

General topic

Varying degrees of crazy:

http://en.wikipedia.org/wiki/Non-rocket_spacelaunch

More specific topic

http://en.wikipedia.org/wiki/Mass_driver

High Level Concept

SpaceX and other companies are doing the best they can within the physical limitations of rocketry. Even with an infinitely reusable rocket, we would expect to never get below ~\$700/kg into orbit. Rockets are limited to ~2% payload due to physics, have decently high material cost, and associated maintenance cost.

The concept here is to build a mass driver to get the marginal cost per kg into the \$5-100 range. The mass driver/launcher exists entirely in a fixed installation on the ground, making the entire endeavor significantly simpler than traditional rocketry. Operating conditions are fixed, and maintenance on a fixed installation is less expensive than engineering a rocket to operate under extreme conditions.

The downside is that a short mass driver, while less expensive than building a rocket program, has severe limitations in what you can launch due to high payload accelerations. At 1000g, we will not be launching delicate satellites (the vast majority of existing satellites), nor humans. A result, it would not compete with existing companies. Rather, the vision is to expand the space market by an order or magnitude, and be cooperative with existing players.

Market Vision

The primary business plan is to make fuel extremely cheap in low earth orbit, thus enabling any destination (higher orbit, moon, mars, etc) for the same cost as getting into low earth orbit. Existing market players (SpaceX, Boeing, etc) are experts at getting to low earth orbit, and we would be supplementing their business. Business model options:

- Fuel/propellant depot (http://en.wikipedia.org/wiki/Propellant_depot), basically a gas station. Conservatively \$2.5B/year with existing government missions based on NASA estimates, though probably more if private companies (e.g. SpaceX) want to do missions beyond low earth orbit (estimated cost of fuel for a single crewed Mars mission is ~\$1B). Cost of fuel will come down significantly over time, but hopefully will see an order of magnitude increase in these missions once the primary obstacle is just getting to low earth orbit and refueling.
- Tug service (LEO to any other orbit, see http://en.wikipedia.org/wiki/Space_tug), also known as “orbital transfer vehicle”, which drags around other satellites to their desired position. Unknown market size, presumably a large chunk of existing launch \$ for anything above LEO, since current higher-orbit costs are about 3-6x LEO costs.

The other market opportunity is to launch bulk items (e.g. structural components for a space station, or rugged equipment). This would allow resupply to the ISS (first NASA contract that

SpaceX signed), or significantly cheaper stations (which we might want to build ourselves, on contract with NASA, to house our fuel depot).

There has been some financial feasibility analysis based entirely on replacing existing market (older analysis, satellite volume has actually increased beyond expectation), which is a completely different business model, but one we could fall back on:

<http://techdigest.jhuapl.edu/td/td2003/gilreath.pdf>

<http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2219&context=smallsat>

Tech

We would be creating an electrical launch track. The track would be approximately 1.5km long, situated at high altitude (ideally exiting above 12000 ft, ~3600m), at 15-20 degrees inclination. Presumably this would be built in a trench up a mountain side to minimize construction cost, and be located where the 60-100 miles (~100-150 km) downrange are not populated due to the sonic boom (see "Issues" below).

Optimal technology, based on research (see alternatives below), would be a dynamic Halbach array ([patent](#) from Lawrence Livermore we could license, easy to prototype and cheaper) or a linear induction motor (a well understood technology with some limitations and slightly more expensive). Other electrical system solutions (rail guns, gauss guns, etc) have some limitations that make them sub-optimal, and are discussed in the Appendix.

NASA had a proposed version of this based on the linear induction motor called the [StarTram](#), though the economics of their proposal do not work out. Their Gen1 concept is similar to our concept, though with some key differences. The size of their tunnel is 130km instead of 1.5km, and correspondingly much more expensive. The advantage of their platform is lower acceleration, though for launching fuel/bulk items that holds no significant advantage, and in their case was a stepping stone to low-acceleration manned launches which is outside of our scope.

