is a requirement for vehicles servicing the Space Station.

Communications

For the OTV communications subsystem, we selected two commercially available TDRSS transponders and three commercially available UHF transponders from Motorola. The UHF transponders have built-in encryption technology that satisfies a NASA requirement. The TDRSS transponders do not appear to have this ability. Three UHF transponders were chosen to make the system doubly redundant as loss of communication during

approach to the ISS would be a catastrophic hazard.

Guidance, Navigation and Control

The Guidance, Navigation and Control (GN&C) system is composed of two GPS receivers, two IMUs, and two star trackers, and the control system software. This design provides a great deal of capability and redundancy for the OTV. All of the equipment is space-qualified and commercially available. Prices for star trackers and for space qualified GPS receivers have decreased significantly in the last five years.

Command and Data Handling (C&DH)

We have selected here redundant LRH-3000V flight systems. These space-qualified systems are fairly massive, with a published weight of 20kg. This is an area for further design optimization where we may gain mass margin with a higher fidelity design. Two LRH-3000V's have triple redundancy.

Docking Sensors

We have included two MSFC Video Guidance System (VGS) sensors. These are heavy and require significant power, but they have a verified space-heritage. For back up and additional ranging capability there are four Sandia National Labs Scanning Range Imagers (SRI). The Sandia combined sensor and electronics weigh only 2 kg. The Sandia sensor currently has a published maximum effective range of 46 m in space, but 1.5 km on the ground. Additional space qualification and testing is needed. $1 Million has been budgeted in the non-recurring cost of this sensor to allow for the needed testing and qualification. The range is presumably expandable with a more powerful laser. We assume that by 2003, the sensor will be ready for use and be capable of measuring range and attitude up to 300 m from the ISS. This package satisfies the risk reduction requirement of double fault tolerance and having an alternate means of determining visiting vehicle (VV) distance from the ISS. So our primary sensors are the MSFC VGS's and our backup are the Sandia SRI's. If ISS GPS data is available,

then relative GPS also satisfies the risk reduction requirement.

There are docking sensors on the front and rear faces of the OTV, including two MSFC VGS cameras and four Sandia scannerless range imagers. One VGS camera is mounted looking forward and the other looking aft. Similarly, two Sandia cameras are mounted looking forward and two looking aft. The cameras are recessed as much as possible in the OTV body. The VGS sensors are the primary docking sensors, with the Sandia sensors providing secondary backup. Two sensors pointing in each direction provide full redundancy in enabling the OTV to see the space station in almost any orientation.

An unobstructed view of the rendezvous and berthing control camera(s) and their placement on the OTV body is essential, both during the final ISS approach and the subsequent return and docking with the 3rd stage. This is consistent with the desired OTV/cargo canister orientations, subject to the required OTV thrust sequence and the approach path geometry.

The sensors must look in the direction along the attached cargo canister because the autonomous approach and docking with the 3rd stage, for receiving new cargo and also for attaching the waste canister to the 3rd stage. Consequently, the approach orientation to the Station must be reversed to allow the OTV camera(s), pointed in fixed forward direction, to see the Station during the final approach phase.

Power System

A robust design with three batteries (24 cells) was chosen here. These cells provide much more power than currently required. However, this is a critical subsystem and redundancy is required for this subsystem in a period of eclipse. There are a variety of space qualified cells available; this is another area where we can trade between mass margin and power margin.

The OTV was lengthened from earlier versions from 0.97 m to 1.27 m in order to accommodate additional surface area for solar cells. Currently, this vehicle can generate

almost twice as much power as is required for the quiescent mode with just the solar cells alone.

Structure

We've assumed a structure consisting of a monocoque shell made of IM7/PEEK and support structures made of aluminum. Making the shell with Kevlar (currently 0.09" thick) would more than satisfy the structural requirements and possibly satisfy the micrometeoroid safety requirements. One-eighth inch of Kevlar would give substantial impact protection while maintaining nearly the same mass as an IM7/PEEK composite.

Thermal

The thermal subsystem is cold biased with makeup heaters and its mass is estimated to be 10% of the vehicle structure mass. This includes allocation for thermal insulation and any heating elements required.

Docking and Grapple Fixtures

There is one Michigan Aerospace probe and one Power Data Grapple Fixture (PDGF) on the OTV. The size of the PDGF and the clearance requirements demand that the PDGF be placed on either end of the OTV. Launch vehicle constraints will likely require the PDGF to be recessed.

The Michigan Aerospace Docking System probe designed specifically for our OTV is shown in Figure 5. It is the protruding cylinder with conical endcap that lies next to the cubical Video Guidance Sensor. This probe element weighs 13.56 kg. The cone element that the probe docks with weighs 4.49 kg. The cone will be placed on both ends of the cargo canister for ISS resupply. During docking, the probe (mounted on the OTV) aligns itself with the cone (mounted on the cargo canister) and enters the cone where the two pins insert into the holes in the outer ring of the cone and lock the probe into position, completing the docking process.

