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.**

Earlier electromagnetic launch (EML) concepts, such as linear motors and rail guns, encountered serious feasibility issues when scaled to the velocities required for space launch. VPSL solves these issues by largely eliminating costly power conversion and power conditioning hardware and replacing it with low-cost components that perform momentum transfer instead. The result of is that 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 linear motor components of earlier EML concepts.

A full-scale digital twin implementation of the architecture has been developed to simulate and validate the operational dynamics of the architecture, and a small-scale physical prototype has been constructed and is undergoing testing. A cost model within the digital twin estimates the capital cost of a human-rated launcher that can accelerate 27,940 kg vehicles to 11,123 m/s to be $32 billion USD in 2024. The cost-per-kg of payload delivered to the surface of Mars is estimated at USD 3,858, assuming just 560 spacecraft are launched to Mars over the lifetime of the system.

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, create favorable conditions for a mission architecture that leverages launch-assist infrastructure instead of using an all-rocket approach.

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.

To date, the system has been validated through the development of a high-fidelity digital twin – comprising over 27,000 lines of code – and a small-scale physical prototype, both of which provide early confirmation of the underlying engineering principles and the feasibility of the overall architecture.

Still, it is important to recognize that chemical rockets have advantages – advantages that any less technically mature system like VPSL must contend with. They are the product of over a century of research and engineering refinement, much of it publicly funded during the Cold War and now deeply embedded in national and commercial infrastructure. Rockets benefit from existing launch facilities, regulatory pathways, and a broad base of institutional knowledge, not to mention their strategic relevance as a dual-use technology. They are

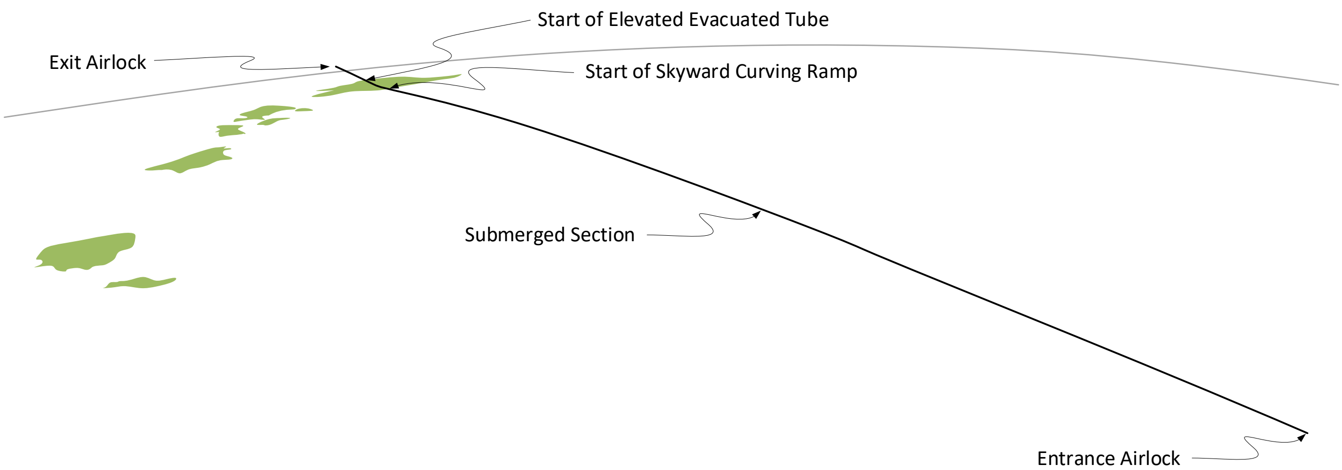

Figure 1:Illustration of the VPSL System

also highly flexible – capable of launching in any direction, adapting quickly to changing mission requirements, and already proven across a wide range of use cases.

Like many long-established technologies, chemical rockets have reached a point where their advancement is shaped more by legacy systems and institutional continuity than by disruptive innovation. The rocket ecosystem is so mature that it often seems more practical – or politically feasible – to pursue incremental improvements within that system than to consider fundamentally different approaches. Tasking existing teams to make rockets a little bigger or a little cheaper fits comfortably within established workflows, funding structures, and institutional cultures. Launch-assist technologies like VPSL, by contrast, require rethinking key assumptions about how launch works – and that kind of shift rarely aligns with the path of least resistance.