The launcher we build would drive a hypersonic vehicle at approximately mach 25. The vehicle does not need to exist in atmosphere for very long, and is essentially a dumb missile with a useful payload of approximately 15,000-25,000kg (higher is actually better, as you get less aerodynamic slowing). The vehicle would be made up of the aerodynamic shell, a payload, and a small rocket motor (probably hybrid) to circularize the orbit once at zenith. Hypersonic vehicles traveling at this speed have been tested, and our problem is easier because we can dispense with control surfaces and air intake. These vehicles would be launched continuously, and ideally would be mass manufactured and disposable. A power-law shaped steel/aluminum body would be ideal for reducing hypersonic drag, and an ablative coating would reduce heat transfer and eliminate much of the friction drag. One major complication is the relative air density at the launch elevation, which makes higher elevation sites more attractive. The vehicle comprises the majority of the marginal launch cost.

Why It's Interesting Now

These mass driver concepts have been around for a while. NASA, Sandia Labs, and others did quite a bit of research back in the 70s and 80s into this concept. The economics never worked out, mostly because the most feasible solutions (rail guns, light gas guns) could never get the launch velocity above 6km/s, and other solutions were too expensive. The equipment cost for electrical components were prohibitive, especially microsecond-level electrical switches and supercapacitors.

Traditional low-latency, high-power electrical switches have relatively limited lifespans (10s of cycles), and are fairly expensive. Operating a launcher requires a large number of very precisely timed switches. These would have had to be replaced fairly often if they failed after a small number of cycles, and that cost would be prohibitive. Spending into renewable energy in recent years has led to the development of high-power MOSFET switches, which can handle millions of cycles and microsecond timing.

Supercapacitors, another critical component of an electrical launch system (which needs to dump ~300-500+ GJ into a launch vehicle in under a couple seconds), have become significantly cheaper over the last few years. Collectively, these developments reduce the capital requirements for building an electrical launcher, and bring it into the realm of profitability.

Funding Thoughts

Estimated for costs range in the \$500M range for analogous projects (such as Quicklaunch, see below), but this is a bit of a WAG. The majority of this funding would ideally be non-dilutinal (e.g. DARPA or NASA) after an initial prototype shows promise. The initial prototype will probably cost in the \$30-50M range, which would probably require venture style financing. A large percentage of the cost will be commodity equipment, so venture debt financing may be able to offset the majority of the initial round.

Ironically, after the prototype phase, another potential source of funding are the traditional rocketry companies (e.g. Boeing, SpaceX, etc). After a functional tug service is built, there is no incentive for any rocket company client to launch past low earth orbit and contracting the tug to get into their desired orbit. By investing (non-dilutinal, ideally) in this project, the rocketry companies purchase a discounted tug/fuel fare for their future clients as a type of future option. Any discount purchased gives these companies a pricing advantage in the rocket-based market. Funding through this route could be offered as an auction, or something similarly competitive.

Similar Analogues

A previous attempt at this sort of company (different tech, similar concept) was Quicklaunch:

<http://en.wikipedia.org/wiki/Quicklaunch>

<https://medium.com/looking-up/q-a-dr-john-hunter-b3b2af5bbf71>

NASA's StarTram (similar tech, designed for human transport) is the closest conceptually:

<http://en.wikipedia.org/wiki/StarTram>

Major Issues

The primary issue with a launcher is finding a suitable location. The location:

- Ideally uses mountain peak to launch above 12000ft, for reduced atmospheric drag
- Ideally launch eastward (3-5% boost from earth's rotation, matches up with ISS orbit)
- Ideally no one downrange for 60-100 miles due to sonic boom while in atmosphere.

There are remarkably few places in the world that fit these requirements, especially those that have established industrial capacity without any habitation down range. Interestingly, some of the best locations are in the US:

- Nevada (launching over weapons test area north of Vegas, slightly lower elevation)
- California (launching over China Lake weapons test area)
- Colorado (north of Durango launching over wilderness areas north of the Taos plateau)
- Hawaii (Mauna Loa, launching southeast over edge of Volcano National Park and ocean)

Other technically feasible locations include the Peruvian Andes and Kenya/Tanzania (Mt. Kenya or Kilimanjaro), though operating a major construction project in these areas may be problematic.