5. OTV Cost Estimate

The following table shows the OTV development cost breakdown, including vehicle design and fabrication costs, integration, assembly, and test costs, program level costs, ground support equipment costs, launch ops and orbital operations costs, and software development costs. The total OTV cost from preliminary design through launch and initial orbital operations is $ 81.6 Million (in FY 00 $K). The costs presented here are based on a spacecraft cost model from *Space Mission Analysis and Design*, 3rd ed. (Wertz and Larson, 1999).

Table 3. OTV Development Cost Breakdown

System Element	Non-Recurring Cost (FY 00 $K)	Recurring Costs (FY 00 $K)	Total (FY 00 $K)
1. Payload (R&D Sensors/Actuators)			
1.1 Sensors			
1.1.1 MSFC VGS		5,000	5,000
1.1.2 Sandia Laser Sensor	1,000	2,000	3,000
1.2 Docking Hardware			
1.2.1 Mich Aerospace System		1,500	1,500
1.2.2 Power Data Grapple Fixture		1,000	1,000
Payload Total	*1,000*	*9,500*	*10,500*
2. Spacecraft			
2.1 Structure	2,642	393	3,035
2.2 Thermal	792	110	902
2.3 Electrical Power System	1,365	1,175	2,540
2.4 TT&C/Communications	6,212	5,376	11,588
2.5 Attitude Determination/Control	3,152	2,123	5,275
2.6 Propulsion	1,220	2,997	4,217
Spacecraft Total	*15,382*	*12,174*	*27,556*
3. Integration, Assembly, Test	4,511	2,359	6,870
4. Program Level	6,874	7,391	14,265
5. Ground Support Equipment	4,703		4,703
6. Launch & Orbital Operations Sppt		1,112	1,112
7. Flight Software (50 K Lines)	10,875		10,875
Total Without Contractor Fee	43,345	32,536	75,881
Contractor Fee (7.5%)	3,251	2,440	5,691
Total With Fee	**46,596**	**34,976**	**81,572**

6. OTV Design Alternatives for Other Missions

The current OTV design for payload canister delivery to ISS is flexible enough to allow modifications that would be better suited for other on-orbit servicing tasks and other applications involving orbital proximity operations. In Section 2, six alternate applications were discussed for such an OTV. Straightforward changes to the OTV design for ISS servicing discussed in Section 4 can be implemented to optimize the OTV for other various applications.

For example, if the primary mission objective is to perform repair and resupply of satellites, the OTV can use the same docking hardware (Michigan Aerospace probe and cone configuration) and even the same sensors that are employed for ISS servicing. Lower cost sensors may be a more attractive option, depending on accuracy required, and safety requirements.

For transferring a satellite to an operational orbit slot, in a constellation for instance, the OTV can employ identical docking hardware components as those used for ISS docking. Instead of the OTV picking up a payload canister as is the baseline for the ISS, it would use the same docking components to pick up a satellite and transfer it from a launch vehicle drop-off orbit to the operational orbit slot. The OTV for this purpose may need more fuel for several orbit transfers during its lifetime. This can be accomplished by using a larger propellant tank and/or refueling the OTV from a fuel depot located near the OTV's nominal parking orbit. For this type of application, the ISS-specific Power Data Grapple Fixture (PDGF) device is not required, as the docking is achieved solely using the Michigan Aerospace probe and cone system. The lower OTV mass without the PDGF on it (mass of 36.3 kg) will allow the OTV greater maneuverability (more   V capability) with the same size payload, or alternatively, allow more propellant to be added to the vehicle, with a

reduced dry mass, but with 36.3 kg more propellant than the baseline ISS OTV design.

For inspection of another satellite on-orbit, the OTV design can be modified to eliminate the docking hardware, as well as any sensors that are largely used in the docking process. For the baseline OTV design for ISS servicing, we can take away the PDGF, the Michigan Aerospace probe device, as well as the MSFC Video Guidance Sensors. All of this hardware is required for docking. With no docking, the OTV no longer requires these components. This would reduce the OTV mass by 68 kg, again allowing more maneuverability for a fixed propellant quantity, or addition of 68 kg of propellant keeping the same initial OTV mass. This additional maneuverability will be important for inspection missions to observe a target from all sides, and also to observe multiple targets throughout the mission lifetime.

The OTV design for ISS servicing is flexible enough to allow easy modification for the various applications.

7. Conclusions

The OTV design, its functions and operating sequences described here offer a vantage point for further, more detailed system definition and analysis of satellite servicing features and the range of applications. With a class of small-size servicing vehicles and low servicing cost being a principal concern, the concepts discussed in this paper indicate design and operating features that should be considered and implemented. It may be necessary to separate servicing activities between those that can be provided by a low-cost vehicle from those that require a more elaborate design and operating capabilities. However, the availability of a lower-cost option will be important, and often sufficient, for most of the expected frequent ISS resupply operations. This should be considered in the planning and projected performance of ISS operational support activities.

Clearly, there are key issues that have not been fully covered in our Alternate Access to Space Station study (Ref.9) for NASA/MSFC. Further evaluation, and discussion of these results with specialists and mission planners at NASA, will be essential in directing the next level of system design and operating studies. Cost-benefit evaluations and trades are not reflected in this paper and should be further pursued , to compare alternate approaches and select those that promise greatest practical advantages and cost benefits.

7. Acknowledgements

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