Ironically, the same rich legacy that gives rockets their credibility also locks them onto a growth trajectory where each incremental gain becomes exponentially more difficult and expensive, due to the unforgiving nature of the rocket equation. Meanwhile, new ideas often face skepticism not because they have been disproven, but because they challenge deeply held convictions and do not fit easily into existing institutional or regulatory frameworks. In such environments, staying within the comfort zone of what is already known often wins out over confronting the risks and complexity of a potentially disruptive change.

To achieve transformative change in space access, it is essential to address three core challenges – each representing a reason why the broader space community might hesitate to embrace a system like VPSL.

First, there is a widespread (but incorrect) belief within the space community that chemical rocket launch is already on a path toward dramatically lower costs. Many attribute this to experience curve effects, increased commercialization of launch services, and advances in reusability. It is not uncommon to hear spokespeople for commercial launch service providers claim that partial reusability has dropped launch costs to LEO by an order of magnitude, or that reusability can reduce launch costs by two orders of magnitude [1][2][3][4]. However, a close examination of the evidence shows that reusability – though long promised as a path to dramatically lower launch costs, from the Space Shuttle to Falcon 9 and now Starship – has so far failed to deliver the exciting cost reductions many had anticipated. Therefore, the first challenge is to confront the prevailing belief within the space community that chemical rocket launch costs are falling rapidly. This is covered in Section II.

The second core challenge is to foster an intuitive understanding among influential members of the space community that chemical rocket cost-per-kilogram rises exponentially with mission delta-v. There is a tendency to apply linear thinking to what is fundamentally an exponential problem, as illustrated by Heinlein's aphorism: 'Once you get to orbit, you're halfway to anywhere.' But as space exploration increasingly focuses on destinations well beyond low Earth orbit, this exponential relationship quickly makes traditional rockets prohibitively expensive. Relying on a linear mental framework is perilous, as it obscures the exponential growth in cost and difficulty that chemical propulsion faces as missions demand higher delta-v. This is covered in Section III.

The third core challenge is to demonstrate the fundamental difference between VPSL and other electromagnetic launch technologies and illustrate why this difference is so significant for the space launch application. The fundamental difference is that the cost of VPSL scales with the **square** of the required velocity, whereas better-known electromagnetic launch technologies involve power conditioning components whose cost will scale with the cube of the required velocity. At orbital velocities, the steep cost growth of these components dominates the system's total cost, ultimately removing these technologies from serious contention. VPSL avoids this steep cost growth, so as mission delta-v's increase, VPSL overtakes rocket-based architectures in cost-effectiveness.

This paper examines these three core challenges in detail and presents a cost model for the VPSL architecture, demonstrating that its impact on mission economics could be truly transformative – despite the significant upfront investment required to build the necessary infrastructure.

II. The Chemical Rocket Launch Cost Trend

A. Cost of Past Space Programs

Space exploration has historically been an expensive endeavor, with flagship-class missions like Apollo, the Space Shuttle, the International Space Station (ISS), and Artemis illustrating the financial challenges of advancing humanity's presence in space. These programs provide important context for evaluating the cost-effectiveness of the Variable Pitch Screw Launcher (VPSL).

The Apollo program, which achieved humanity's first manned lunar landing, cost approximately $257 billion in 2020 U.S. dollars. The funding was a direct result of Cold War priorities, showcasing how political motivations can drive large-scale investments in space [5].

Designed to enable reusable spaceflight, the Space Shuttle program cost approximately $196 billion over its 40-year lifespan (1972–2011+). While it may have lowered the cost per launch compared to expendable rockets, its operational complexity and maintenance requirements kept costs high [6].

A symbol of international cooperation, the International Space Station (ISS) provides useful information on the cost of operating a research lab in low-earth orbit. In 2021, the NASA Office of the Inspector General reported that NASA's share of annual ISS costs, fiscal year 2010, was "$2 to $4 billion a year on the ISS, including operations and maintenance, research activities, and transportation costs" [7]. There have been a total of 280 visitors to the ISS, of which 167 (60%) were from the United States [8]. The ISS is designed to support a crew of six; therefore, the operating cost per person-year has been between 500 million and 1 billion USD.

NASA's current Artemis program aims to return humans to the Moon and establish a sustainable presence. NASA's Office of the Inspector General estimates that NASA is projected to spend $93 billion on the Artemis effort up to FY 2025 [9].