The other open issue would be the details of the hypersonic vehicle, which would be pushed off until after launcher prototype construction (you can use the prototype to optimize the vehicle very cheaply). Hypersonic vehicles have fairly high friction drag and heat transfer, and while there are a variety of tested solutions (such as ablation, aerospikes, and hot gas injection), some work (though fortunately low risk) would be required to integrate all of them into a dumb missile configuration. Much of this work has been done before (HTV-2, ICBMs), and will need to be re-purposed. The hypersonic vehicle, however, is a high source of technical uncertainty and risk.

Appendix

History

Crazy history of space guns (slightly different than this, but still a good read):

<https://medium.com/looking-up/space-guns-fa2dda0561ec>

Alternate Technologies

There exist other mass driver technologies, though most are limited to about 6km/s. While better than nothing, orbit without a significant rocket (a small one is still required to circularize the orbit) would require leaving atmosphere at around 8km/s. At 6km/s, the useful rocket payload is only about 20%. As a result, most of these technologies have all of the hurdles involved with developing new technology and dealing with the difficult world of rocketry:

- Rail gun
 - They require some degree of sliding contact or plasma which would probably limit this to ~6km/s, due to erosion of the contacts above this speed (basically you'd need to replace or refinish your rails every launch or improve material science).

- Plasma railguns have analogous problems with bore erosion and [other issues](#).
- Heat from sliding friction is a huge problem, causes issues for rails and tunnel.
- Gauss gun
 - In theory this can get to 8km/s but requires bore contact between the projectile, and induction ring in a sabot (potentially limiting speed, though a gas bearing might work), and potentially exposes the payload to huge magnetic fields. NASA chose a Linear Induction Motor over this with their StarTram.
 - Other issue is in energy density is lower, maybe only 200g sustained?
- Light gas gun
 - One of my favorites (significantly less expensive technology), and what Quicklaunch proposed using. However, getting above 6km/s would be near impossible, and it requires bore contact which has friction issues.
 - There are variants that use transverse gas that solve these issues, but they are only theoretical, and maybe not worth doing basic research to develop.

Other plausible options beyond mass drivers:

- Rocket/Spaceplane
 - This uses atmospheric oxygen to accelerate, greatly reducing fuel weight. However, this has all of the downsides technically with building a hypersonic vehicle (huge capital costs--e.g. 747 is \$350M dollars--and huge maintenance costs) and the downsides of building a rocket (extremely difficult to build given operating environment).
 - Eventually may supplant traditional rocketry, but will not get the \$/kg into our range or even near it.
- Microwave beamed electrochemical rocket (phased microwave array on ground)
 - This actually does work, though net payload is probably ~20%, and requires huge phased array on the ground to be synchronized.
- Space elevator (probably not feasible in a 50 year timeframe due to material science gap)
 - Carbon nanotubes are strong enough in theory, but lose 70% of tensile strength if damaged (e.g. have a carbon atom missing). Drops below useful point.
 - Maybe benzene, high pressure polymer, higher theoretical tensile strength. Worth basic research.

Random Notes

(not worth diving into)

Launcher:

- ~1.5km track
 - Probably linear, or slight curvature
 - Could be circular + spur for launch, though acceleration would top out at 5000-15000 g's for a 1km track, meaning the track would have to switch from 1000:1 tangential acceleration to levitation to 1:10 tangential:levitation, so probably not worth the extra complexity
- very high acceleration (2000-3000g)

