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ARCHITECTING A FAMILY OF SPACE TUGS BASED ON ORBITAL TRANSFER MISSION SCENARIOS

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The potential benefit from extending satellite lifetimes or correcting the orbits of stranded satellites drives the need for architecting and designing a space tug vehicle. The main goal of this paper is to analyze various realistic mission scenarios and discuss the potential for creating a family of tugs, possibly using a common platform. In contrast to previous special-purpose tugs, a more flexible, reusable vehicle that could serve various types of missions is considered. The paper illustrates a mission-driven concurrent engineering methodology that provides an efficient quantitative assessment of tug system architectures. First, the current on-orbit satellite population was examined and several most populated areas, referred to as "target orbital zones," were identified. Two case studies describe the establishment of one geosynchronous (GEO) and four low Earth orbit (LEO) satellite groups, inhabiting these zones. The "optimal" architecture for each of these five target orbital zones was obtained by varying the propellant type, parking location as well as the tugs's hardware and software complexity. The mapping to the utilities of response time, capability, and delta-v shows that promising tug designs are located below the "knee" in the cost-versus-utility tradeoff that is mainly dictated by the rocket equation. It is shown that while the GEO mission tug uses electrical propulsion, a conventional bipropellant tender with a wet mass of approximately 4,100 kg could accomplish any of the considered LEO missions. A family of tugs could potentially be developed by selectively reusing grappling, bus or propulsion modules.

NOMENCLATURE

Δv	=	Applied Incremental Velocity, [km/s]
a	=	Semi-Major Axis, [km]
g	=	Gravitational Acceleration, [m/s^2]
h	=	Altitude, [km]
i	=	Inclination, [deg]
Isp	=	Specific Impulse, [s]
M_0	=	Initial Spacecraft Mass, [kg]
M_f	=	Final Spacecraft Mass, [kg]
M_{grap}	=	Mass of Grappling Mechanism, [kg]
v	=	Velocity, [km/s]
V_c	=	Value of Capability Attribute
V_v	=	Value of Delta-V Attribute
V_t	=	Value of Timeliness Attribute
W_c	=	Weight of Capability Attribute
W_v	=	Weight of Delta-V Attribute
W_t	=	Weight of Timeliness Attribute

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INTRODUCTION

Motivation for Space Tug Missions

THE consequences of satellite misplacement or malfunction can be far reaching. Recall the sudden computer failure of the PanAmSat Galaxy IV satellite, which caused the satellite to start spinning in an incorrect orientation on May 19, 1998. As a consequence, about 90 percent of the 45 million pagers in the United States failed, and some television, radio and retail store networks lost service, totaling considerable losses.[1] This incident exposed, not for the first time, the vulnerability of today's society to individual spacecraft failures. Unfortunately, using redundant systems, launching back-up satellites, or trying to improve the performance of launch vehicles can be extremely expensive. Moreover, while the cost of such efforts would likely exceed the expected revenue of individual satellites, they would still not be able to guarantee one hundred percent risk-free missions. Currently, when a satellite fails due to erroneous orbit placement or exhaustion of station-keeping propellant, replacement is the only option. An alternative is to use a space tug. A robust ability to ferry satellites back into working orbits and to extend their operational lifetimes on-demand could drastically change the way satellite missions are planned and conducted. Table 1 lists seven major cases for which space tugs could be useful, along with their corresponding mission type. This paper concentrates on architecture and design of tug vehicles for such missions.

Definitions

A "space tug" is a vehicle that is designed to rendezvous with a target satellite, make an assessment of its current position, orientation and operational status, "capture" it, and then move it to a different orbit with subsequent release. In this paper, satellites are sometimes referred to as "tenders" rather than "tugs" to emphasize their role as service vehicles in a restricted neighborhood of orbits, designed for as-yet undetermined observation, servicing, and moderate delta-V orbit changes (e.g. disposal, repositioning). As an example of a tug-to-satellite orbital transfer, Figure 1 shows a basic Hohmann transfer from tug parking orbit to target orbit in LEO (with plane change).

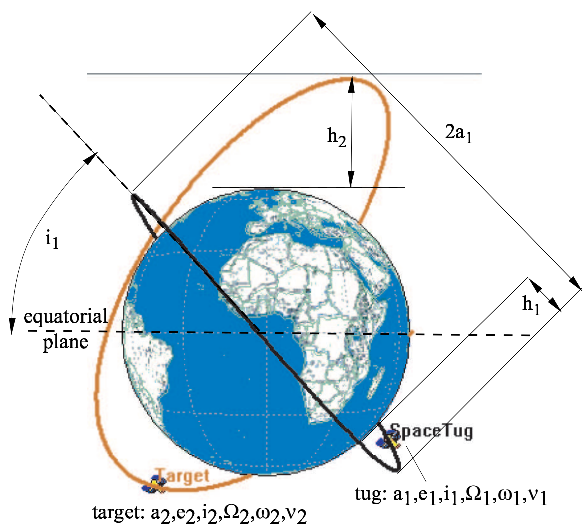

Fig. 1 Tug-to-Satellite Non-coplanar Transfer Geometry in LEO Orbit. The classical orbital elements are: a - semi-major axis, e - eccentricity, i - inclination, Ω - right ascension of ascending node (RAAN), ω - argument of perigee, ν - true anomaly.

