An Orbiting Magnetic Arrest System for Rocket-Free Transportation to Earth Orbit

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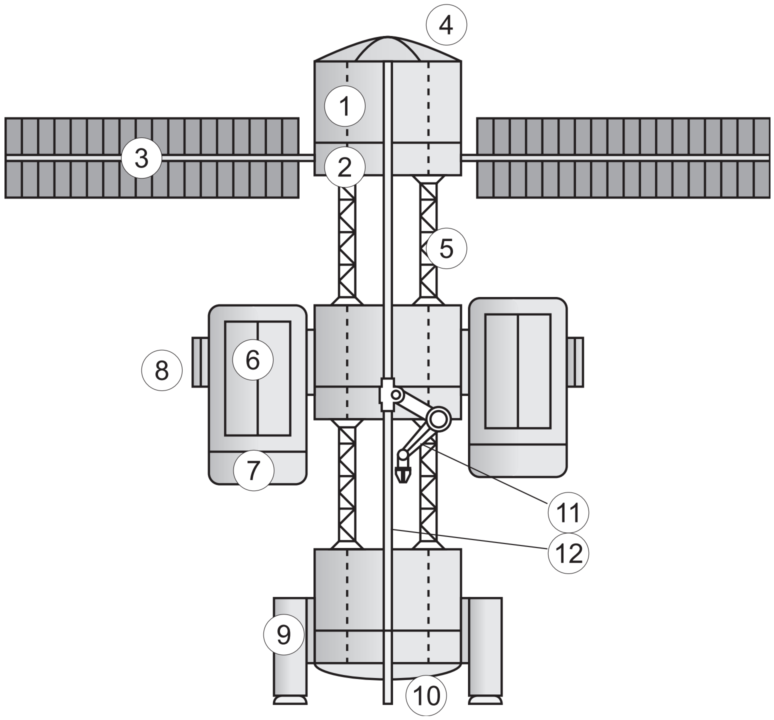
Abstract
If transport to earth orbit could be decoupled into the two separate tasks of reaching orbital altitude and maintaining an orbit, rocket-free transportation to orbit would be possible with straightforward improvements to existing technology. The capability to achieve the first task, reaching orbital altitude, has been demonstrated by several cannon-launch systems. The second task, maintaining an orbit by compensating for atmospheric drag and other disturbances, can be performed by available low power, high-efficiency propulsion methods, such as plasma or ion thrusters. However, a link between these two tasks is required, namely, capturing a payload at orbital altitude and accelerating it to orbital speed. A magnetic arrest system can fulfill this critical role.

1. Concept

The minimum altitude necessary for stable earth orbit is about 150 km. The initial speed necessary for a projectile to reach this altitude when launched from the earth's surface is only about 2 km/s, depending on the projectile's ballistic coefficient. There are several existing methods available for accelerating macroscopic masses to this speed. During the 1960s, conventional explosively driven guns of McGill University's High Altitude Research Program (HARP) accelerated ballistic gliders with masses of 100 kg to speeds as high as 2100 m/s, with apogees of about 180 km (and did this fifteen times during a four-day period in 1966). Rail guns have accelerated projectiles on the order of a kilogram to 2 km/s while operating at reasonable efficiency, and have commonly demonstrated speeds as high as 6 km/s. Los Alamos National Laboratory operates a light gas gun that can accelerate 15 grams to 8 km/s. Superconducting linear motors now under development promise to attain the same or higher speeds with better efficiency. All of these methods have drastically lower costs than carrying payloads on rockets. As an indication of the potential cost reduction, the electricity needed to accelerate 1 kg to 10,000 m/s costs, at residential rates, only about $2.

The difficulty lies not in reaching an apogee of 150 km, but in providing the added velocity needed for the projectile to enter orbit. At 150 km, the orbital speed is 7800 m/s. Because of this large speed difference, rockets launched from cannons have not been expected to show markedly higher payload capacities than rockets alone. An alternative means of providing the energy difference between reaching orbital altitude and reaching orbital speed is needed.

