Revolutionizing Space Launch - The Economic and Operational Benefits of the Variable-Pitch Screw Architecture

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***Abstract*— This paper introduces a novel ground launch assist technology, the Variable-Pitch Screw Launch (VPSL), which utilizes magnetic coupling with variable pitch leadscrews to achieve high exit velocities at significantly reduced costs compared to traditional chemical rockets. VPSL addresses the limitations of current linear accelerators by circumventing the switching constraints of linear motors and eliminating the rail wear commonly associated with railguns.**

Significantly, the capital cost of VPSL is proportional to the square of the exit velocity (ΔV^2), providing a more favorable economic scaling compared to the exponential cost increases ($\exp(\Delta V/V_e)$) inherent in chemical propulsion systems and the cubic cost growth (ΔV^3) observed in some linear motor components. A parametric model estimates the capital cost of a human-rated launcher capable of accelerating 21,181 kg vehicles to a speed of 11,129 m/s to be 32 billion in 2024 USD.

Keywords—electromagnetic launch, variable-pitch screw launch

I. Introduction

As space exploration expands to include not only low-earth orbit (LEO) missions but also ventures to the Moon, Mars, and various asteroids—motivated by scientific and geopolitical interests—the need for sustainable, cost-effective launch solutions becomes critical. The delta-v requirements for reaching and returning from these distant planetary bodies are significantly higher than those for typical LEO missions. The round-trip requirement, crucial for missions involving human crews, almost doubles the delta-v needed. To mitigate crew exposure to cosmic radiation and optimize provision mass efficiency, missions with shorter durations but higher delta-v trajectories may be preferred. These delta-v-increasing requirements, when combined with the exponential effect of the rocket equation, favor mission architectures that leverage launch-assist infrastructure over all-rocket approaches.

In contrast to the prohibitive expense of traditional chemical rockets, Variable-Pitch Screw Launch (VPSL) offers a scalable and environmentally friendly alternative. By leveraging an infrastructure-based approach, VPSL technology not only promises significant cost reductions but also aligns with global climate objectives, marking a pivotal advancement in the economic and environmental sustainability of space exploration.

II. A Specific Implementation

An implementation for a 22-year-long Mars human outpost space program is analyzed in this paper. It has three main sections: a 774 km long submerged section (Figure 1), an 83 km long underground ramp, and a 122 km long aeronautically elevated section (Figure 2). All three sections are housed within an evacuated tube with an airlock at each end. It accelerates vehicles with an initial mass of 21,181 kg and a payload mass of 10,986 kg to 11,129 m/s relative to the surface of the Earth. These vehicles, travelling eastward, exit the elevated evacuated tube into the rarified atmosphere at an altitude of 15 km.

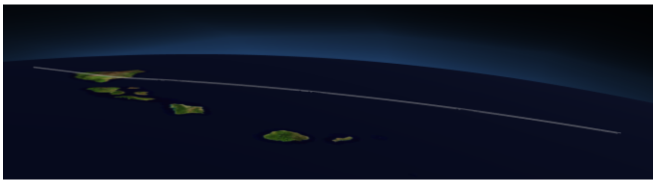

Figure 1: Launcher's scale compared to the Hawaiian Islands.

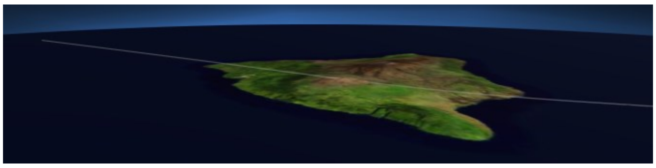

Figure 2: Ramp and aeronautically elevated evacuated tube.

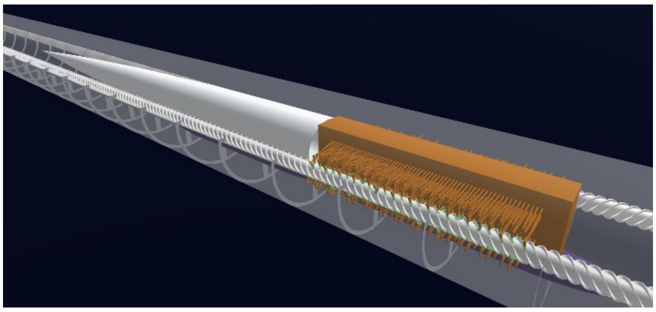

Figure 3: A launched vehicle (white) being accelerated by an adaptive nut (orange) that couples to the variable pitch screws.

The operating principles of the screws, rail, (see Figure 3) and magnetic coupling without mechanical contact were covered in the "Space Launch" section of [1]. Favorable economic conditions for launch assist infrastructure and the aerodynamic drag aspects were covered in [2].

The implementation, in the form of a digital twin[3], which is available on GitHub[4], was analyzed to estimate the capital and operating costs. Table 1 provides a breakdown.

A variety of techniques were used to make conservative estimates. For example, the cost-per-meter of the aeronautically levitated evacuated tube was estimated by dividing Spirt Aerosystem's 2023 net revenues by the total length of airline fuselages that they shipped in 2023. The cost of the screws, brackets, and evacuated tube was estimated by multiplying the volume of material (obtained from the digital twin) by the cost of the materials used and then applying a factor to account for the cost of building and operating a factory to produce and assemble these components. In most cases, comments in the digital twin's code provide sources for values used in the calculations.

