A NOVEL SPACE TRANSPORTATION CONCEPT DESIGNED TO REDUCE PER-MISSION COSTS FOR REPEATED TRAVEL TO/FROM A CELESTIAL BODY

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Part of the expense associated with deep-space missions derives from the inefficiency of chemical propulsion, the large amounts of fuel and propellant required to achieve mission-necessary $D_V$, and the need to carry all consumables from the start of mission.

We propose a new space transportation paradigm which relies on the buildup of certain space “infrastructure” to minimize per-mission cost. Making a comparison to 19th century travel across North America, this is similar to replacement of Conestoga wagons with the trans-continental railroad.

The infrastructure we propose is a set of man-made space stations or man-modified natural celestial bodies (e.g., small asteroids), maneuvered into a set of useful orbits, and equipped with electromagnetic launchers (railguns) as well as human habitats, depot facilities, power systems and orbital maneuvering systems (e.g., electromagnetic thrusters). On each space station or asteroid, the railgun allows small mission vehicles (spacecraft) to achieve large $D_V$’s in short time without consuming onboard propellant. The orbital maneuvering system (e.g., nuclear or solar-powered system of electromagnetic thrusters) allows the space station or asteroid to compensate for the $D_V$’s so imparted, and adjust its orbit to achieve desirable parameters.

The railgun, combined with gravitational assists from Mars and aerobraking, and perhaps some residual $D_V$ provided by traditional means, offers an efficient and economic rendezvous technique for spacecraft departing the space station or asteroid for Mars.

1. BACKGROUND

All space travel today, and most space travel concepts for tomorrow, envision one-shot “missions” which are fully self-contained (with the exception of energy from the sun). All necessary hardware, fuel and propellant are available at the start of the mission. Unfortunately, as a consequence of the need to start most missions from Earth, most of this material is jettisoned within the first few minutes after launch and during the course of the mission. For example, in the case of Apollo, we started with a 36 story rocket and ended with a space capsule less than one story high. This approach has been effective for our first forays into space, but extremely expensive due to the need to carry all consumables needed for the entire mission, and jettison expensive equipment along the way.
If we look to the historical development of the American West, we see that early explorers and settlers took all their durable equipment and many consumable items with them (supplemented by foraging for food and water). Relatively self-contained wagon trains followed. The purchase of a wagon was a significant expense. This was followed by the hardship of a lengthy journey across the continent.

Eventually, wagon trains were replaced with a trans-continental railroad. This ran on an expensive piece of infrastructure (the railroad track) and refueled from depot facilities along the way. The system was expensive and time-consuming to develop - but once developed, one could ride across the country in relative comfort for a very reasonable fee. In a fundamental sense, the cost of travel changed from the cost of procuring an entire wagon and operating it for the duration of the journey, to simply the marginal cost of carrying one’s weight across the country in someone else’s vehicle (the train), plus an allocation for wear and tear.

In a more modern context, consider a simple trip in an elevator. This is one of the most efficient ways to change energy state relative to a gravity well, since the system only moves the payload, the car and the cable. The motive force is provided by an electric motor (and ultimately an electric utility company) which do not travel up and down, but merely supply the necessary work.

We all recognize the inefficiencies of space travel today, and there are many programs under way to address them. The SSTO will help us with launch to orbit, the space station will help us with learning to work and live in space, and Mars mission concepts which involve pre-delivery of equipment and in-situ development of fuel (for example) will help us to bring down the cost of these missions tremendously. We propose an additional concept which could possibly serve to minimize the cost of interplanetary travel by moving us at least part of the way from wagon trains to railroads and elevators.

2. THE BASIC CONCEPT FOR A SPACE RAILROAD

A space railroad would only be useful if it went where we wanted it to go. Let us assume, fancifully, that a large space station or asteroid conveniently orbited between Earth and Mars as shown in Figure 1, with the added feature that it passed close to the Earth at each perihelion and close to Mars at each aphelion. Orbital mechanics prevents this from happening, but consider the possibilities if it could be achieved:

- It could serve as a depot facility for air, water, food and fuel;
- Human travelers could live in a large enduring habitat which had usefulness over many missions. This habitat would be safer and more effective than a cramped spacecraft designed for minimum possible size and weight;
Actual mission spacecraft could be small (much of a mission would be spent in the station habitat);

The required change of velocity ($DV$) for Mars orbit insertion, etc., could be achieved with an electromagnetic launcher from the station or asteroid (i.e., a railgun);

A large station or asteroid of this type could be multipurpose, providing facilities for astronomical research, manufacturing, etc.