Previous Work

A number of previous studies have discussed the potential advantages and design challenges of orbital transfer vehicles. Most of these vehicles simply provide additional velocity beyond LEO, but do not possess autonomous rendezvous and grappling capability. For several years, Orbital Sciences Corporation was developing the Transfer Orbit Stage (TOS) based on a solid fuel engine with a total thrust of 200,000 [N] and burn time of 150 [sec]. Relevant discussion was presented by Mehoves[2] and Thompson.[3] Prospective systems discussed were the Orbital Maneuvering Vehicle (OMV), designed to be an autonomous modular bipropellant vehicle; the TOS/Apogee and Maneuvering Stage, which would be capable of placing $65,000$ lbs into GEO on the basis of derivative technology; the Adaptable Space Propulsion System; the Aeroassist Flight Experiment of NASA's Civil Space Technology Initiative; and the reusable Orbital Transfer Vehicle (OTV).

In 1989 Gunn provided a comprehensive review of five US orbital transfer vehicle programs.[4] The intent of OTVs was to carry spacecraft to higher energy orbits than achievable by the Space Shuttle or various expandable launch vehicles alone. The capabilities of the examined vehicles ranged from providing spacecraft with only preprogrammed perigee velocity additions to man-in-the-loop remote controlled spacecraft rendezvous, docking, retrieval, and return to a space base.

In 1994, Martin Marietta Astronautics performed a preliminary study of tugs as "efficient means of transferring payloads once they are in orbit". Described by Earley,[5] the selection process determined that the two best concepts were the reusable nuclear thermal propulsion (NTP) tug and the bimodal tug, which would utilize NTP to move payloads and arcjet propulsion for station keeping or to return to its parking orbit. A cost analysis for a nuclear space tug was presented by Ortiz in 1993.[6] It was suggested that the nuclear thermal propulsion engine concept has the potential for significant cost reductions, provided that the regulatory hurdles can be overcome.

A more recent body of work exists on the potential for upper stage or transfer vehicles to act as servicing or refueling platforms for other satellites. In 2001 Turner (Space Systems - Loral) presented an overview of potential benefits of transfer stages in this context.[7] This study limited servicing to nonintrusive activities such as captive-carry to orbit, adjust maneuvers, refueling, power transfer, and monitoring, especially during deployment of stowed equipment.

A number of other publications focus on more detailed aspects of space tug technologies and cost estimating. Various propulsion system options for space tugs were compared by Heald (General Dynamics Space Systems) in 1995 and the range of options from solids to electric propulsion was summarized.[8] Emphasis was placed on the cryo-

Table 1 Major Classes of Potential Space Tug Missions

Identified Problems	Missions
1. Satellites reaching suboptimal orbits	1. Rescuing
2. Massive, large-scale space systems	2. On-orbit assembly/building
3. Demand uncertainty for constellations	3. LEO constellation reconfiguration
4. Obsolete technologies	4. Repositioning of upgraded satellites
5. National security	5. On-demand military satellite maneuvering
6. Satellite lifetime limitations and retirement	6. GEO satellite retirement boost maneuver
7. Crowding, collisions	7. Selective orbital debris removal

genic high performance propellants hydrogen and oxygen. Historical studies of innovative ideas were also discussed in this study.

A critical analysis of the conceptual or operational reasons for past failures of space tug and upper stage programs is very important. Ray and Morrison[9] summarize the history of the Orbital Maneuvering Vehicle (OMV) cancellation based on estimated cost being greatly increased while the OMV's capabilities were significantly decreased. Indeed, cost-inefficiency was the reason why most space tug designs were abandoned. It appears that reusability and flexibility are key to amortizing the recurring and non-recurring costs of space tug vehicles over a range of missions. Despite these difficulties a number of recent technological trends (high thrust electric propulsion, on-board autonomy, space robotics) and the need for adding flexibility and new mission capabilities to the current space infrastructure warrant a fresh look at this problem.

Research Approach

The idea of having one "universal" tug that can cover the entire Near-Earth orbital space and perform many types of tugging missions in sequence (without refueling) is not a viable option at this stage of technological development. This can be illustrated by considering the Δv budget of a reasonably sized vehicle. Assuming H_2/O_2 propulsion ($Isp = 450$ sec) for a tug with an initial mass of 4,500 kg (suitable for an Atlas V401 or Delta IVM+ launch to GTO) and a final burnout mass of 500 kg, the rocket equation yields:

$$\Delta v = g(Isp) \ln \frac{M_o}{M_f} = 9.81(450) \ln \frac{4500}{500} \approx 9.7\ km/s \tag{1}$$

A trip from GEO ($v = 3.075$ km/s) to LEO ($v = 7.613$ km/s for $h = 500$ km) and back with no plane change requires a delta-V of twice the difference between the velocities in LEO and GEO, which in this case amounts to 9.076 km/s. This allows the tug to execute some local maneuvers in GEO that require a Δv of up to 600 m/s. This budget will be reduced with a piggyback payload such as a target satellite. Evidently, multiple round-trips between GEO and LEO would not be possible without refueling, and large inclination plane changes (particularly in LEO) are prohibitive.

Thus, an underlying hypothesis of this research is that more benefit could be gained from having a family of smaller and simpler tugs that operate locally. The orbital regions are investigated independently and it is explored how the locally acting "optimized" tugs differ from each other. A trade study enables the evaluation of various types of space tug vehicles, recommending the most cost-effective option for each mission in terms of timeliness, orbital transfer, and grappling capabilities. The last major issue discussed in the paper is the development of a modular family of tugs, potentially derived from a common platform. The design approach is summarized in Figure 2.

