

Orbital Tug in Low Earth Orbit

An exploration into the challenges, and a first attempt at designing a viable construction

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With contributions from Jan Kaliciak (EOS Mars Program, Graphic Design),
Ueli Scheuermeier, James Brown

Summary

The need for an orbital tug emerged from discussions of the NEAmines Group (<http://www.asteroidmines.net>) on required logistics for Asteroid Mining. A conceptual exploration and debate on an Orbital Tug in LEO was enhanced by a CAD-based graphical representation that acted as a sounding board to test and explore structural and operational ideas. This graphic is presented as a design under process of continuous change. This paper represents a "milestone" on the ongoing design process.

The tug now has two grapppling/docking interfaces at the two ends of its main axis, with a boosting capacity in both directions. Manipulator arms include two types, ie. "graspers" for holding irregular debris and space junk or spent satellites, and "twiddlers" that can apply specialized tools or lock onto predesigned sockets on cargo containers. Propulsion is by Microwave Electrothermal Thrusters that use plain water as reaction mass and solar electricity from PV panels as source of power.

Tugs will catch payloads launched from Earth into very low orbits (200-250km) and transfer them to wherever they need to be, thus earning a first income. Tugs will refuel satellites and bring replacements such as batteries – another source of income. Tugs will also hunt space junk and collect it in one spot near an orbital base, where it will be used later for other purposes. Junk removal will also be a source of income.

The orbital base will be a crewed facility that has a "garage" where assembly of space vehicles will happen. When working on building the infrastructure for mining asteroids, the tugs will mainly service this base.

The orbital tug is initially refuelled by cheap launches of "water cartridges" from Earth, which it captures in imprecise low orbits, and which it then sticks with its own arms into predesigned sockets on itself. Empty cartridges are collected at the orbital base. Later, water for refuelling will come from asteroids.

This article is published both as a printable document as well as a webpage at http://www.asteroidmines.net/documents/LEOtug/LEOtug4_3.html
(The webpage is preferred for viewing graphics and downloading large versions of them)

Situation

The need for an orbital tug in Low Earth Orbit arose from operational considerations for asteroid mining.

Work on the milestone "Rig for Mining Asteroids" by the NEAmines Group

(<http://www.asteroidmines.net/documents/MiningRig/RigForMining.html>) surfaced the following operational concept:

1. Asteroid material is processed at the asteroid itself only to the point of separating stuff that is of no use in LEO – such as plain rock – from stuff that can be further processed at LEO, such as metal grains, water, carbonaceous compounds and any other useful volatiles.
2. Containers of useful stuff (metallic "grit" and volatile slurry, mostly water) will be boosted to meet Earth and be aerocaptured into LEO orbits.
3. These containers will then be orbitally manoeuvred to a processing plant in LEO, which then processes the semi-processed asteroid material further into bullion of rare metals, metal parts for constructions, fuel, etc....

It was then seen that for these operations the following infrastructure would be needed in LEO:

- *A staging base*, this will initially be a fuel depot and a "garage" for assembling outgoing craft, later upgraded with the processing plant itself.
- *An orbital tug*, to move cargos and construction supplies and other items to and from the orbital base.

Further backtracking down the steps to achieve this orbital capacity showed that the orbital tug is the key for achieving it: The orbital tug will be required to begin to assemble the staging base in orbit because of large diameter structures that are too expensive to launch from Earth. It also turns out that the capabilities of the orbital tug will allow it to hunt and collect orbital junk, and to transfer satellites launched into LEO to their final orbits and even to service them there. Both these capacities will allow the tug to already tap a first income stream long before asteroid material begins to arrive from asteroids.

Envisaged Operations

Minimal capability for refueling with water

1. Leave the base and drop to orbit at around 200km to pick up a can of water boosted there with a cheap launch from Earth.
2. Rendezvous and grapple the water can.
3. Reorient and boost up to base orbit.
4. Rendezvous with fuel depot at base, deposit water can there.
5. Refuel (with water) for a second trip to bring a further can of water, leaving some water in the depot to be accumulated.

