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THE LAUNCH LOOP: A LOW COST EARTH-TO-HIGH-ORBIT LAUNCH SYSTEM*

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ABSTRACT

The launch loop is an Earth surface based launching utility that stores energy and momentum in a very long, small cross section iron ribbon loop moving at high velocity and magnetically suspended in an evacuated sheath. The ribbon, moving faster than the payload's exit speed, supports both itself, the sheath, and the payload at high altitudes against gravity with the force necessary to deflect it from its otherwise straight path. A preliminary system is presented that can launch five metric ton payloads to geosynchronous or near-lunar orbits at rates of 12 per hour, with a sufficient power supply.

INTRODUCTION

Since the liquid fuel rocket was first proposed for space propulsion by Tsiolkovsky, great strides have been made in making an abstract idea into a laboratory curiosity, and then into a practical form of propulsion. Rocket performance will always be limited by the requirements of the vehicle carrying its own power plant and fuel, and having only its own waste products as reaction mass. Inherent in these requirements is that most of the mass, and much of the engine and tank structure must be discarded with each launch. Energy efficiency is very low for chemically fueled rockets, especially when the original energy required to produce and refrigerate the fuels is considered.

Large scale space industry and space colonization will not become practical until the cost of space transportation drops far below the costs projected for the Space Shuttle and its derivatives. Proposed schemes for electromagnetic launch from the moon [1] or from the Earth [2] involve very high accelerations suitable only for raw materials. Methods involving payload capture by other orbiting systems requires a lot of mass to be placed in orbit initially [3], or require material strengths not yet available [4].

The goal of any launch system is to supply momentum and energy to the payload at a rate that will get it up to orbital speeds in a reasonable time, but not destroy it with crushing acceleration. To accelerate a payload to 11 Km/sec at 3 g's requires an acceleration path of 2000 Km. The kinetic and potential energy change necessary to take a payload from the earth's surface to escape velocity is modest, about 63 MJ/Kg. If the energy is provided at 100% efficiency from electricity costing 3 cents per KWHr, this energy would cost 53 cents per Kg. The earth itself provides a virtually infinite source of reaction mass.

This paper presents a scheme to provide energy and momentum to the payload that is more efficient than rockets, and yet uses simpler mechanisms on each payload than rocket engines and tanks. The principles involved are primarily the ballistics of high speed continuous flows of materials (such as those encountered in fire hoses or conveyor belts, but at much higher speeds) and ferromagnetic levitation using active control of the attraction between a magnet and an iron ribbon.

THE LAUNCH LOOP

A highly schematic view of the launch loop is shown in fig. 1.

The launch loop is a very large, gossamer structure built around an iron ribbon loop moving at 12 Km/sec. The iron ribbon is 5 cm wide and 2.6 mm thick and suspends a *non-moving* aluminized fiber composite sheath, that rides on permanent magnets. The ribbon and sheath structure each weigh about 1 Kg per meter, and the outer sheath has a diameter of 10 cm. To provide a long, low friction acceleration path for sensitive payloads, the portion of the loop used to accelerate the payload is 2000 Km long and elevated to 80 Km. Before and after the elevated acceleration track are two sections sloping down to the surface at a 20° angle. The ribbon and sheath are joined to these sections by two curved, 1350 metric ton deflector sections containing magnets, control systems and elevators from the surface. The upper deflectors will be referred to as the "east" and "west" stations, with payloads hauled up by elevators on the support cables for west station and launched from there. Near the Earth's surface, each sloping section joins into a upwards curving ramp with magnets that deflect the ribbon to or from the horizontal plane. Once the ribbon is horizontal, it is twisted on its length axis 90°, so that the flat surface points at the horizon. The ribbon is then deflected 180° in the horizontal plane in a large, flat semicircular section (~ 10 Km radius) of high-energy magnets. The windings for the linear motors that

* This is an abridgement by the Editor. The full paper, which includes more detailed engineering information, is available from the author.

drive the ribbon are spaced at intervals in the semicircular sections. The ribbon is then twisted back to flat, and it travels near the surface from the back end deflector to the front deflector.