- solid state electronics are pretty durable to 10000g.
- Massive capacitive discharge, high inductance (electromagnets), possible ringing, will need high power MOSFET (or alternative) switches/relays, may need very long cycle times (so open question on switches + capacitors + diodes to make this work efficiently). Looks feasible given off the shelf parts now available in the last couple years.
- Would maybe use an array of homopolar generators (pretty cheap to build) or compulsators instead of traditional capacitors, though supercapacitors would be easier to work with (but more expensive), but have discharge rate issues.
- Ideally SMES loop, instead of capacitors or homopolar generators.
- 29.6 MJ/kg for ISS orbit, assuming orbital inclination of launcher matches ISS
 - efficiency estimates at the 80% range (actually not too far off, given theoretical efficiency of technology, ignoring severe atmospheric drag, and payload %)
 - Exit speed of 10km/s
 - Exit energy of 50MJ/kg, 63MJ/kg with 80% efficiency (builds in payload %, may be unrealistic).
 - 17KWh/kg => ~\$1.7/KG electrical cost (assuming \$0.10/kWh), ~\$0.70/lbs
 - 5000kg vehicle
 - Back of napkin calculation:
 - 315GJ energy, ~87.5MWh in ~.2 seconds is approximately 1.5TW for those 0.2 seconds.
 - Launching every hour requires a ~88MW power plant to regenerate capacitors, approximately 4.4% of the output of the Hoover Dam
 - Would maybe get a loan from DOE to build out solar power plant, or do some debt financing, probably take 3 years to build based on comparables (AVSR1), though seems like a bit of a distraction.
- Vacuum pumped (probably, temperatures would get too high otherwise?)
- Multi-iris at the end to open onto atmosphere
 - Possibly plasma window (1.6MW per meter radius? unclear if necessary over and a silencer-like flight chamber.
 - Possibly just something destructive (highly deformable plastic that lasts the 200ms after the iris opens before the vehicle hits it, e.g. cellophane :))
 - Plasma window has potential advantage of keeping vacuum between launches for faster turnaround
- Drag
 - Huge forcing function on design, temperatures are extreme (>10000 K)
 - Disassociation of atmosphere, some radiation
 - Ideally exits launcher at high elevation (less time with air drag), so needs to be on a mountain side somewhere.
 - Lower angle (10 degrees) has better orbit insertion, higher angle (20 degrees) has lower air drag
 - optimum depends on launch vehicle, probably closer to 20 degrees unless we magically invent a low drag hypersonic vehicle, though extensive research exists in this space.

- Ideally near infrastructure base (e.g. major city)
- Sonic boom
 - requires no down range population for X miles
 - X is based on speed + launch angle + diameter of vehicle
 - Approximate footprint is 60 miles down, 10-30 miles across for 20 degree launch
 - Dies off at surface after vehicle above 100K feet

Vehicle:

- Probably power-law body (AX^Y , $Y=0.25$ to 1.5 , possibly near 0.68 for stability based on (??))
- Drag directly proportional to area, so R^2
- Diameter probably 3 meters at tail or less (length ~ 33 meters, $A \sim .139$)
 - Max Volume = $\pi * .139^2 / 2.36 * X^{2.36} \sim 98.6 \text{ m}^3$
 - Is approximately net volume of large shipping container, though thinner
- Highly ablative surface
- Ablative aerospike (carbon-carbon, PICA, chromium, something)
 - Both dissipates heat, but also changes speed of sound along body by introducing lightweight reactants (e.g. disassociated hydrogen)
- Drag:
 - Huge issue, will lose a high percentage of speed
 - Ideally no more than 1000 m/s
 - Acceleration inversely proportional to mass, so higher mass ($5000 \text{ kg}+$) probably essential ($a=F/m$, F is based on $v^2 * R^2$)
 - Can maybe use energy deposition using electrical heating ahead of craft (pulsed laser + discharge) or a primary body and payload body as separate launches, kind of crazy though.
 - "Numerical Study of Novel Drag Reduction Techniques for ..."
- Reduction/temperature control techniques:
 - Supersonic gas injection (hydrogen, est 30% reduction?)
 - Aerospike (60% reduction?)
 - Air spike (90% reduction)
 - C-C/chromium/PICA/etc ablative material (est 40% reduction)