Construction Material

Analog as with water can. Instead of water can, it will be a can full of cheap elements for building the base and/or cheap elements for space-craft to be fully integrated at base (in the "garage").

Capture of Incoming

1. Leave the base and match up with orbit of aerocaptured cargo from asteroid
2. Rendezvous and grapple with cargo (and its drive assembly).
3. Reorient and boost to base (where the processing plant is)
4. Rendezvous with processing plant at base and hand over cargo to grapples of the base.
(Base grapples decouple interplanetary drive and park it in predestined slots).
5. Rendezvous with fuel depot and refuel.

Placement of Outgoing

1. Base grapples hand over outgoing cargo to tug (previously cargo and its interplanetary drive have been mated by base).
2. Navigate the outgoing assembly to insertion orbit for transfer trajectory.
3. Decouple, reorient and boost back to base. (Outgoing drive then independently fires its engines to insert into transfer trajectory).
4. Rendezvous with fuel depot and refuel.

Satellite Delivery

1. Leave base and drop to LEO at around 200km to pick up a satellite payload boosted there from Earth.
2. Rendezvous and grapple satellite
3. Reorient and boost to final orbit of satellite
4. Release satellite
5. Reorient and boost back to base
6. Rendezvous with fuel depot and refuel.

In-situ Servicing

1. Pick up supplies and fuel for satellite at base
2. Leave base and boost to orbit of satellite to be serviced
3. Rendezvous and grapple with satellite, refuel and service the satellite, etc.
4. Disengage and return to base
5. Rendezvous with fuel depot and refuel.

On-base Servicing

1. Leave base and boost to satellite
2. Rendezvous and grapple with satellite.
3. Reorient and boost back to base
4. Rendezvous with "garage" at base and hand over satellite to grapples of the base
(The satellite will then be serviced in the "garage" of the base).
5. Rendezvous with fuel depot and refuel.

Junk Removal

1. Leave the base and match up with orbit of junk.
2. Rendezvous and grapple space junk.
3. Reorient and boost to base.
4. Rendezvous with "junk pile" near base and deposit junk there.
5. Refuel at depot.

Encountered challenges and ways to deal with them:

Propulsion

Propulsion for the tug will be with Microwave Electrothermal Thrusters (METs), using water as fuel: Microwaves heat water to just beyond the point where it cracks into Hydrogen and Oxygen, then releases this out a nozzle to create thrust (actually "fuel" is the wrong word here, as the water is just the reaction mass, and the energy comes from the Sun via photovoltaic panels as electricity to power the microwave generators). METs are shown to achieve up to 800s of ISP which is higher than most chemically fuelled motors including even the motors operating on cryogenic liquid oxygen and hydrogen. Furthermore it has been shown that METs can be built in a compact way, and that they are scalable. The thrust levels are suitable for orbital manoeuvring, ie. big enough to achieve fast response, and yet with a high ISP. The most important advantage is that they run entirely on water alone. Water is the best fuel option in terms of ease and risks of handling, ease of stockage, and ease of processing from asteroid material.

Refuelling

Earlier attempts at conceiving orbital tugs have been shelved because it turned out to be impractical and too costly to refuel them in orbit. However, with water as "fuel" it is seen that very cheap launches will put cans of water into very low orbits for the tugs to pick up.

Refuelling the tugs from Earth is only a temporary measure. Once water arrives from asteroids, this costly launch of plain simple water will be replaced. For this reason tugs only have to pay for themselves until asteroid processing has begun. First material to arrive from asteroids in LEO is expected to be water.

How to avoid snaking lines of fuel, search for sockets on a moving tug, pumping in zero-G, etc? The concept of "water cartridges" evolved: These are cans of water that are specifically designed to be picked up by grapples of the tug and stuck into predesigned sockets on the tug where they feed into the fuel lines to the METs. Empty cartridges are pulled out by the tug itself and stuck into refilling sockets on the fuel depot. It is expected that future satellites will refuel also by simple exchange of cartridges.