A newly conceived orbiting magnetic arrest system can make it possible to use any of the existing cannon launch methods to place payloads into orbit. The system would operate as follows: Each projectile would carry a loop or tube of conductive material. This loop could either be integrated into the body of the projectile, or, for larger diameter loops, could be deployed at a high altitude. The launch would be timed so that, as the projectile reaches its apogee, and is approximately stationary, an orbiting arrestor approaches the projectile. The main component of the arrestor is a series of large diameter solenoids, most likely composed of second generation high temperature superconducting cable (see Fig. 1). As the projectile enters the bore of the orbiting solenoid, currents are induced in the projectile's conductive loop in a sense opposite to those in the solenoid. In this manner, the solenoid drags the projectile up to orbital speed. The total system slows slightly, but the speed difference can be made up by any one of a number of available low power, high-efficiency propulsion methods, such as plasma or ion thrusters. Power for the station-keeping propulsion can be supplied by means such as solar arrays, with reaction mass resupplied by the cannon-launched projectiles.



1. Superconducting solenoidal magnet
2. Power supply and cooling for magnet
3. Solar array
4. Front shutter
5. Truss
6. Cargo storage
7. Telecommunications, control, etc.
8. Docking for orbital maneuvering vehicle
9. Stationkeeping propulsion
10. Backup mechanical arrestor
11. Manipulator
12. Manipulator track

Figure 1. Major components of orbiting magnetic arrestor. Arrangement and relative sizes of components are to be determined.

It is estimated that a series of three solenoids, each 20 m in length and operating at a field of about 4 T, is necessary to accelerate the projectile from 0 to 8000 m/s (see detail in following section). Payloads can be collected by a robot arm and stored for later transport to other orbits by an orbital maneuvering vehicle.

Feasibility questions that must be studied are the accuracy required of the cannon, whether control surfaces on the projectile can be used to compensate for trajectory errors during the projectile's flight through the atmosphere, fine control of the projectile immediately before interception by the arrestor, the diameter of the arrestor as a function of accuracy, the requirements for the material used to generate the magnetic field, and the diameter and material properties required of the conductive material in the projectile. Other components of the system should be specified in enough detail to give confidence in the system as a whole, including components such as the cannon, the projectile, the means of station keeping, and the general characteristics of the orbital maneuvering vehicle. The conceptual design of the arrestor must also address the ability to be carried by launch vehicles that are available in the near term and deployment in orbit.

2. Basic requirements for feasibility

This section will address basic issues of feasibility, using plausible values of payload mass and material properties, with first order approximations of the physics involved. More detailed models are to be developed.

2.1. Dimensions and field of arrestor

The primary job of the system is producing a force to accelerate the projectile to at least 8 km/s in a distance sufficiently short for construction in orbit. The force between two magnetically coupled circuits is given by

$$F_{12} = -\nabla M_{12} I_1 I_2,$$

where M_{12} is the mutual inductance between the two circuits and I_1 and I_2 are the currents flowing in the circuits. For a first analysis of feasibility, several simplifications of the system can be made. First, the inductance of each of the arrestor segments is much larger than the inductance of the projectile loop, so the currents in the arrestor segments are approximately constant during interaction with the projectile loop. The arrestor segments are far enough apart so that each one acts independently. The projectile loop is treated as a current filament, and each arrestor segment is treated as a series of current filaments. Parameters for a preliminary system estimate, arrived at through several iterations, are shown in Table 1. Solving differential equations for the current in the projectile loop, projectile speed, and projectile position produces results for interaction with the first segment of the arrestor as shown in Fig. 2.

The first segment reduces the difference in speed between the arrestor and projectile to 5000 m/s. The induced current in the projectile loop peaks at about 4×10^6 A. The peak acceleration experienced by the projectile is about 200,000 *g*, which can be withstood by properly selected electronics. The force on the conductive loop must be transmitted to the rest of the projectile; methods of accomplishing this have been successfully developed during HARP and other projects, and will be addressed in a more detailed study.

The magnet dimensions and current density produce a maximum central field of about 4 T. This size and field is well within the range of so-called low temperature superconducting materials, and should soon be within the capabilities of second generation high temperature superconducting wires.

Table 1. First estimate of system parameters.