Major advantages would stem from the ability to achieve necessary $DV$ by electromagnetic means (i.e., a railgun) without forcing a mission spacecraft to carry chemical fuel, propellant and consumables, and from the ability to keep a mission spacecraft very small - more like an elevator than a wagon train.

Unfortunately, one of the more serious problems with this scheme is that physics prevents it. A simple orbit as shown has a period of 17 months - hopelessly wrong for our purpose.
A larger semi-major axis could solve this problem, but even if we put a station (or maneuvered an object) into an orbit with a semi-major axis of 1.66 a.u. (i.e., to achieve a period of roughly 26 months), we would still have two problems:

1. the natural period between Earth-Mars travel opportunities is not an integer multiple of Earth’s year, so Earth will not be in the same place in its orbit when the object returns at each perihelion; and

2. if perihelion is maintained at 1 a.u., then aphelion is at 2.3 a.u. So the object would cross Mars orbit at a substantial angle, increasing $\Delta V$ requirements for Mars orbit insertion. This in turn affects the design and cost of the railgun used to launch a spacecraft into the appropriate rendezvous trajectory.

Either of these problems might be sufficient to prevent the inauguration of economical “space railroad” services.

3. MANAGED TRAJECTORY

If nature will not give us what we want, perhaps she will allow us to buy it. Figure 2 illustrates in schematic form a possible trajectory which could be repeated on a 26 month cycle. Here, a gravity assist at Mars is used to increase the energy of the trajectory and also rotate its axis about the Sun. During the long cruise from Mars back to Earth, thrust may be applied with high Isp engines (such as ion or electromagnetic thrusters) in order to re-adjust the energy requirements of the trajectory and provide for Earth rendezvous in the time window for a subsequent Earth-Mars transit on a similar trajectory. It is certain that such a trajectory can be defined. The question is: what is the path which minimizes the cost in terms of applied thrust, can the required thrust be generated with feasible technology, and how should the cost of applied thrust be balanced against the need to ensure appropriately-low $\Delta V$ requirements at both Earth and Mars?
We have mentioned ion and electromagnetic thrusters because of their high Isp (on the order of 3500 sec to 10,000 sec depending on specific technology), but these require a lot of energy. The required energy can be provided by either nuclear power or large solar collectors - either way, we are talking about a large investment in infrastructure. We will see that the railgun is also a large investment.

The selection and refinement of a suitable trajectory is a future exercise.

4. THE RAILGUN

Assuming we could put an object in a suitable trajectory, the next piece of the puzzle is the rendezvous system. Ideally, recalling our elevator example, we achieve large $D_V$ and successful Mars orbit insertion and rendezvous without expending any fuel or propellant. One possible means to achieve this is an electromagnetic launcher — a railgun.

A railgun is a maglev train on steroids... a mission vehicle is magnetically levitated, accelerated down a track, and launched into space. The mission vehicle is a passive participant - all motive force is provided by fixed infrastructure. So there is no need for the mission vehicle to carry fuel or propellant (for this initial $D_V$). Small railguns have demonstrated high accelerations for small payloads, and of course maglev trains have been demonstrated which provide much lower accelerations to large payloads. Assuming that the engineering challenges of imparting a high acceleration to a large payload can be solved, what are the other constraints we need to consider?

It turns out that the size of the railgun is determined by the desired $D_V$ and the maximum tolerable acceleration. Figure 3 illustrates the relationship. If we adopt 1 km/sec as a benchmark for concept feasibility, and impose an acceleration constraint on the order of 10 g (which may
be considered the maximum desirable for human travelers), we find a required length of 5 km. It must be sturdy to support the load. Again, we are talking about sizable infrastructure!