Attitude Control

Fuel mass is by far the most expensive operational item. Therefore all must be done to increase fuel efficiency. Large gyroscopes in the tug shall therefore take care of attitude control instead of directional thrusters. This is not trivial due to the large masses attached to the tug. In order to save on the need for turning the whole orientation, the tug will be doublesided, with a back-and-forth capability of boosting. This also allows some measure of redundancy and therefore higher operational security.

Grappling

The operational requirements appear to demand two types of arms on the tug:

1. "Graspers": Grapples that can grasp and reliably hold irregular debris not designed for docking with the tug, ie. space junk, old satellites, etc.
2. "Twiddlers": Arms reminiscent of industrial robot arms with selectable toolheads. They are for doing specific work on whatever is being grasped.

Control of these arms is expected to be via telerobotics from Earth, ie. adaptations from "Robonautics".

Energy

Electricity is required for the manipulative operations, for spinning up the gyroscopes for attitude control, and particularly for firing the METs. Energy will be supplied through PV panels strategically placed around the tug. Batteries need to take care of operations during nightside of orbits. Boosting with the METs may require to always wait until the tug is again in the sun.

Overall Concept

The illustration shown on the next page is the state of concept by the time this synthesis was written. The figure does not depict what will finally fly in orbit. It is just a sounding board to test ideas and identify clashes and test possible solutions in configurations. It has also been instrumental in identifying structural challenges. The figure is therefore in continuous change and thereby reflects the ongoing debate on searching for solutions.

The figure depicts the tug with one "hopper" firmly docked on one side and approaching another, with a robotic "twiddler" arm extended to lock with sockets on the target. "Hopper" here refers to containers arriving from asteroids with semiprocessed mixed asteroid material for further processing at the base. Instead of hoppers also think of cargo cans from Earth, space junk, or satellites.

The tug is two-sided with identical interfaces on both ends.

Graspers are here depicted using the template of hydraulic arms used on construction machines on Earth. However, here they have a "thumb" that can help in clasping an irregular object. Hydraulics may become useful in case force has to be applied to really grasp well, or to crush some debris.

Twiddlers are here adapted from industrial robots and also using some ideas from the CanadArm on the International Space Station, in particular the folding back of unused tools.

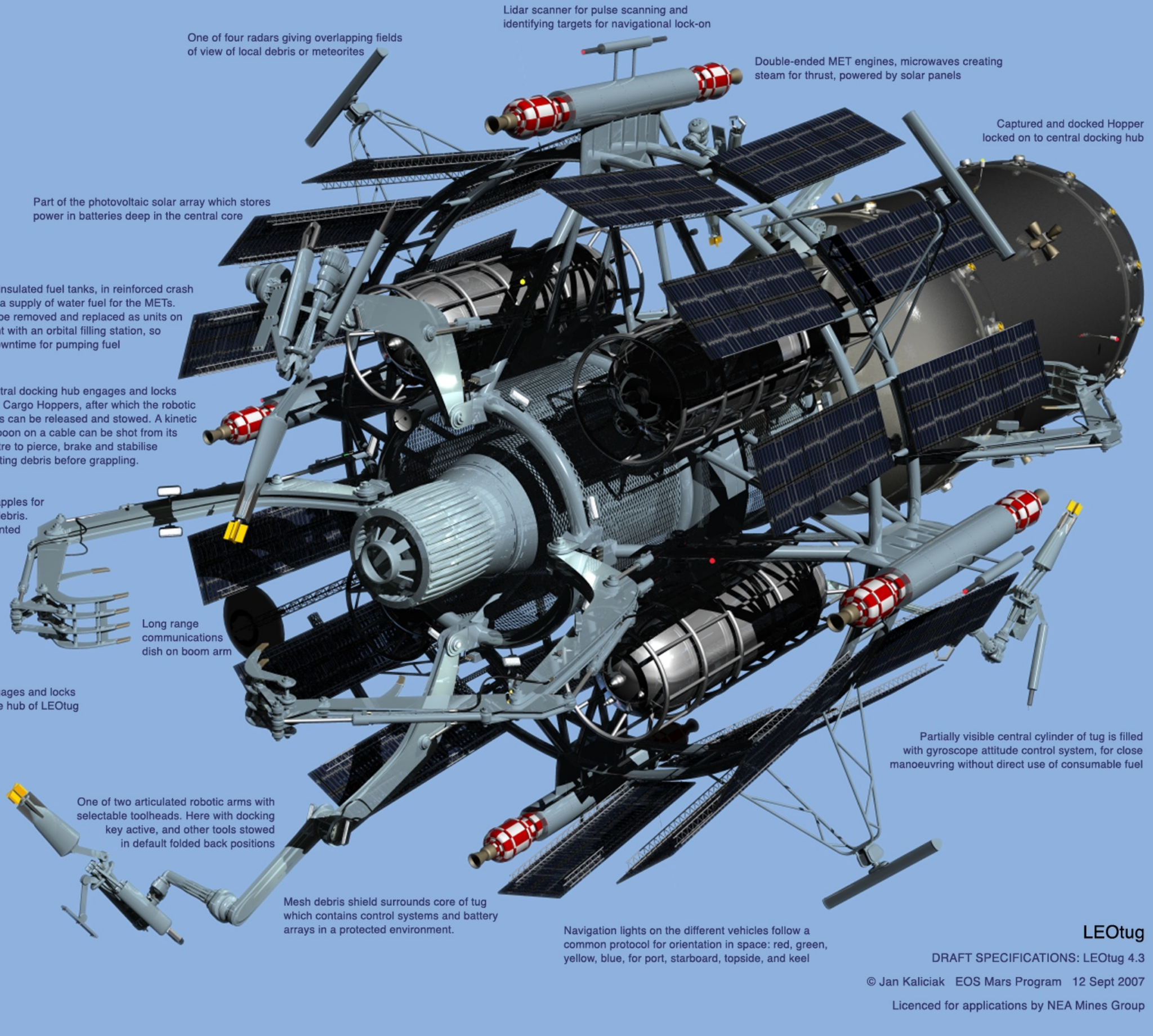
All the rest can be understood when reading the annotations on the figure. The anaglyph (next figure) is for viewing with blue-red glasses. This helps to understand the 3D relationships in the structure:



THE DESIGN BRIEF for this vehicle required an ability to move fore and aft without wasteful rotations using direct motor thrust, so the MET engines are double-ended, as is the tug itself. The whole structure is therefore symmetrical along its main axis, and also bilaterally symmetrical in the deployment of its tool arms. This allows pairs of arms to coordinate capture of cargo modules or debris, without applying off-centre momentum.

The purpose of the tug is to service Low Earth Orbit (LEO) movement of cargos as well as tractoring construction supplies and other items between various orbital stations. It is also expected to play a large role in the capture and recycling of errant or defunct satellites, and other debris, for profit.

The Cargo Hopper is ringed with a collar of capture nodes, that the LEOtug robotic arm can engage with, insert a vaned key tool, and rotate to lock so preventing inadvertent disengagement. Once one arm is secured, the second can be engaged, and the Hopper drawn into docking and locking position on the tug's hub



One of four radars giving overlapping fields of view of local debris or meteorites

Lidar scanner for pulse scanning and identifying targets for navigational lock-on

Double-ended MET engines, microwaves creating steam for thrust, powered by solar panels

Captured and docked Hopper locked on to central docking hub

Part of the photovoltaic solar array which stores power in batteries deep in the central core

Four silver insulated fuel tanks, in reinforced crash cages hold a supply of water fuel for the METs. These can be removed and replaced as units on engagement with an orbital filling station, so reducing downtime for pumping fuel

Central docking hub engages and locks with Cargo Hoppers, after which the robotic arms can be released and stowed. A kinetic harpoon on a cable can be shot from its centre to pierce, brake and stabilise rotating debris before grappling.

One of a pair of high powered grapples for symmetrical capture of irregular debris. Has floodlights and minicam mounted

Long range communications dish on boom arm

Docking collar engages and locks with central core hub of LEOtug

One of two articulated robotic arms with selectable toolheads. Here with docking key active, and other tools stowed in default folded back positions

Mesh debris shield surrounds core of tug which contains control systems and battery arrays in a protected environment.