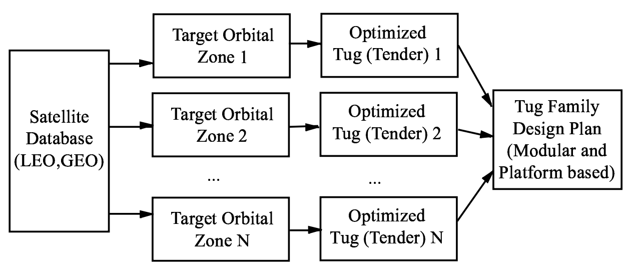

Fig. 2 Space Tug Design Approach

TARGET POPULATION

What makes this research different from previous work is the starting point of the analysis. Instead of *first* exploring the design concepts of a space tug and then finding the limits of its application, this study first explores the current on-orbit satellite population and identifies the most populated regions based on a large LEO-MEO-GEO database compiled by the authors. The database includes information such as orbital elements, satellite size and mass as well as the type of attitude control system. Figures 3 and 4 show the distribution of all LEO and GEO satellites from the database and

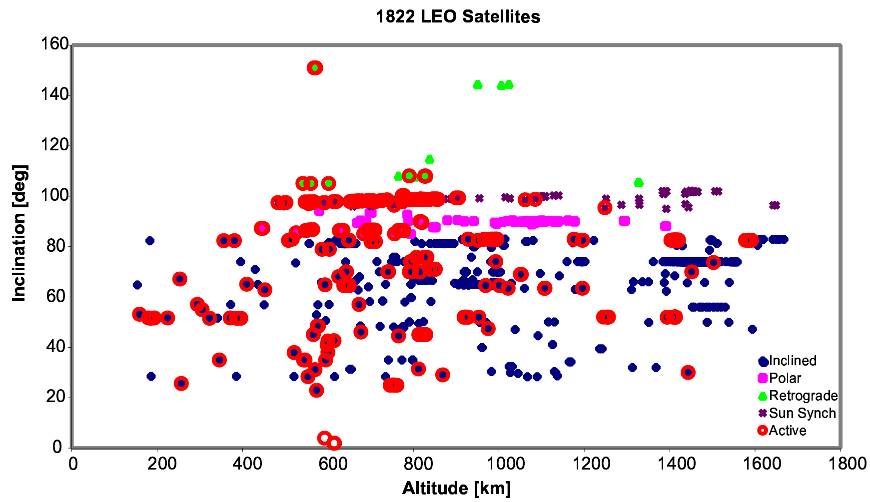

Fig. 3 Distribution of LEO Satellites

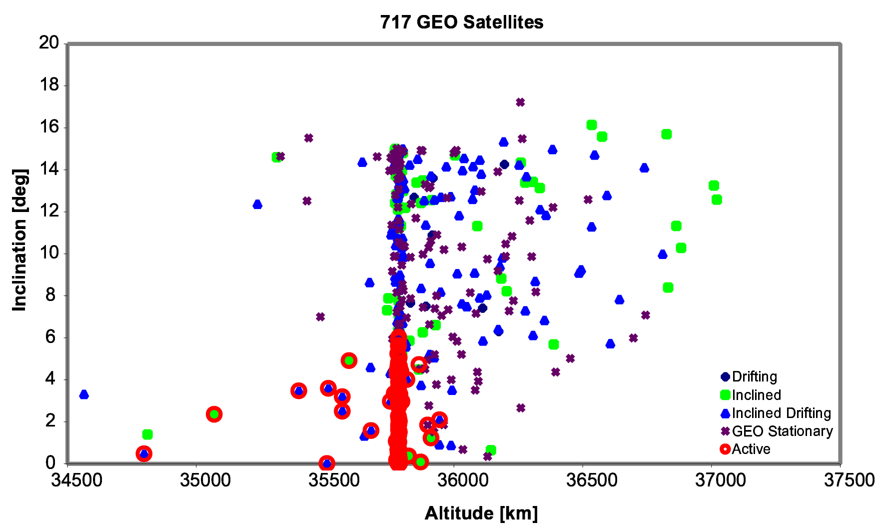

Fig. 4 Distribution of GEO Satellites

mark all satellites launched after 1990 as active. A major assumption of this research is that these "active" assets are the most probable customers of a space tug capability.

Of primary interest are US satellites that are still functional or have just been retired (the GEO retirement case). Tugging foreign satellites raises a number of complicated policy issues that are outside the scope of this paper. To define the bounds of each target zone, constraints on altitude and inclination ranges were set. Based on astrodynamics calculations, it was assumed that ranges of $1-2$ degrees in inclination and 100 km in altitude for LEO and 5 degrees in inclination and $1,000$ km in altitude for GEO were reasonable for a tender's area of action. These limits helped to identify one GEO and four main LEO target zones of interest. A summary of the main specifications of these target orbital zones and the satellites within them is presented in Appendix A.

MISSION ATTRIBUTES, UTILITY

Attributes

After identifying potential space tug customers and the requirements they would most likely impose on the system, capability metrics were formulated that best capture the customer needs in terms of space tug performance. The metrics comprised the following attributes:

Timeliness: *How fast is the tug?* As shown in Figure 5, timeliness is defined as the sum of Response Time (starting when mission order is received and ending when the target satellite is captured) and Transfer Time (from capture to satellite release at the desired destination).

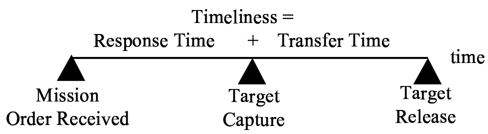

Fig. 5 Definition of Timeliness

Mating Capability: *What targets can the tug handle?* This performance metric is driven by the tender's hardware complexity and the degree of autonomy used for grappling a target satellite. The mating capability is a matter of control and grappling mechanism sophistication and was described in discrete levels as low, medium, high, or extreme in terms of the mass of the grappling mechanism used (allowable values are shown in Table 2).