Parameter	Value
Projectile mass	20 kg
Projectile conductive loop diameter	1 m
Number of arrestor solenoids	3
Arrestor solenoid diameter	10 m
Arrestor solenoid length	20 m
Arrestor solenoid winding thickness	2 m
Arrestor solenoid current density	4000 A/cm^2

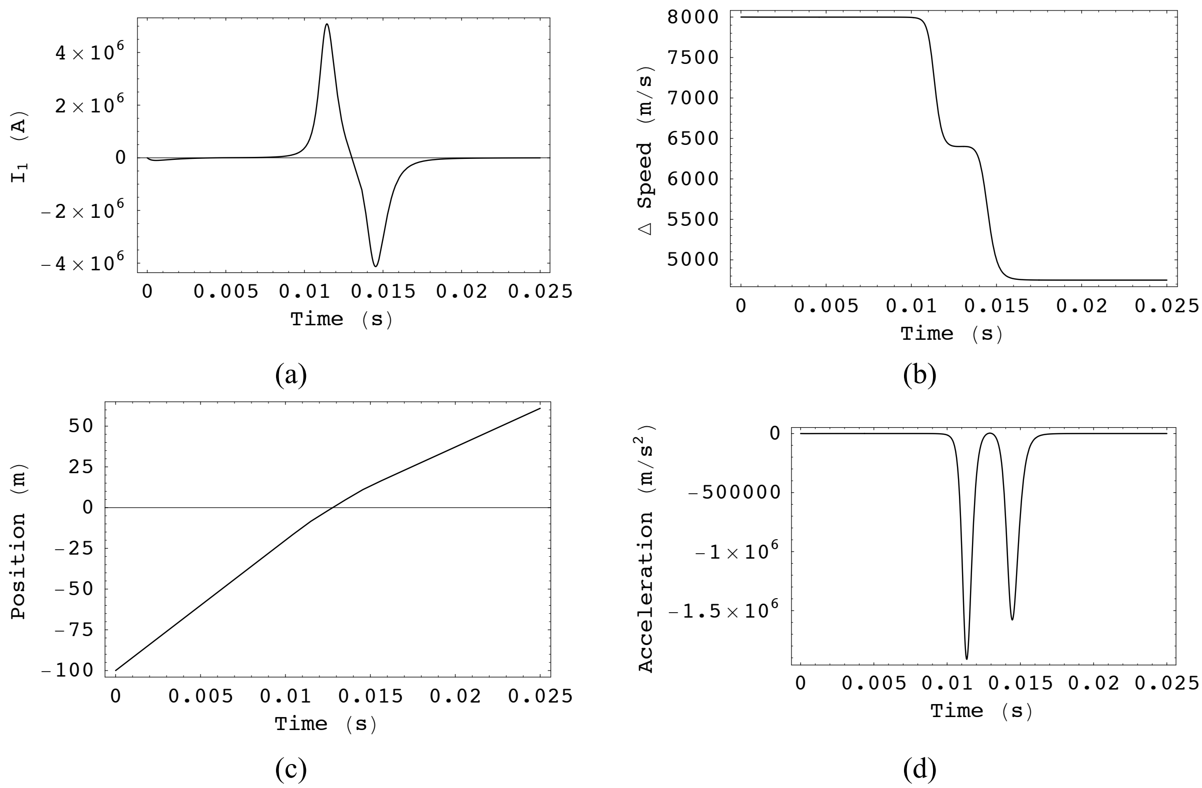


Figure 2. Effects of first arrestor segment on projectile (a) current in projectile (b) speed difference between projectile and arrestor (c) position of projectile (0 is the midpoint of the arrestor solenoid) (d) acceleration of projectile

Successive stages of the arrestor produce lower peak accelerations and currents. Using the final speed due to the first arrestor segment as the starting speed for a second identical arrestor segment, a plot of the change in speed due to the second segment is shown in Fig. 3. The second segment accelerates the projectile to a speed 1500 m/s slower than the speed of the arrestor. Using this speed as the initial speed for a third identical segment, the speed difference is reduced to zero (Fig. 4).