The elevated sheath has permanent magnets spaced in a thin iron double-rail system on the bottom side of the sheath, hanging the sheath about 2 cm below the iron ribbon. The sheath is 10 cm in diameter, and made of Teflon coated, aluminized Kevlar fabric and epoxy impregnated Thornel carbon fiber hoop spreaders that stand off atmospheric pressure at startup. The thin aluminum coating interferes only slightly with the moving magnetic fields of the payload, but it's tight crystal structure greatly slows gas diffusion. The sheath, plus magnets, electronics, pumps, and tethering cables weighs 1.3 kilograms per meter.

A system of small wires and cables join the sheath to 5 mm diameter main cables running down to anchor points spaced 10 Km on axis and 30 Km perpendicular to the axis on the ground. These cables are used to adjust the vertical force on the sheath and ribbon, and are relaxed when a payload passes overhead to compensate for the payload's weight. A lot of force is required to deflect the ribbon; the weight of the sheath and the cables are designed to deflect the ribbon into a circular orbital arc. At more widely spaced intervals are vacuum pumps that keep the sheath evacuated if it is pinholed. The elevated section will also have to support some sensor and control electronics packages yet to be determined, as well as parachutes or some other form of slowdown mechanism to protect sections of sheath during catastrophic system failure.

The sloping sections on the way up to and down from the acceleration section are much heavier, as the hanging cables must be used for control of the sections against wind, and the sheath requires more layers and stronger, higher volume pumps to work in the heavier lower atmosphere. To compensate for the extra weight, the sloping sections curve more than the earth's surface. The tension on this section is relieved by diagonal hanging cables. The entire structure is located somewhere on the equator to minimize payload apogee Δv as well as weather and Coriolis effects.

DYNAMICS OF THE HIGH SPEED RIBBON

Imagine a stream of water from a hose pointed at an angle into the sky. Neglecting effects of air friction, the stream forms a continuous parabolic arc, the ballistic trajectory of the individual particles in the stream. If the stream of water is moving very fast when it leaves the hose, the height of the trajectory and the distance it traverses is well beyond the structural limits of most materials, certainly beyond the compressive strength of the water itself. If a flat plate is brought up against the stream at a slight angle downwards, the stream is deflected downward and puts an upward force on the plate. In this way, the moving stream may be used to support a stationary weight.

If the stream is surrounded by a frictionless hose, the downward deflection of the stream may be used to support the weight of the hose. When the stream reaches the ground at the end of its trajectory, it may be deflected from downwards to horizontal in the original direction, then deflected backwards 180°. The stream then travels through a hose over the surface to the starting point, where it is deflected another 180°, then upwards to start the parabola again. If the hose is truly frictionless, large apparently static structures may be built whose heights are limited only by the tensile strength of the hose.

If the stream is replaced with a ribbon of iron, and the hose is replaced by a long evacuated tube (the "sheath") the two may be held separate by magnets along the bottom of the sheath. The gradient of the magnetic field through the ribbon will generate eddy currents, that result in drag. Lift is produced by the magnetic pressure $B^2/2\mu_0$ [5].

The ribbon will be analyzed assuming a uniform weight per length w_R, and without tensile or bending forces. A ribbon moving at velocity v_R may be deflected by an angle Θ with a force of

$$F = 2 w_R v_R^2 \sin\left(\frac{\Theta}{2}\right) \tag{1}$$

at an angle of $\frac{\Theta}{2}$ from the ribbon perpendicular. Note that if the ribbon remains moving at constant speed (equivalently, no friction), the deflecting force is perpendicular to the ribbon. The deflection propagates in the direction of ribbon movement; there is no effect "upribbon" from the disturbance. This eliminates most oscillatory modes, although the sheath may oscillate around the ribbon unless the spacing control system is used to remove energy.