Delta-v Capability: *Where can the tug go?* The Delta-v capability can be measured as the Δv required to perform a given mission. The relationships used to calculate the value of this attribute are provided and explained in a companion paper by McManus and Schuman.[11]

Utilities

These attributes are combined into a weighted, unitless measure of utility, U_{tot}, that ranges from 0 (poor) to 1 (best). For the case studies discussed in the paper, the following weights were assumed: 0.3 for mating capability, 0.6 for Delta-v capability and 0.1 for timeliness. Refer to the companion paper[11] for more detail on the choice of utility weights and a sensitivity analysis with respect to these weights. The weighted sum of attribute values is captured in a total utility function, U_{tot}, as follows:

$$U_{tot} = V_c W_c + V_v W_v + V_t W_t \qquad (2)$$

where V_c, V_v, and V_t are the values of (mating) capability, delta-V, and timeliness, and W_c, W_v, and W_t are their respective weights (and normalization factors). Mapping the total utility against the estimated lifecycle cost of a tug is what was used for evaluating various architectures in the design tradespace.

SPACE TUG DESIGN

Design Variables

To create the space tug design tradespace, a design vector was selected that was composed of independent variables having a significant impact on the attributes. A change in each of these variables produced a different architecture in the tradespace. The variables chosen for this study were: propellant type, parking location, degree of autonomy, and hardware sophistication. To facilitate computation, the number of design options was narrowed down by assigning no more than four different levels to each variable. The design variables and their allowable settings are summarized in Table 2. Table 3 shows what attributes are affected by each variable.

Mission Phases

When modeling individual scenarios, the same set of generic steps was used, starting from the initiation of the tug mission and ending with the return of the tug to its parking or safe orbit. Depending on the scope of the selected mission, the following steps (or phases) are reiterated or arranged in a different order according to the particular mission scenario. Figure 6 shows a Markov state diagram for all 8 mission phases modeled.[10]

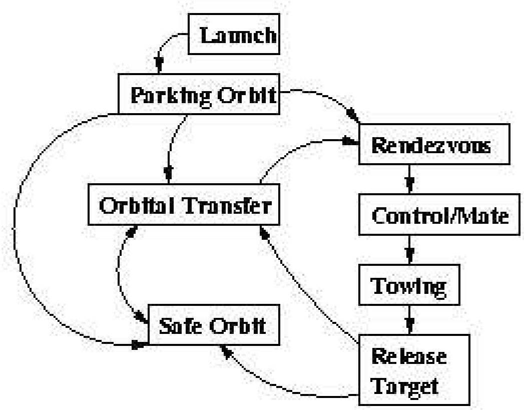

Fig. 6 Markov Transition Diagram for Mission Phases

ICE Design Tool and Problem Modeling

An Integrated Concurrent Engineering (ICE) tool was developed to mathematically model the relationships shown in Table 3. The ICE environment was based on ICEmaker, a spreadsheet-based (Excel) parameter exchange tool that facilitates sharing of information among members of the design team.[10] Together with MATLAB and Oculus/CO, ICEMaker was effectively used to create a software model of the

Table 2 Design Variables

Design Variable	Symbol	Units	Allowable Levels
Tug Parking Location	h	km	0-36000
	i	deg	0-180
Propulsion System	Isp	sec	3000 (electric)
			1500 (nuclear)
			450 (cryogenic bi)
			300 (storable bi)
Level of Autonomy	type	-	3000 (remote control)
			1500 (key decisions)
			450 (target info only)
			300 (full autonomy)
Hardware Sophistication	M_{grap}	kg	300 (low)
			1000 (medium)
			3000 (high)
			5000 (extreme)

Table 3 Key Relationships of Design Variables and Utility Attributes

Top Trades	Parking Location	Propulsion System	Level of Autonomy	Hardware Sophistication
Mating Capability	N/A	N/A	Human supervision affects the risks of damage at grappling	H/W sophistication drives mating capability and mass and cost.
Delta-v Capability	N/A	High Isp yields high delta-V, but usually low thrust	N/A	N/A
Timeliness	Plane changes and launch windows are key drivers	Electric propulsion is slow due to low thrust.	Synchronous communications with Earth slows down mission	Time for rendezvous and mating is affected by sensors

system comprised of linked spacecraft subsystems ("clients"). All relevant parameters were centrally stored in a "server". Publishing and subscribing to variables and parameters was done through ICE-Maker, while local calculations were done in MATLAB in real time via a CO link. A design session typically lasted three hours and was facilitated by one team member (responsible for the Systems module) who monitored the global convergence of the design. Although this design process is automated, with flags for convergence and automatic area and weight sizing, human operation at each workstation (subsystem) is still preferred to ensure feasibility. Figure 7 displays a sample of the detailed information that could be drawn from one of the tool's subsystem sheets, including efficiencies, mass budgets, degradations, temperature tolerances, and sizing areas.

Assumptions

The software tool described above relies on a set of key assumptions. The most important are listed below.

1. One vehicle per mission/design session. No exploration of multiple vehicle designs in one iteration.

2. Only Hohmann transfers modeled, allowing for direct or combined plane changes and phasing maneuvers.

3. Database limited to US launch vehicles, cf. Fig. 3 and 4.

4. Every possible mission is modeled by a combination of the eight generic phases, described in Fig. 6. Every phase generally includes only burns, transfers or ADACS maneuvers.

5. Users define the target satellite data by pointing to a database entry, also selecting launch vehicles to be used, as well as the parking and safe orbits.