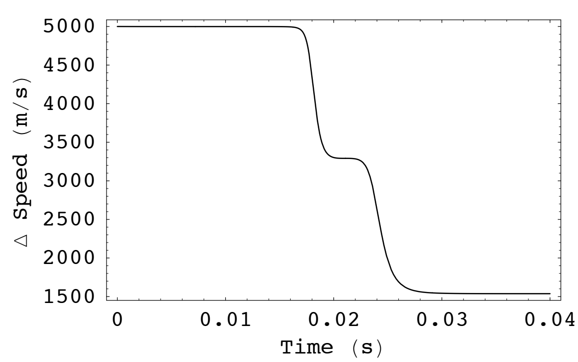


Figure 3. Effect of second arrestor segment

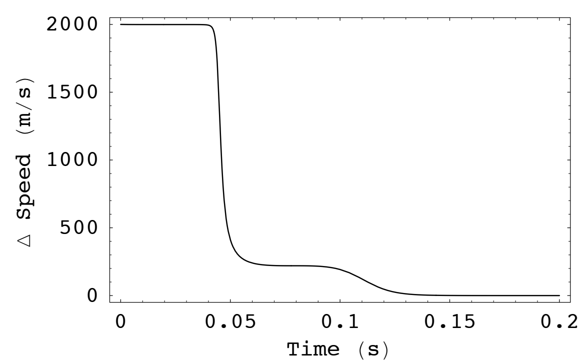


Figure 4. Effect of third arrestor segment

2.2. Dimensions and mass of projectile conductive loop

Large currents are induced in the conductive loop in the projectile. The loop must be able to carry these currents without melting, and must be able to do so while having a mass that is a reasonable fraction of the total projectile mass. For short duration pulses, copper and aluminum can sustain higher current densities than superconductors. Resistance in the projectile loop is also necessary to make the force on the projectile asymmetrical with respect to the midpoint of an arrestor magnet — Without decay of the current, the projectile would be repelled as it passed the midpoint, and decelerate back to its original speed.

The maximum allowable current density as a function of the duration of the current pulse can be found by using a materials property that is called, because of a superficial resemblance to the action integral in mechanics, its "action." The action includes the specific heat and resistivity as functions of temperature. The energy per unit time deposited in the material is given by

$$\frac{dQ}{dt} = \rho[T]J^2 .$$

For adiabatic heating, dQ/dt can also be expressed as

$$\frac{dQ}{dt} = C_V[T]\frac{dT}{dt} .$$

Rearranging produces

$$J^2 t = \int_{T_i}^{T_f} \frac{C_V[T]}{\rho[T]} dT .$$

Aluminum has a smaller action than Cu, but also a lower mass density, making it superior for weight-critical applications. For precooled Al with $T_i = 77$ K and $T_f =$ melting, $J^2 t = 5 \times 10^8$ $A^2 s/cm^4$. A current pulse of 4×10^6 A for 0.002 s implies that a cross-sectional area of 8 cm^2 is needed. A one meter diameter loop with this cross section has a mass of 7 kg. Increasing the number of arrestor stages while decreasing their magnetic field would lower the peak current in the projectile and therefore the mass of the conductive loop. The material in the loop can, of course, be reused for other purposes once in orbit.

2.3. Stability of payload during arrest

In order to maximize the accelerating force on the projectile, the projectile's conductive loop should be coaxial with the solenoidal magnets in the arrestor. Furthermore, a centering force on the payload would decrease the accuracy required to avoid collisions with the inner walls of the solenoids. It appears likely that both of these conditions will occur automatically for the proposed configuration, because the part of the loop that is closest to the solenoid during its approach experiences the largest repulsive force, tending to align and center it. The converse is true after the projectile has passed the midpoint, but the force is smaller during this time, for a net centering action.

A more detailed simulation of the dynamics of the interaction in three dimensions will be performed. If it is found that stability is unsatisfactory, supplemental conductive loops can be added to the projectile to enhance stability, or an active control system could be added to the arrestor.

2.4. Accuracy requirements

Interception of the projectile by the arrestor is significantly different from conventional orbital rendezvous maneuvers. In arrestor interception, the projectile is approximately stationary at its apogee, and success depends on the projectile arriving and staying at the intended point as the arrestor approaches. This can be greatly facilitated by including small reaction jets in the projectile. The arrestor can provide a means to assist the projectile in finding the correct position, for example, by projecting an array of laser beams for the projectile to follow.

The earth's atmosphere is both a source of errors, due to variations in meteorological conditions, and a possible means of correcting those errors, because control surfaces can be used during ascent to correct errors, whether caused by the cannon or by the atmosphere itself. Successful interception of the projectile by the arrestor is essential, and should therefore constitute a large part of research on the concept. The effort can begin with a review of control methods developed by NASA, the military, and aerospace companies. Opportunities for collaboration are sought. A simulation of the fluid dynamics specific to this application will also be developed.