Partially visible central cylinder of tug is filled with gyroscope attitude control system, for close manoeuvring without direct use of consumable fuel

Navigation lights on the different vehicles follow a common protocol for orientation in space: red, green, yellow, blue, for port, starboard, topside, and keel

LEOtug

DRAFT SPECIFICATIONS: LEOtug 4.3

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LEOtug

ANAGLYPH: LEOtug 4.3

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Further encountered challenges:

Cheap Rockets

Initially the tugs will have to be refuelled by water cartridges launched from Earth. This refuelling process will be cost-critical. However it was recognized that launches of such cans of water into LEO should be possible with rockets that can be designed to be particularly cheap:

- They could be small, just big enough for whatever a full cartridge weighs, but they can also be large.
- They only need to reach a very low orbit, such as aiming for 220km by 350km.
- They may be unreliable, ie. a failed launch does not have to pay for the lost payload, since the payload is easily replaced.
- They can be quite imprecise, ie. undershoot the insertion-apse by 20km - achieving 200km minimal height, and underboost on the non-insertion apse by 100km, achieving 250km. This double imprecision would result in a 200km by 250km orbit which is still stable for several days and therefore good enough for a tug to pick up. This cuts down on costs for avionics.
- Fairings or shrouds are not needed, as the can itself is the fairing.

It is now clear that a tug only makes sense in combination with such cheap rockets for very cheap payloads. The combination of launching cheap rockets for easily replaced payloads with highly reliable rockets for expensive payloads dovetails with the capability to assemble in orbit in the "garage" of the base. There is then a cost-tradeoff between assembly of spacecraft in space versus launching them fully integrated from the launchpad on Earth.

So the orbital tug can only be seen in conjunction with the cheap rocket that can send up cans of water for refuelling the tug.

Longhaul Tug

This tug may be adapted into an interplanetary longhaul tug (to asteroids and back) with minimal adaptations: One end may hold a large tank of water for fuel, while the other end holds the payload (hopper, crewed habitat on a spinner, etc...).

Manipulative Capabilities

Robonautics are expected to become very important. This will help in coordinated movements of arms during grappling procedures etc. It is also conceivable that small robonauts are attached to the ends of arms, which would bring them into position to perform small detailed manipulative work – similar to what we have at present when an astronaut stands on the end of the CanadArm of ISS.

Bootstrapping the System

For bootstrapping such a system the following seems to suggest itself:

Phase 01: Proof of Concept

1. Launch a fully fuelled miniature tug with enough manipulative dexterity into orbit.
2. Launch three fuel cartridges on one cheap rocket and have them captured by mini-tug.
3. Mini tug boosts the three full cartridges to orbit of future "base".
4. Mini tug refuels with one cartridge, leaving one empty cartridge along with the remaining two full ones, and is thereby fully refuelled for next operations.

Phase 02: Accumulation

Accumulate more and more fuel at base. Build a "cartridge rack" as preliminary fuel depot for mini tug. Possibly launch further mini tugs.

Phase 03: Large Tug

Launch a large tug in bits and pieces that can then be assembled by the mini tugs at the base (through tele robonautics).

Phase 04: Begin Regular Operations

Begin to earn money by providing transfer services to satellites and collecting space junk.
Mini tugs may begin to concentrate on collecting small space junk in the important orbital regions.
Begin to build base with "garage".

PV Panels

The configuration of panels around a tug are still very preliminary. It could be that for long boosts it will be advisable to have large arrays stuck out on booms and tracking the sun.

METs

Due to an interesting relationship between available electricity, total mass and size of METs, there is a tradeoff between large METs and small METs. Large METs provide strong thrusts with fast response of total mass, something worth having during final approaches and rendezvous. But for long burns small METs on longer burns may be advisable, since the mass of the large METs can be saved. Analogue to tugs shoving around large ocean ships, orbital tugs will have large METs with little fuel. But longhaul tugs will have large fuel tanks with relatively small METs. More work needs to be done on METs to achieve space-worthiness on first tugs.

The NEAmines group welcomes feedback on these preliminary designs.

We also welcome people who may want to join the effort.

Please surf to <http://www.asteroidmines.net>

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