6. Control/Mate is a *black-box* operation defined only by the target mass, predefined small ADACS adjustments, and the grappling mechanism that was modeled as a monolithic, cylindrical solid with a radius and height of 1 [m],

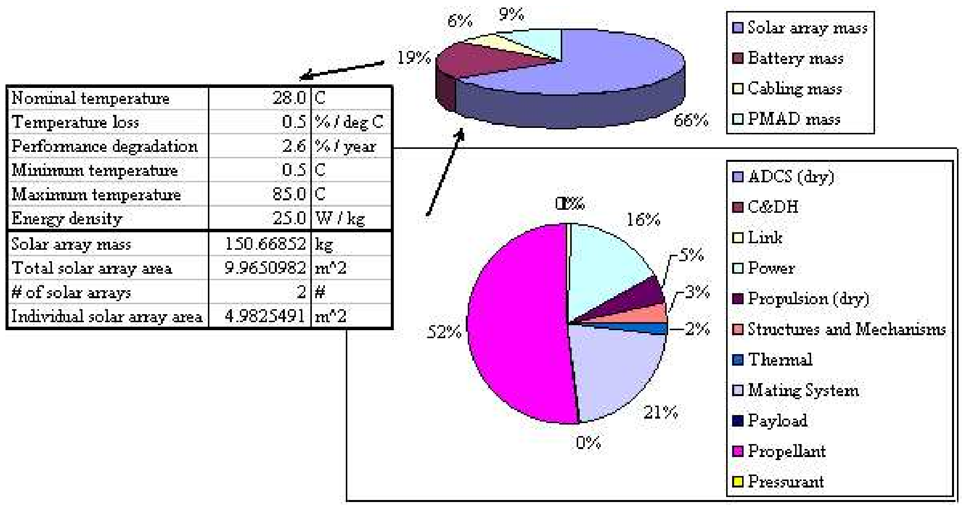

Fig. 7 ICE Tool Outputs Example[15]

cf. Fig. **??**, and the mass levels, M_{grap}, from Table 2.

7. Only critical subsystems were modeled in detail. The non-critical, generic subsystems were simplified with constant inputs and outputs, in order to participate in and yet not affect the iterative design process (e.g. ADACS).

A notional diagram of the ICE tool used for space tug design is shown in Figure 8.

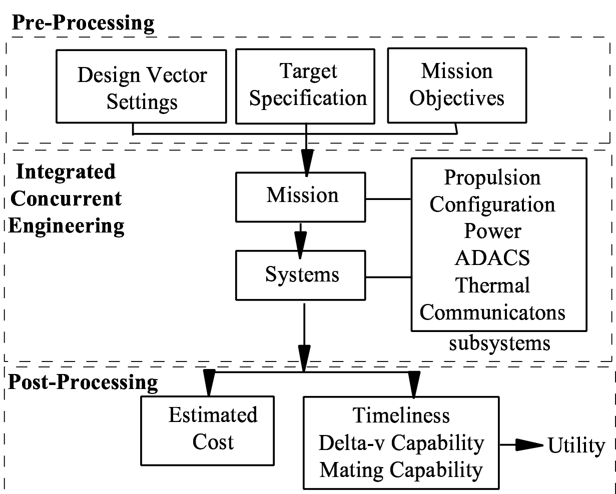

Fig. 8 Integrated Concurrent Engineering (ICE) Environment - Block Diagram

Efficiency of The Design Process

The tool described above provides fast convergence on any mission-determined point design. The estimated convergence time, including human operation and decision-making, is between one and three hours. This rapid design process allows an immediate analysis of the trade space and supports exploring different options throughout the design process. The trade space approach is modeled in greater detail in the companion paper.[11] From the analysis presented there, it is evident that the ICE tool is not only useful for a feasibility study of a particular point design, but also for showing the key trends worth exploring. The capabilities of the tool are demonstrated for the two case studies discussed below.

CASE 1: GEO SAT RETIREMENT

Motivation

GEO communication satellites are large and expensive. However, if market demand remains stable and no satellite malfunctions occur, significant revenues can accrue over time. Figure 9 shows statistics for the communications satellite revenue stream from 1996 to 2002.

Usually, it is the amount of available station-keeping fuel that determines the lifetime of a satellite. Without such fuel the satellite cannot maintain its operational orbit (as represented by the drifting of most non-active GEO satellites in Figure 4) and thus becomes useless. In addition to that, the United Nations debris mitigation policy requires

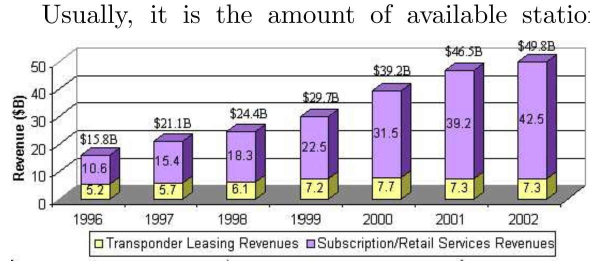

Fig. 9 World Satellite Services Revenue[12]

that "at the end of operational life, geostationary spacecraft should be placed in a disposal orbit that has a perigee at least 300 km above the geostationary orbit."[13] If tugging services are available, GEO satellites do not have to use their own propellant to move to such a graveyard orbit, thus lengthening their effective design lives. Estimates of the amount of "wasted" lifetime for GEO satellites vary between six months to two years. Instead, the satellites can be left in an operational orbit while their propellant supplies last and then be moved to a disposal orbit by a space tug. Assuming a typical commercial communication satellite that has 24 Ku-band and 24 C-band transponders with bandwidths of 36 MHz and using the most current transponder indexes (in US$/MHz/Month),[14] the profit that the satellite owner will earn for only one extra year of satellite operation is more than one hundred million dollars. Clearly, the total revenue would depend on the number of months and transponders of each type used, as well as the market fluctuation. As long as the cost of the tug mission is less than the expected profit, a significant demand for tugging services in GEO might be expected.