The same deflection results from a distributed force. If the ribbon is moving over a very large horizontal distance, the curvature of the surface of the earth itself implies a deflection of the ribbon. For a ribbon moving at circular orbital velocity, the upwards deflection force is equal to its weight. If it is moving faster than orbital velocity v_O, there is a net upwards force per unit length of

$$F = a_G w_R \left(\left(\frac{v_R}{v_O}\right)^2 - 1\right) \tag{2}$$

Given the orbital velocity of 7860 m/sec at an altitude of 80 Km, a ribbon moving at 12000 m/sec and weighing 1 Kg/m, the net upwards force of 12.9 N/m can support a weight of 1.33 Kg/m while remaining parallel to the earth's surface.

LAUNCHING PAYLOADS

A five metric ton (gross weight) payload would be typical for this loop size. The payload is equipped with rocket engines for orbital circularization at apogee, a shell with a slight negative lift, and a heat shield and parachutes for reentry of human cargo. Magnets hold the payload off the ribbon (and therefore the sheath) using eddy current repulsion. The payload is stabilized with thrusters, but instability is minimized by keeping the center of mass on-axis with the ribbon. Machine tools and raw material that can affordably be lost because of system failure, and never has to return to Earth, may be shipped up in cheaper containers.

Payloads are hoisted from the ground to the west launch station (at the beginning of the acceleration section) via elevators on the station anchoring cables. In the west station, the payload is lowered over the sheath and started down the acceleration section. The magnets on the payload are designed to generate a drag force of 150 KN and a lift force of 50 KN on the ribbon that holds the payload up against gravity and accelerates it at 3 g's. With the payload near rest velocity, the ribbon is decelerated 12 meters per second, and deflected downwards 4 m/s, and angle of .33 milliradians. As the payload accelerates, the speed relative to the ribbon drops, decelerating the ribbon by 150 m/s at a payload speed of 11 Km/s. To compensate for the weight of the payload on the sheath, tension must be released on the hanging cables as the payload passes overhead.

The drag of the payload on the ribbon results in ohmic heating of the ribbon; the rate the ribbon can remove the generated heat limits the force that can be placed on a payload, that limits the payload velocity and mass. Maximum throughput can be achieved with smaller payloads and higher starting temperatures, allowing more dissipation and higher payload rates.

ENERGY CONSIDERATIONS

A complete launch loop system will draw power in the gigawatt range. Nearly all this power is dissipated in the ribbon or becomes payload kinetic energy, although some will go into refrigerators, motors, measurement and control electronics, and other miscellaneous items. The energy into the ribbon comes from deflection related currents, payload drag, and residual gas drag, and is dissipated purely by black body radiation. A 5 ton payload launched at 11 Km per second removes 660 GJ of kinetic energy from the ribbon. If 800 MW is assumed available for acceleration, the loop can launch a 5 ton payload every 14 minutes.

The maximum payload rate is limited by the power plant available and the heat dissipation ability of the iron ribbon. 2.5 GWe of power plant allows the maximum loop output of 12 five metric ton payloads per hour. Power plants may be brought on and off line as necessary; the energy storage capacity of the loop will allow it to launch at high rates for short periods with less than full power plant capacity.

WEATHER EFFECTS

The sheath and cables are subject to wind loading in the lower atmosphere, although the bulk of the system is in near vacuum. The sudden loads caused by wind gusts cause extra strain on the structure, and the static loading of steady winds can distort the structure and contribute inaccuracies to payload trajectories.

Equatorial winds tend to be unpredictable and vary greatly with altitude [7], but their maximum speeds are relatively low and the lack of Coriolis force inhibits cyclones. The most severe stresses can be expected during squalls. The equatorial site should be chosen such that the system is torn down by storms rarely for a given maximum wind load.