Figure 3 Achievable $\Delta V$ as a function of railgun length and tolerable acceleration.

Is a 10 g acceleration for human travelers reasonable? This requires further study. With these operating parameters, the period of acceleration would last for only 10 seconds.

Inanimate cargo could be accelerated at a higher rate, allowing wider “launch windows” for a given planetary rendezvous.

For a given acceleration constraint, railgun length is proportional to the square of required $\Delta V$. So if we cut our required $\Delta V$ in half, we can reduce railgun length by a factor of 4. This is very desirable from the standpoint of cost and risk. So there is a critical design tradeoff among the following aspects of the concept:

- orbital trajectory (yields required $\Delta V$)
- orbital propulsion system required to maintain trajectory (considering any possible gravitational assists)
options for aerobraking

- options for auxiliary propulsion on the mission vehicle itself.

For example, it may be determined that a small auxiliary propulsion capability is more cost-effective than an additional km of railgun length. Certainly, our first effort in this area should be a small system for “proof of concept”.

For the purpose of concept exploration, we will assume railgun lengths from 0.5 to 5 km.

5. CONSTRUCTION ALTERNATIVES

A short railgun (0.5 km) is potentially within the realm of current engineering capability for construction in space. It would be the major element of a large “space transit station” which would also feature a power subsystem (nuclear or solar), orbital propulsion system (ion or electromagnetic), habitat, docking, depot and research facilities (along with necessary thermal, attitude control, etc). Given the total mass of the facility, we need not concern ourselves over the loss of efficiency due to “recoil” when we launch a vehicle with the railgun. Momentum is always conserved, but the mission vehicle receives virtually all of its nominal $\Delta V$, and the momentum imparted to the station can be compensated over time with the orbital propulsion system.

The power subsystem must be sized for the needs of the orbital propulsion system and normal station activities. The railgun imposes a high peak power requirement, but it operates with very low duty cycle. So it does not impose a significant average power requirement on the power subsystem (although we must select an efficient way to store power over time, and release it quickly).

The habitat should be large — since the transit station will be used for many years by many missions, its cost can be effectively amortized. The habitat will of course require closed-cycle life support, and should provide for all needs of the human travelers including radiation and micrometeor protection. Mission vehicles (i.e. those used for actual planetary rendezvous, descent, ascent, etc) should be used for transportation and not long-term habitation. They should use open-cycle life support and they should be designed for short operations (days or weeks instead of months and years). This keeps them small and relatively inexpensive. A small vehicle eases railgun design.

A key design issue is maintaining railgun rigidity and stability under the stress of accelerating a small spacecraft at 10g over a length of 0.5 to 5 km. In this regard, one might look for a nice piece of bedrock on which to anchor the device. Such bedrock might exist in the form of small
asteroids currently plying the inner Solar System. Our knowledge of these objects is limited. The larger ones appear fairly solid, but is this also true of the smaller ones? A pile of rubble would not be suitable. Furthermore, even a small asteroid has very large mass - it would be difficult to maneuver with thrusters we can build today, and it would pose a environmental hazard if it hit the Earth. On the other hand, if a suitable asteroid could be found, and if we could design a suitable trajectory which relied primarily on gravitational assist and required a minimum input of thrust, we might find that this was an interesting engineering option. It would provide the civil engineering basis for a large facility; the rock could be used to shelter human habitats against radiation and micrometeors; there would be room for growth as well as a large number of research facilities; and the rock could even be used as a crude form of propulsion (i.e., by launching it with the railgun). This might be used as a means to initially tailor the orbit to desirable characteristics, and also as a means to jettison undesired mass. (We should employ high accelerations when launching rocks, to ensure they depart the Solar System forever, and are not a future hazard.)