GEO Mission Scenario

The satellite database for this particular case study consisted only of currently functional US satellites in GEO. The focus was exclusively on commercial communications satellites launched after 1990. Military satellites were investigated as a separate class, having different customers, utility weighing factors, and applicable mission scenarios. The information in the database showed that all recent US commercial communication satellites were located between $34,948 - 35,972$ km altitude and $0 - 5$ deg inclination. These were set to be the bounds of the GEO target orbital zone. Out of the 48 satellites considered in this cluster, the majority had similar physical characteristics. Hence, for the GEO mission scenario tested it was assumed that all targets had a mass of $2,200$ kg, a shape of a $2.3 \times 2.2 \times 2.3$ m box, 25 m span solar arrays, as well as 8.3 m deployed antenna diameters. The scenario considered visiting five satellites, three randomly selected within a 400 km altitude and 5 deg inclination range, and two in a 1500 km altitude and 15 deg inclination range. For example, any three satellites within $h = 35,600 - 36,000$ km and $i = 0 - 5$ deg , one at $h = 34,900$ km and $i = 0$ deg, and one at $h = 35,800$ km and $i = 13$ deg could be selected. The mission phases were ordered as follows: 1) Orbital Transfer, 2) Rendezvous ($\approx$ 100 m/s), 3) Mating and Control 4) Disposal (increase the altitude of 400 km) or Towing ($\Delta V = 219$ m/s; 180 deg in one week), 5) Return to GEO safe/parking orbit.

Optimal GEO space tug design

By the time tugging services are actually needed for GEO Retirement missions, the target satellites will be practically considered space debris, so timeliness of response would be of less importance. Delta-v capability remains the driving factor in determining the relative weights in the total utility function. For the lack of a sophisticated mating device model, a 300 $kg/1kW$ grappling mechanism was assumed for the evaluation of all architectures. The results from running the GEO Satellite Retirement scenario showed that although the tested mission scenarios could be accomplished by using a storable bipropellant tug, the total utility value increases significantly if electric propulsion was used instead, see Figure 14 which will be discussed later. This extra utility represented the additional delta-V that is achieved with electric propulsion and could be used not only for satellite retirement but also for rescue missions in GEO. Thus, the "optimal" design for GEO missions is an "Electric Cruiser" that weighs 745 kg (dry mass) and uses an electric propulsion system to provide high delta-V capability at comparatively low cost, although for slow transfers (shown in Figure 10). The optimal design assumed that the tug was already parked in GEO orbit. This means that most of the required delta-V is used for rendezvous maneuvers. The delta-V distribution for a local mission requiring 0.7 km/s is shown in Figure 11.

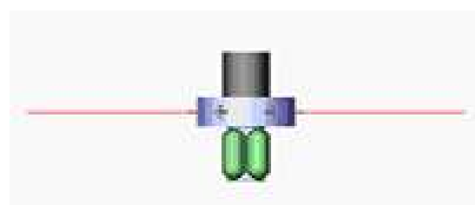

Fig. 10 GEO Electric Cruiser CAD drawing (simplified)[16]

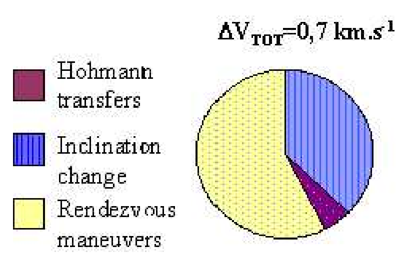

Fig. 11 GEO Electric Cruiser Delta-V Budget[16]

CASE 2: LEO CONSTELLATIONS

Motivation

There are a number of realistic scenarios that can be tested for LEO tugging missions. The first item of interest are the constellations of LEO communication satellites. The traditional way of designing such constellations is to optimize the design for a specific global capacity, based on a forecast of the expected number of users and their activity level, both of which are highly uncertain. This can lead to economic failure if the actual demand is smaller than the one predicted. It might be of value to the owners of the constellations if instead of attempting to predict a future market demand, they are given the option to deploy the constellations progressively, increasing the number of satellites as needed through reconfiguring the existing constellation on orbit. The benefits of this approach increase with greater levels of demand uncertainty.[15] A tug is needed so that the satellites do not exhaust their own fuel, especially since they may have to alter their location several times. Another interesting issue is LEO on-orbit assembly. It allows for expensive projects to be initiated without the need of having the entire budget available up-front. Additionally, it reduces the financial risks in case of launch failure or a satellite system failure, since only the failed module would need to be replaced. It might be cost-effective to have tugs moving the assembly parts and modules, as opposed to adding propulsion tanks to the separately launched parts of the assembly.

LEO Mission Scenarios

Removing all space debris (dysfunctional satellites, rocket bodies, satellite part, etc.) from the LEO database and focusing on active satellite led to the formation of four main LEO target orbital zones, shown in Figure 12. Each target zone included at least 25 satellites launched after 1990, having similar orbital parameters, mass, and geometry. Three of the LEO groups consisted almost entirely of satellites from the three big constellations: *Iridium, Globalstar, and Orbcomm.*

The mission scenarios that were created for the LEO groups were similar to the GEO scenario but used different altitude and inclination envelopes, target characteristics, time constraints, and tender's parking location. Details are shown in Appendix A. Since there were two very different classes of satellites in the "Miscellaneous" zone (due to the attitude control methods used) two scenarios were designed for this group that differed only by the targets' specifications.