TABLE I. COST MODEL PARAMETERS

Description	*Value*[1]
launcherMassDriverLength	773949 m
launcherRampLength	82975 m
elevatedVacuumTubeLength	121572 m
massDriverBracketsCostOfMaterials	0.021 B USD
massDriverRailsCostOfMaterials	1.535 B USD
massDriverScrewsCostOfMaterials	2.106 B USD
massDriverTubeWallCostOfMaterials	1.159 B USD
massDriverTubeLinerCostOfMaterials	0.002 B USD
launcherMassDriverTotalMaterialsCost	4.822 B USD
launcherMassDriverTotalMaterialsCostPerMeter	6229 USD/m
launcherMassDriverScrewMotorsCost	1.548 B USD
launcherMassDriverTotalCost	11.191 B USD
rampTubeWallCostOfMaterials	0.124 B USD
rampBracketsCostOfMaterials	0.002 B USD
rampRailsCostOfMaterials	0.164 B USD
rampTunnelingCost	2.899 B USD
launcherRampTotalMaterialsCost	4.822 B USD/m
launcherRampTotalCost	3.481 B USD
launcherRampTotalCostPerMeter	41946 USD/m
elevatedVacuumTubeTubeCostPerMeter	115018 USD/m
launcherElevatedVacuumTubeTubeCost	13.983 B USD
massOfElevatedVacuumTubeTube	16503093 kg
buoyancyOfElevatedVacuumTubePerMeter	54 kg/m
aeronauticLiftCapitalCostPerKgOfPayload	208 USD/kg
launcherAeronauticLiftTotalCapitalCost	3.438 B USD
elevatedVacuumTubeTotalCost	17.421 B USD
launcherTotalCapitalCost	32.093 B USD
massDriverCostPerMeter	14458 USD/m
rampCostPerMeter	41946 USD/m
elevatedVacuumTubeCostPerMeter	143299 USD/m
costOfAeronauticLift	1.371 B USD
interiorVolumeOfVacuumTubes	31967042 m^3
pumpDownTime	19 days
capitalCostOfPullingVacuumInsideTubes	0.121 B USD
operatingCostOfPullingVacuumInsideTubes	0.005 B USD
airlockPumpDownTime	0.038 days
operatingCostOfPullingVacuumInsideAirlock	1081 USD
energyCostPerLaunch	23159 USD
totalEnergyCostForAllLaunches	12969292 USD
launchVehicleCost	7194812 USD
totalCapitalCosts	32 B USD
totalOperatingCosts	0.013 B USD
totalPayloadToMars	6152367 kg
costPerKgOfPayloadToMars	5238 USD

[1] The precision of the values generated by the model is not known and should not be inferred from the number of digits used to print out the values calculated by the model.

The variable-pitch twin screw launcher's cost scales with its exit velocity *squared*, which differentiates it from most other electromagnetic launchers where a significant portion of the cost scales with the exit velocity *cubed*. Consider that a human-rated space launcher will be quite long and thus must be comprised of many individually powered segments. If the vehicle travels past a segment faster, then the power electronics in that segment will have less time in which to add kinetic energy to the vehicle. So, that segment must do more energy conversion in less time. Thus, it needs to be designed to handle more power. Thus, there is an aspect of segment cost that is proportional to the passing vehicle's velocity.

$$C = Cost_{EnergyConversion} = k_1 v(t) = k_1 at$$

The rate at which the vehicle passes by segments is…

$$R = k_2 v(t) = k_2 at$$

The rate that the vehicle is passing by energy conversion hardware *cost* is the product of the previous two equations…

$$\frac{dC}{dt} = CR = k_1 k_2 a^2 t^2$$

We can integrate to determine the total energy conversion cost of the launch system…

$$C_{total} = k_1 k_2 a^2 \int_0^{t_{Muzzle}} t^2\, dt$$

$$C_{total} = \frac{k_1 k_2 a^2 t_{Muzzle}^3}{3}$$

To express energy conversion cost as a function of muzzle velocity and acceleration, then we can substitute in…

$$t_{Muzzle} = \frac{v_{Muzzle}}{a}$$

… which then gives us the total energy conversion cost as a function of muzzle velocity and acceleration.

$$C_{total} = \frac{k_1 k_2 v_{Muzzle}^3}{3a}$$

This is still better than all-rocket systems where a curve fit to empirical data revealed an exponential relationship between cost and ΔV characterized by the equation

$$CostPerKg \cong 0.4235\, e^{0.0011\, \Delta V}$$

However, devices such as coil guns and long railguns, where the cost of power conversion hardware for rapidly converting stored electricity into kinetic energy is proportional to ΔV^3, are not optimal for affordable space launch. The VPSL architecture scales better because it avoids the ΔV^3 hardware costs by first gradually converting electrical energy into the kinetic energy of the rotating machinery and then rapidly transferring that rotational energy into the passing vehicle more mechanically. It thus avoids the need for distributed (and expensive) pulsed-power electronics. The VPSL's relatively expensive hardware is concentrated within a small reusable component called the adaptive nut (Figure 3).

CONCLUSIONS

The capital cost of VPSL is proportional to the square of the exit velocity (ΔV^2) – better scaling than the exponential cost increases ($\exp(\Delta V/V_e)$) inherent in all-rocket systems and the cubic cost growth (ΔV^3) observed in the expensive components of other linear motors. A parametric model estimated the capital cost of a human-rated launcher capable of accelerating 21,181 kg vehicles to a speed of 11,129 m/s to be 32 billion in 2024 USD. This places the technology within the budgetary reach of space agencies that seek to establish human-occupied outposts on the moon or Mars – destinations that are economically inaccessible with all-rocket systems.

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