China's space program has grown rapidly, with expenditures approaching $20 billion annually as of 2024, according to Statista [10]. China's efforts include funding for the Tiangong space station, Chang'e lunar program, and Mars rover missions.

The next nine countries listed on the Statista site, including Japan, Russia, the EU, India, and several others, spent roughly $27 billion in 2024.

These examples underline the significant investments required for traditional space programs. However, these expenditures are often justified by their broader benefits: they stimulate economic growth through technological innovation and high-skilled job creation, strengthen geopolitical alliances by demonstrating leadership in cutting-edge science and engineering, and project the effectiveness and ambition of a nation's governance to domestic and international audiences.

B. *Cost of Chemical Rocket Launch Versus Time*

In the realm of space exploration, enthusiasm and optimism about technological progress have often led to overly ambitious cost projections. Renowned astronomer Carl Sagan highlighted a similar phenomenon during his 1977 Christmas Lectures. Reflecting on historical misconceptions about Mars and Venus, Sagan noted that people once believed Venus to be a swampy planet inhabited by dinosaurs, and Mars to host a canal-building civilization. These "charming ideas," as he called them, were driven by humanity's desire to find life elsewhere but were distorted by emotional investment. Sagan warned:

> *"Accept only the most rigorous standards of argument; do not accept inadequate, poorly thought out, flawed arguments, especially where our emotions are involved."*

This cautionary principle about the dangers of motivated reasoning applies equally to modern discussions about the cost of space exploration. While some claim spaceflight costs are dropping by 10X every 10 years, akin to Moore's Law for computing or the cost reductions in DNA sequencing, reputable historical data suggests a more modest trend – approximately a 2X reduction over 30 years.

Psychologist Dr. Orion Teraban provides further insight into this cognitive bias:

> *"When something happens and in that moment people perceive that it aligns with their personally relevant goals, they judge that something as good and project that judgment into reality. ... People believe they are experiencing a good thing, like the thing itself is good, and not their own externally projected judgment of goodness."*

This psychological phenomenon highlights the danger of conflating subjective optimism with objective reality. In the context of spaceflight costs, such biases may lead to unrealistic expectations about the scalability and affordability of chemical rocket launches, obscuring the persistent challenges and limitations imposed by physics and economics.

Falcon 9 launched 134 times in 2024, and SpaceX led the world in terms of kg placed into low Earth orbit; therefore, Falcon 9 is the dominant reference point for understanding present-day launch costs. To accurately assess the rate at which launch costs are falling, we need to determine the cost-per-kilogram for SpaceX's Falcon 9.

Launch Pricing: SpaceX's official pricing in 2024 for a Falcon 9 mission to Low Earth Orbit (LEO) is $69.75 million.[11] This is not the price of the expendable configuration, as evidenced by the footnote under the price that says "Up to 5.5 mT TO GTO". The expendable payload to GTO is 8.3 mT. Therefore, the price is more likely to be associated with the most cost-effective configuration, which is probably the price of a configuration that embraces reusability and minimizes the use of marine assets for booster recovery - that is, the Return to Launch Site (RTLS) configuration. This configuration has two variants – one with a full-size nozzle on the second stage and one with a reduced-size nozzle. We assume that the list price is associated with the reduced-size nozzle. Additionally, NASA's Launch Vehicle Performance Website[12] lists some "Ground Rules" for Falcon 9, including a statement that says, "Payload mass greater than 7,250 kg (15,983 lbm) may require mission-unique adapter/accommodations, resulting in cost and/or performance impacts." This statement hints at undisclosed surcharges that may come into effect when payloads exceed the 7,250 kg threshold.

Payload Capacity with RTLS Recovery: To estimate the payload capacity of Falcon 9 in its lowest-cost RTLS configuration, we can use several approaches:

Scaling from GTO Payload: By assuming that the payload to Low Earth Orbit (LEO) scales in the same way as it does for payloads to Geostationary Transfer Orbit (GTO), we can estimate:

$$Payload_{RTLStoLEO} = 22{,}000 \times \frac{5.5}{8.3} = 14{,}578\ kg \qquad (1)$$

This approach is based on the publicly available Falcon 9 performance data for expendable and reusable launches.

Using the NASA Launch Vehicle Performance Website: A query for an altitude of 400 km and an inclination of 28.5 degrees will include Falcon 9 in the results. Selecting the "Falcon 9 (Full Thrust, RTLS)" vehicle and then "plot" will generate the chart shown in Figure 2.