6. CONCEPTUAL MISSION PROFILES

A conceptual mission profile might contain the following phases:

a) Conventional launch from Earth into a suitable parking orbit;

b) Conventional burn to match velocity with Mars transit station (which is passing Earth and near its perihelion);

c) Rendezvous and dock with (or land on) transfer station;

d) Crew transfers to habitat on transit station for interplanetary cruise leg (Earth shuttle craft can remain on transit station to support eventual crew return to Earth, or be launched back to Earth immediately with the railgun);

e) Approaching Mars, provision and check-out Mars shuttle craft docked in railgun;

f) Crew transfers to Mars shuttle craft;
g) Mars shuttle craft launched from railgun, which provides some or all of the DV required for Mars orbit insertion (may also use aerobraking or conventional chemical propulsion);

h) Crew performs extended Mars mission with “own” and “pre-delivered” equipment and consumables;

i) Eventual ascent from Mars and return to Earth (26 months later?) follows a similar profile.

The key advantage is that, with the exception of planetary ascent phases, virtually all DV is provided “free of charge” by the transit station and possibly aerobraking. Also, the shuttle craft used for actual planetary descent and ascent (both at Earth and at Mars) is idle for the long interplanetary cruise phase (crew lives in the transit station habitat). As a consequence, the bulk of the cost is in the infrastructure rather than the vehicles used to actually transport the crew and cargo between planetary surface and space.

An added consequence is that resources can be accumulated on the transit station over many years and many missions, and amortized over decades. Humans live in a large and well-equipped habitat which is far superior to what could be achieved in a self-contained Mars exploration spacecraft. Radiation and micrometeor shielding is easily provided.

Since the transit station does not ever enter orbit around any planet, we are not burdened with the energy cost of rapidly changing its DV for orbit insertion (all trajectory changes for the transit station are based on gravity assist and low-acceleration, long-term thrust by EM thrusters over months and years).

Finally, the major subsystems on the transit station are inherently redundant and fail-soft. These include the railgun (which is composed of many small modules), EM thrusters (many redundant units each providing limited thrust), and possibly the power subsystem (e.g., multiple solar arrays). Multiple habitats can also be built, including special “shelters” for radiation protection and short-term life support in the case of an emergency which requires repair to a major habitat.

Aside from the obvious cost considerations, a key issue is the interplay between transit station trajectory, propulsion system design and railgun design. A system solution should be supported with current or foreseeable EM propulsion and railgun technology, and use gravitational assist to economically balance the EM propulsion system as well as railgun
design. The optimum solution from a cost standpoint may also involve auxiliary \( DV \) provided by the shuttle craft themselves, i.e. to minimize railgun length.

If our needs exceed railgun capability, or we simply want to ease the task of achieving a more modest \( DV \), we could use several stations, each with a railgun, to achieve our objective (see Figure 4). Assume a large station in low Earth orbit is equipped with a railgun. We could launch from Earth and rendezvous with this station in a conventional manner. We could then launch a shuttle craft from this railgun to the Mars transit station as it passes by, substantially reducing the fuel and propellant needed to get the crew and their supplies onto the interplanetary leg of their journey. This is staging on a grand scale! As with the interplanetary transit station, the momentum imparted to the station could be compensated over time with EM thrusters. A similar orbiting station around Mars could be built - Mars already has two small moons ready for upgrade.

\[ \text{Figure 4} \quad \text{Conceptual mission profile using one transit station and two orbiting stations.} \]

Orbiting stations around Earth and Mars could be used as stepping stones for both the outbound and return legs of the journey. If such stations are considered, our design space becomes more interesting and potentially more feasible (i.e., since we have essentially introduced the concept of staging).
7. SUMMARY & FUTURE WORK

We have introduced a space transportation concept which relies on large space stations and railguns, which provide the motive force for needed DV. Mission vehicles are small and low-cost. The stations provide habitation for the crew, and also support research and possibly manufacturing. Future work involves exploration of the design space defined by trajectory options, EM propulsion constraints, railgun constraints, shuttle craft auxiliary propulsion and aerobraking, staging concepts (multiple stations) and human factors. An interesting possibility is the potential to use a small asteroid as a foundation for one or more of the stations. However, this option must consider the extreme mass of an asteroid from the standpoint of orbital propulsion as well as environmental hazard to Earth — how close are we willing to let it come? An incremental development plan which provides for early benefits would also be desirable — perhaps in the context of a station orbiting between Earth and Moon. This would allow all key subsystems to be explored on a small scale while providing economic benefits, in an environment where safety and rescue (if needed) can be more easily assured.