SYSTEM STARTUP AND CYCLING

The launch loop ~~will be~~ probably ~~started on~~ the ground, at rest. Startup imposes some of the most severe stresses on the system, as the normally unstrained acceleration sheath must stand off a full atmosphere, with wind buffeting. The sheath must now support the ribbon, not vice versa, and disturbances may propagate backwards along the ribbon while moving slower than its speed of sound. The ribbon weighs 5000 metric tons; to get it moving at 12 Km/sec requires 3.6×10^{14} Joules of kinetic energy. If this energy is put in at a 1 GW rate, the system will require 100 hours to pump up to speed. It is important that the ribbon can be dumped from the sheath in a way that is not damaging to the structure or to the environment. 360 trillion Joules is enough energy to boil one million cubic meters of water; it would be handy to dump the ribbon into a large pond when the loop fails.

CONSTRUCTION AND OPERATING COSTS

A detailed estimate of the costs involved would be premature, but some costs can be at least identified, and some may be compared to existing construction projects.

Among the costs are: $154 million for 22 United Technologies 56MW dual FT4 gas turbine power plants, $5 million for 200 metric tons of Union Carbide Thornel carbon fiber, $25 million for 1000 metric tons of DuPont Kevlar aramid fiber, and $160 million for 4000 metric tons of formed Alnico 8 magnets.

Other as yet unmeasured costs are sheath manufacturing, motors, ramps, pumps, electronics, and so forth. If the loop is built on land, many square kilometers of land must be purchased; if at sea, floats and anchoring cables must be added.

If the total cost of the launch loop, including research costs, comes to three billion dollars (a guess), is used at 20 percent capacity of 1 GWe (35,000 metric tons per year), and must be amortized over 1 year as a high-risk venture, the cost per gross kilogram (including 6 cents per KWHr oil fuel cost) is $90.

Later, at 85 percent payload capacity, 3 GWe power capacity (500,000 tons per year), 5 year amortization, 6 billion dollar capital cost (another guess), and 1.3 cents per KWHr fuel cost, the cost per gross kilogram is $3. At this cost, labor and payload systems ~~will probably~~ dominate net payload cost.

It is likely that total launch loop system cost will be well below that of Earth-to-high-orbit rocket systems.

POSSIBILITIES

This version of the launch loop was designed for launching 5 ton payloads from the Earth to geosynchronous, LaGrange, and lunar destinations, but other applications are possible. Higher speed interplanetary loops are possible, as well as a low speed loop on the moon. Passive ribbons in orbit may capture payloads launched from Earth or Moon, reducing the size of apogee circularization motors. The relatively low ratio of dissipation to energy storage may make the loop an effective form of energy storage for power grids, and an interesting method of transmitting power over long distances.

CONCLUSION

The launch loop promises to greatly lower the cost of launching payloads from the Earth. The structure, while very long, is small in total weight and volume compared to existing large systems, and may prove affordable as a private sector investment.

Much study remains to determine the details of a launch loop operation; the idea may prove impractical because of instabilities, expense, or political obstruction. Regardless of its success, it is hoped that the idea will stimulate others to think about other low-cost approaches to earth launch using existing physics and existing engineering materials.

The rocket has served us well during the last few decades, and will continue to find uses in new applications and at the frontiers of space. Certainly the traffic necessary to justify even a minimum scale launch loop must be established before its construction by rocket systems such as the shuttle. Low cost space utilities such as the launch loop will replace the rocket in many applications as payload rates grow, making space settlement and industrialization economically practical.

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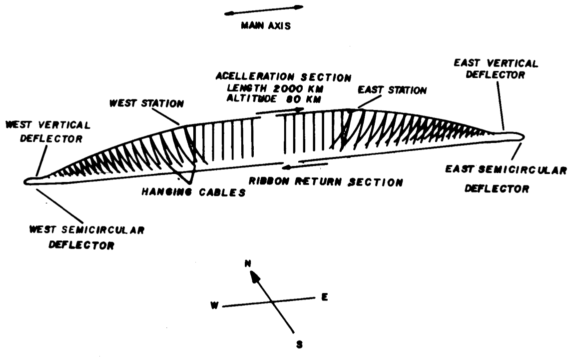
Figures

Fig. 1. A side view of the launch loop. Most cross sections are centimeters or millimeters, making the structure virtually invisible from a distance.



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