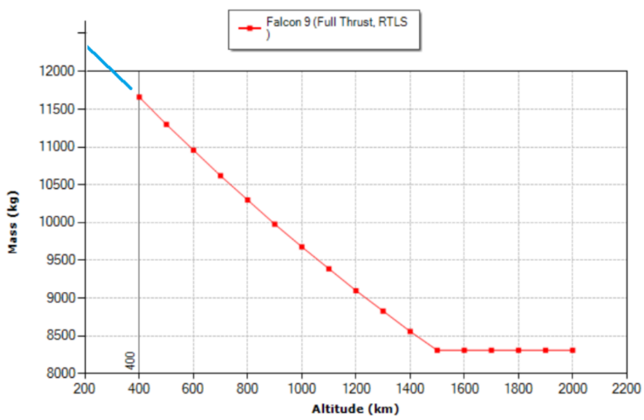

Figure 2: Chart from NASA's Launch Vehicle Performance Website

We can extrapolate to estimate the payload to lower altitude orbits. Extending the curve to an altitude of 200 km results in a payload of approximately 12,325 kg.

Using SpaceX Statements: SpaceX has also provided relevant data points on X.com (formerly Twitter). For example, a tweet shown in Figure 1 indicates that the RTLS payload capacity to LEO is, in practice, closer to:

$$RTLS\ Payload\ to\ LEO = \frac{134}{14} \approx 9{,}571\ kg \qquad (2)$$

This value reflects real-world operational capabilities under typical conditions.

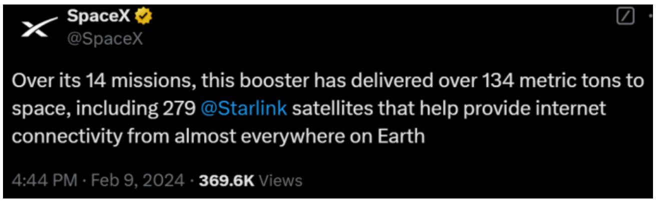

Figure 3: Payload data published in a SpaceX tweet.

Using NASA Site's Ground Rules: If one were inclined to take a conservative view – particularly given cost escalators hidden in the fine print – then the 7,250 kg payload threshold stated in the Falcon 9 ground rules might be treated as a representative upper limit, with any excess mass assumed to incur proportional cost impacts. Under this assumption, a reasonable estimate of cost-per-kilogram would be the listed launch price divided by the threshold value.

Falcon 9 Cost-Per-Kg: Estimated payload values and the corresponding cost-per-kg values are shown in Table 1. Cost-per-kg is calculated by dividing the list price of 69.75M by the estimated RTLS payload value.

Table 1: Estimated Falcon 9 Payloads and Cost-Per-Kg Estimates

Estimation Technique	Estimated RTLS Payload (kg)	Cost-Per-Kg (2024 USD)
Scaling from GTO	14,578	4,784
NASA Website	12,325	5,659
SpaceX Tweet	9,571	7,287
NASA Ground Rules	7,250	9,621

(GEO), heliocentric orbit, and highly elliptical orbit (HEO). Despite initial hopes that Falcon Heavy might provide a substantially lower cost-per-kg to LEO, this has not materialized in practice. As of Q2 2025, Falcon Heavy does not reuse its core stage, which affects its cost efficiency. Additionally, the fact that Falcon Heavy has not been used for SpaceX's Starlink satellite launches indicates that its cost-per-kg is likely comparable to, or even higher than, Falcon 9.

Past Launch Systems:
Present-day launch costs for Falcon 9 (best case) are compared to historical data on launch costs in Figure 4, where historical data was obtained from Figure 1 of [14] and converted to 2024 USD with

$$USD\ Cost_{2024} = \frac{MY}{Mg} \cdot \frac{9000}{35} \cdot \frac{CPI_{2024}}{CPI_{2007}} \qquad (3)$$

where 'MY' is "Man Year", 'Mg' is megagrams, 'CPI_{2024}' and 'CPI_{2007}' are 315.664 and 208.936 – consumer price index values for September of 2024 and 2007.

Additional data points for Delta IV, Long March 4B, Antares, and Atlas V were obtained from [15] and then inflation adjusted from 2021 to 2024 USD by using the ratio of CPI indexes, 315.233/275.203.