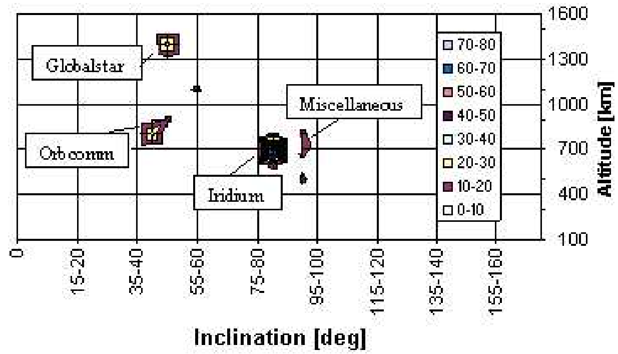

Fig. 12 Distribution of Recent US LEO Satellites

Optimal LEO space tug designs

The ICE design tool described previously was used to create "optimal" designs for each LEO scenario. For comparison, Figure 13 displays three of the LEO tender designs (the LEO 3 tender is very similar to LEO 2 and therefore not displayed), along with the "general LEO tender" 4A. All LEO tenders use storable bipropellant and their main difference is in the propellant mass and tank size. The LEO 4A tender is designed to be able to cover all LEO missions.

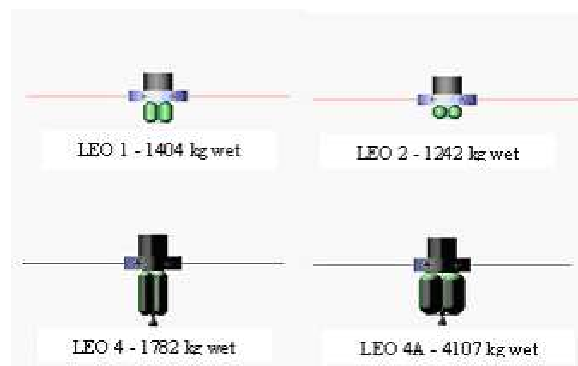

Fig. 13 LEO Tender Designs - CAD drawings (simplified).[16]

CONCLUSIONS

Space Tug Design Comparison

Table 4 summarizes the main differences between the proposed GEO and LEO space tug (tender) designs. For the LEO tenders, a clear family of similar vehicles with different fuel loads can be observed.

An important result is that the LEO 4A "Biprop Tender" could serve not only all four LEO Constellation Reconfiguration missions, but also the GEO satellite retirement case. Figure 14 shows that all of the above bi-propellant tender designs lie on the

Table 4 Space Tug (Tender) Design Breakdown[16]

Tender	Dry Mass [kg]	Wet Mass [kg]	Power [W]	Delta-V [km/s]	Utility U_{tot}	Cost [$ M]
GEO Electric	700	1100	3600	12.6	0.69	140
GEO Biprop	670	2100	1200	2.8	0.47	150
LEO 1 (Iridium)	680	1400	1500	2.2	0.40	130
LEO 2 (Globalstar)	670	1200	1500	1.8	0.37	130
LEO 3 (Orbcomm)	630	1000	1500	1.4	0.33	120
LEO 4	720	1800	1500	2.7	0.44	140
LEO 4A	970	4100	1500	4.2	0.60	230

tradespace Pareto front, i.e. they are non-dominated options for the storable bipropellant design choice.

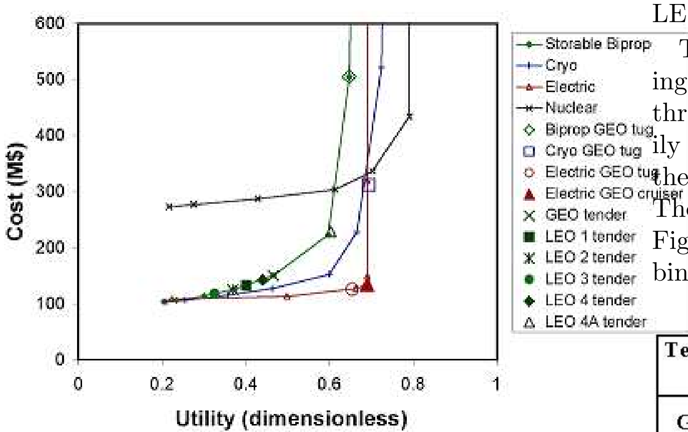

Fig. 14 Space Tug Design Tradespace

Replacing the LEO tenders propulsion system with electric would not add much value (as shown by the proximity of the utility curves for storable biprop and electric propulsion). For the GEO case, however, switching to electric propulsion yields extra value for only a small difference in cost. That is why, as stated before, the optimal design for GEO missions is the "Electric Cruiser". If we emphasize the universality of the target zone-based tender designs, however, LEO 4A can be used to cover all missions (LEO and GEO).

The general tender, LEO 4A is of reasonable cost, and it uses conventional propulsion to visit vehicles in designated orbital target zones and provide services requiring low delta-V transfers. It cannot, however, perform LEO-GEO orbital transfers or out-of-plane rescues without supplemental boosting (e.g. a lower stage and/or direct insertion by the launch system). If a rescue tug is desired, then the family of tugs needs to include both a "Biprop LEO Tender" and an "Electric Cruiser." The "Electric Cruiser" can provide high delta-V capability at relatively low cost, at the penalty of relatively slow transfers. It would also need a bigger grappling mechanism, since the satellites in its target orbital zone are much more massive (on average) as compared to the ones in LEO.

This discussion can be taken further by introducing modularity to the tug family design problem via three modules: bus, propulsion, and mating. A family of tenders could be created that might use at the very least a common bus design as a platform. The feasibility of this idea will require further study. Figure 15 shows how the tender designs can be combined in a family using common or scaled modules.