2.5. Rate of delivery of mass to orbit

In order to maintain orbit, the decrease in arrestor speed caused by interception of projectiles must be compensated by a stationkeeping propulsion system. The mass delivered to orbit is therefore limited by the propulsion system. The average impulse of the propulsion system must be greater than the average impulse of the intercepted projectiles,

$$F_{average}\Delta t > m\Delta v,$$

where $F_{average}$ is the average available propulsion thrust, Δt is the time of thrust application, m is projectile mass, and Δv is the change in speed of a projectile. For a constant thrust of 100 N, the mass that can be accelerated to 8 km/s while the arrestor maintains its speed is approximately 1000 kg per day. If each projectile has a mass of 20 kg, the maximum launch rate is 50 per day. This suggests an arrangement in which multiple launchers, perhaps operated by multiple organizations, are able to target the same arrestor. The orbit of the arrestor can be chosen to facilitate the location of launchers along the orbit path.

Atmospheric drag at the example altitude of 150 km will require roughly an additional 20 N of constant thrust. Higher orbits are therefore preferable if the cannons used for launch are capable of sending an acceptable payload mass to a higher altitude.

2.6. Suitable payloads

Raw materials have few constraints on handling, and are therefore suitable payloads. In the first estimate of arrestor dimensions and performance, payloads must withstand a peak acceleration of 200,000 *g*. This acceleration is near the limit for electronics and mechanisms. A specially designed powered aircraft has been demonstrated to survive accelerations as large as 110,000 m/s^2 in a U.S. Navy program, while a solid state flight data recorder using commercial off-the-shelf flash EPROMs has survived impact testing at over 1,500,000 m/s^2 peak deceleration. Suspension in dense liquids, as used during some HARP launches, can further increase the magnitude of acceleration that is survivable.

The design of the arrestor can be adjusted to accommodate more fragile payloads; more segments can be used, and the segments can be non-identical, with the field strength selected to produce a similar acceleration by each segment. In addition to large accelerations, payloads must also withstand rapid changes in magnetic field, although these will be partially cancelled by induced currents in the projectile's conductive loop. Transfer of force from the projectile's conductive loop to rest of structure must be examined, and should be included in a detailed study.

2.7. Testing

Testing of the system can be split into two paths. One path is testing of the arrestor system using gradually larger masses and higher speeds, using a moving projectile and stationary arrestor. The highest test speed, 8 km/s, is achievable using a two-stage light gas gun such as the one found at Lawrence Livermore National Lab. The other path is testing the reproducibility of cannon-launched projectile trajectories and fine control of the apogee. This would also proceed at incrementally higher speeds and larger masses, with parallel development of control techniques. When each of the paths reaches sufficient maturity, arrest testing could begin, perhaps first with suborbital arrestors carried by aircraft.

2.8. Political considerations

The orbiting magnetic arrest system greatly increases the total mass that can be placed into orbit while also increasing the flexibility of the launch schedule. There are obvious applications for delivery of building materials for construction in orbit, resupply of humans living in space, or the first phase of deployment of small sensor or exploratory packages. However, the orbiting arrestor does this with a minimal disruption to current stakeholders. Heavy launch vehicles will still be required for launch of humans, large satellites, and components of the arrestor itself. By increasing economic activity in space, the operation of the arrestor will expand markets for other space industries.

One of the concerns associated with the development of cannon launch to space is possible undesirable proliferation. A system that includes the orbiting arrestor does not have this risk because placement of the arrestor itself requires heavy launch and advanced space operations capabilities. Once in orbit, the arrestor can serve as a gate, granting access to space only to users authorized by the operator of the arrestor.

3. Research needs

Study of the magnetic arrest system should address each of the feasibility issues outlined above in significantly greater detail, as well as other technical considerations that are revealed in the course of the study, leading to a baseline design for construction and testing in later phases. Two areas should be emphasized, namely, arrival of the projectile at the correct location, which includes trajectory accuracy and fine control at the apogee, and dynamics of arrest itself.

Other components of the system must be specified in order to arrive at a mass and cost estimate. These include the stationkeeping propulsion method, solar array or other power supply size, manipulator arm capabilities, details of the cryogenic system and power supply for the superconducting magnets, and general details of an orbital maneuvering system for transportation of payloads from the arrestor to other locations. Compatibility of the arrestor components with heavy launch vehicles that are currently available or being planned is to be considered.

Subsequent phases of research should focus on testing of hardware based on the results of the feasibility study, beginning at low masses and velocities, and increasing to full scale testing. The testing can follow the same division as the detailed feasibility study, with launcher and projectile testing proceeding on a separate track from arrestor testing.