The three dotted lines represent different possible trends: prices dropping by 10X every 10 years, 2X every 10 years, and 2X every 30 years. While launch costs declined rapidly in the 1960s, the rate at which prices have come down since then is closest to the rate indicated by the orange "2X every 30 years" trend line.

While this paper offers an independent estimate of the rate at which launch costs have been changing over time, other studies have also been published on this topic. A 2023 paper

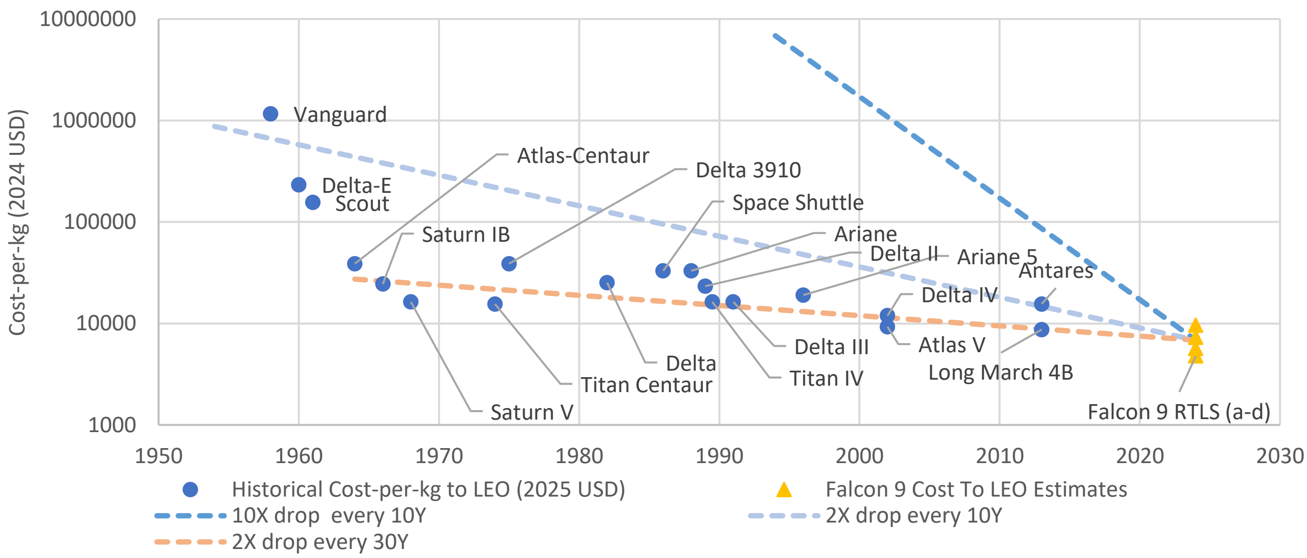

Figure 4: Historical Launch Costs Versus Falcon 9 Cost Estimates

However, it's worth noting that the average cost-per-kg that customers pay on dedicated missions (that is, non-ride-share missions) has been estimated to be as high as $20,770 - largely due to underutilized capacity [13].

Falcon Heavy: Falcon Heavy is used almost exclusively for higher delta-v missions that require delivery to orbits such as geostationary transfer orbit (GTO), geostationary Earth orbit

by one of us reported on how the cost of resupplying the ISS had changed over time[16] and found that while the cost has been highly variable, there was an overall slightly upward trend. NASA also published a study in 2025. This report found that NASA's launch cost increased by an average of 2.8 % annually from 1996 to 2024, even after accounting for inflation [17]. This study is of particular interest because it