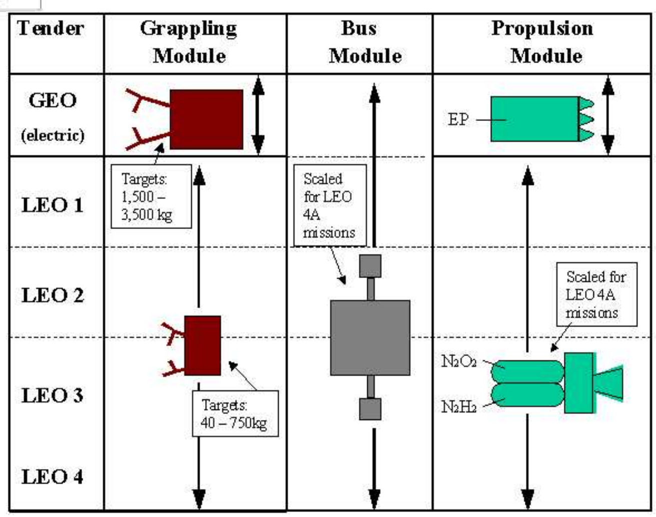

Fig. 15 Space Tug Modularity Concept

Another design comparison was made in order to justify the initial assumption that a round-trip "universal" vehicle is not an "optimal" choice. The delta-V distribution for a GEO round-trip tug and a LEO tender were analyzed and compared. The factors determining the total delta-V requirement are: towing (changing the orbit of the target-tug system), transfer (changing the orbit of the tug), and overhead (local maneuvering and rendezvous). The more efficient combination would be the one that uses less delta-V for orbital transfers. As the distribution in Figure 16 shows, the LEO tender concept is preferable over the universal tug mission in this respect.

Please note, however, that although more efficient, the tenders would still utilize a high delta-V.

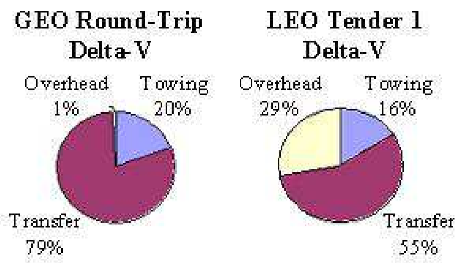

Fig. 16 Delta-V Distribution Comparison[16]

Summary of Results

The premise of this paper is that space tug design should be mission-scenario driven, while accounting for the utility attributes of interest to the customer: timeliness, grappling capability and total Delta-V. A set of locally acting vehicles (tenders) was found by exercising an Integrated Concurrent Engineering (ICE) tool. All of the proposed designs are technically feasible and of reasonable cost, according to initial estimates. When the designs from this work are compared with the overall trade-space, they are found to fall on the Pareto front of possible designs, i.e. they appear to be non-dominated. The LEO and GEO design comparison, suggests that all LEO missions could be performed by the same type of tug by simply scaling up or down the propellant tanks. Thus, the first main conclusion of this study is that tug vehicles with conventional propulsion can be useful "locally" because the restriction of each orbital zone's expanse implies realistic delta-V needs. For mission scenarios demanding higher delta-V's (e.g. rescuing of GEO satellites stranded in LEO, aggressive plane changes), the "rocket equation wall" indicates that the tug design is technically more challenging and may require different architectures and technologies than those currently available.[11] The optimal GEO tender, the "GEO Electric Cruiser" requires a different propulsion system and larger grappling hardware. By introducing modularity to the tug design, a family of tugs using a common platform and sharing various components can be created, which could pave the way for on-demand tugging services in Near-Earth orbit.

Future Work

Further evaluation of the potential value of tugging, relative to current practices, is necessary. This analysis of the "business case" can be explored in greater depth and can be extended over all seven proposed cases of tug missions (Table 1). Another critical architectural and implementation issue pertains to the degree of autonomy of a space tug vehicles, encompassing the entire range of decisions from rendezvous, target identification and capture. Refinement of the ICE tool and subsystem representations is also desirable; it will increase the validity of the results. The assumptions and model fidelity must be carefully examined and verified. Calibration against existing orbital transfer vehicles should be used for re-analyzing the design space. This will allow for a more detailed exploration of the tug family concept and will better validate the research results and conclusions.

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Appendix A - Target Orbital Zones and Satellite Specification

Table 5 Tender Missions Main Differences[16]

Target / Tender	Total Number	1990-2002 US	Orbit Altitude [km]	Orbit Inclination [deg]	Target Mass [kg]	Average Size [m]	Stabilization Type
GEO Comsats/ GEO Cruiser	639	103	35,662-36,667	0-5.2	1,880-2,200	$2.3 \times 2.2 \times 2.3$	3-axis
					750-850	D=3 H=7	spin
Iridium/LEO1	86	82	625-780	86.3-86.5	556-725	$1 \times 2 \times 4$	3-axis
Globalstar/LEO2	36	36	900-1415	51.9-52	400-425	trapezoidal prism	3-axis
Orbcomm/LEO3	32	32	765-829	32-45	40	D = 1.04 H =2.23	gravity grad.
Misc./LEO4,4A	345	29	500-870	98-99	600	$1.27 \times .58 \times 0.94$	3-axis
					520	D = 1.31 H = 3.96	spin

Appendix B - Key Equations[10]

- Mission outputs to propulsion module:
  1. Delta V requirement per mission phase: ΔV_i
  2. Wet mass before maneuver: M_{wet}
  3. Additional mass per mission phase (non-zero only when *towing*): M_{add}
- Add M_{wet} and M_{add} to get $M_{wet_{total}}$
- Use rocket equation to get the fuel mass burned per maneuver:

$$M_{fuel} = M_{wet_{total}}(1 - e^{-\frac{\Delta V}{(Isp)g_o}}) \tag{3}$$

- Add fuel mass burned for maneuver to cumulative fuel mass.
- Keep iterating until mission is over (generally return to Parking Orbit).
- Output total masses to Mission module at each iteration.