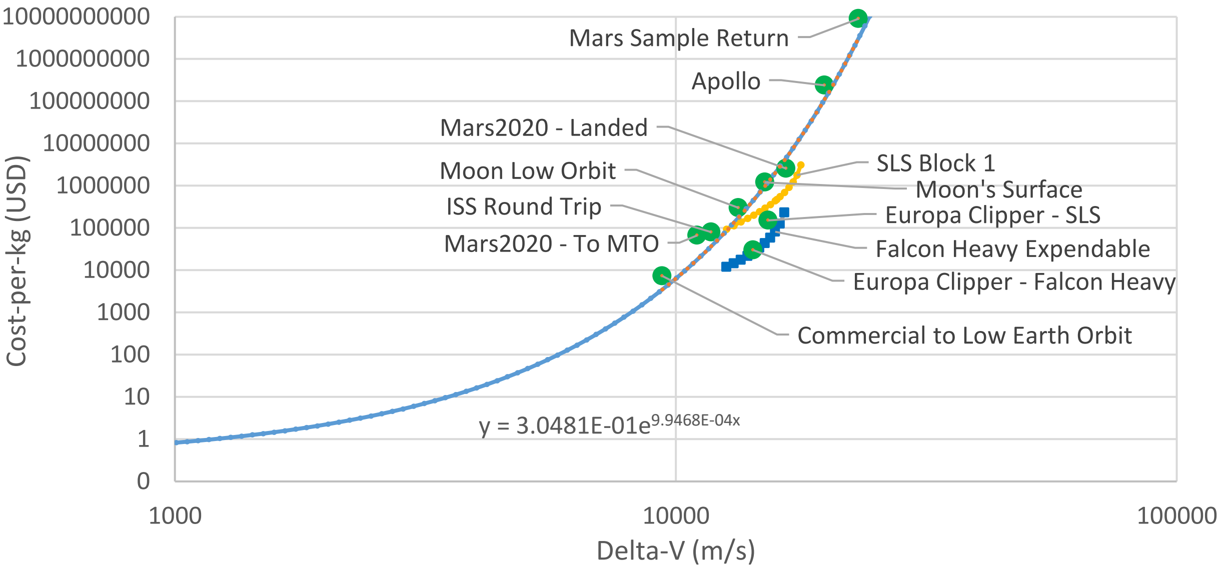

Figure 5: Empirical Data of Cost-Per-Kg versus Mission Equivalent Delta-Vs

stated, "However, the current literature faces data limitations for robust investigations … Proprietary factors restrict access to actual launch cost data, necessitating reliance on the prices advertised by the service providers. This study addresses this knowledge gap with an empirical examination using actual launch costs incurred by the National Aeronautics and Space Administration (NASA)." By using proprietary data, the NASA study may offer greater reliability than those based solely on publicly available information.

III. Cost Versus Delta-V for All-Rocket Systems

The relationship between the cost of launch systems and their corresponding delta-v requirements has long been a topic of interest in space mission planning. The chart of Figure 5Figure 4, derived from empirical data, illustrates a strong correlation between cost-per-kilogram and equivalent delta-v. This analysis builds on the foundational understanding of the Rocket Equation, which reveals the exponential challenges of increasing delta-v. It captures data points from a wide spectrum of missions with different delta-v requirements. An exponential trendline fit to the data provides insights into the underlying economics of chemical-rocket-based spaceflight. More details on the data points and methodology of Figure 5Figure 4 are detailed in the source material [18].

A. *Interest in Higher Delta-V Missions is Rising*

Recent developments in global space exploration indicate increased interest in missions requiring higher delta-v. A growing number of countries are targeting destinations beyond low Earth orbit (LEO), such as the Moon and Mars, underscoring this trend.

Lunar Missions: Historically, lunar exploration was dominated by the United States and the Soviet Union during the Space Race. In recent years, however, several additional nations, including the EU, Japan, China, India, Israel, and the United Arab Emirates, have attempted or successfully sent landers or orbiters to the Moon. For example, China's Chang'e program has achieved significant milestones, including a lunar sample return mission in 2020, while India's Chandrayaan-3 mission recently landed near the lunar south pole in 2023.

Mars Exploration: Beyond the Moon, Mars has become a focal point for higher delta-v missions. China successfully landed its Zhurong rover as part of the Tianwen-1 mission in 2021, becoming the third country to achieve a successful Mars landing. Meanwhile, NASA continues its Mars exploration efforts with the Perseverance rover and the Ingenuity helicopter. A Mars Sample Return mission was identified as a high-priority goal in the latest Planetary Science Decadal Survey, emphasizing the importance of advancing technologies and strategies for interplanetary exploration.

NASA's Shift to Higher Delta-V Systems: The retirement of the Space Shuttle in 2011 and subsequent investment in the Space Launch System (SLS) reflect a strategic pivot toward missions with greater delta-v requirements. The SLS is designed specifically for deep-space exploration, including lunar and Martian missions, highlighting NASA's commitment to higher-energy trajectories.

Space Policy Developments: In 2010, the United States, under the leadership of President Obama, published a Space Policy that directed NASA to, among other things, "Set far-reaching exploration milestones. By 2025, begin crewed missions beyond the moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth;"

The subsequent administration under President Trump revised the policy to "Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the Solar System and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."

These developments signal a clear shift in focus from missions in LEO to more ambitious destinations requiring significantly higher delta-v, demonstrating the increasing momentum toward expanding humanity's reach beyond Earth.

IV. Mass Drivers Versus Rockets

The economics of rockets and mass drivers are fundamentally different, rooted in their respective governing principles. For rockets, the physics of the Rocket Equation dictates that the ratio of a rocket's initial mass to its final mass scales exponentially with the change in velocity, or delta-v (Δv). Empirical data (see Figure 5) similarly reveals an exponential relationship between the cost-per-kilogram and delta-v, making high delta-v missions prohibitively expensive with traditional rocket technologies [18].

In contrast, mass drivers operate on fundamentally different principles. The relationship $v^2 = 2ax$ where 'a' is acceleration and 'x' is length, illustrates that the length of a mass driver (and thus the cost of components that scale with length) will scale with velocity squared. This quadratic scaling provides a more favorable cost trajectory for achieving higher velocities compared to the exponential costs associated with rockets. However, it is important to note that not all components of a mass driver will scale with velocity squared.

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. If we assume that a component's cost is proportional to its power, there is an aspect of segment cost that is proportional to the passing vehicle's velocity.

$$C = Cost_{EnergyConversion} = k_1 v(t) = k_1 at \quad (4)$$

The rate at which the vehicle passes by segments is…

$$R = k_2 v(t) = k_2 at \quad (5)$$

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

$$\frac{dC}{dt} = CR = k_1 k_2 a^2 t^2 \quad (6)$$

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

$$C_{total} = k_1 k_2 a^2 \int_0^{t_{Muzzle}} t^2 \, dt \quad (7)$$

$$C_{total} = \frac{k_1 k_2 a^2 t_{Muzzle}^3}{3} \quad (8)$$

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

$$t_{Muzzle} = \frac{v_{Muzzle}}{a} \quad (9)$$

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

$$C_{total} = \frac{k_1 k_2 v_{Muzzle}^3}{3a} \quad (10)$$

This is still better than all-rocket systems where a curve fit to empirical data reveals an exponential relationship between cost and Δv characterized by the curve-fit equation, from Figure 5,

$$CostPerKg \cong 0.30481 \, e^{0.00099468 \, \Delta V} \quad (11)$$

For example, if a mass driver architecture has a 50/50 cost split between hardware that scales with v^2 and hardware that scales with v^3 when its exit velocity is 100 m/s, that same architecture will be almost 1 million times more expensive when the exit velocity is 10000 m/s because the cost of the v^3 components will dominate at higher speeds.

Therefore, devices where the cost of power conversion hardware for rapidly converting stored electricity into kinetic energy is proportional to Δv^3 (which is often the case for devices such as coil guns and long railguns) are not optimal for affordable human-rated space launch.

The VPSL architecture [19], which utilizes magnetic coupling with variable-pitch leadscrews to accelerate payloads, is more optimal because it avoids the Δv^3 hardware costs by initially converting electrical energy into the kinetic energy of the rotating variable pitch screws. The rotational energy is then rapidly transferred to the passing vehicle via magnetic coupling, akin to a magnetic gear. This eliminates the need for distributed, high-frequency pulsed-power electronics – one of the primary cost and complexity barriers that has historically limited the scalability of coilgun-style launch systems – solving a key challenge that has long prevented electromagnetic launch infrastructure from emerging as a truly disruptive space launch technology.

VPSL's drive system *gradually* converts electrical energy into distributed kinetic energy which is stored within the screws and flywheels. Then it sequentially activates clutches to quickly transfer kinetic energy from the flywheels through the screws to an adaptive nut that advances the vehicle. Critically, this transfer is done through mechanical momentum transfer as opposed to energy conversion to eliminate power conversion hardware.

Table 2 defines a hypothetical launcher to illustrate difference between VPSL and earlier EML concepts.

Table 2: Sample numbers for illustrating the difference between VPSL and earlier EML concepts

Accelerated Mass	$m_a = 38{,}940kg$
Spacecraft Mass	$m_0 = 27{,}940kg$
Rate of Acceleration	$a = 80\ m/s^2$
Vehicle Exit Velocity	$v_{ex} = 11{,}123\ m/s$
Time Between Launches	$t_{bl} = 2400$
Efficiency	$\epsilon = 0.5$

Launch time is $t = v_{ex}/a = 139s$. Launcher length is $l = 0.5at^2 = 773\ km$. If made up of discrete segments, each 5 m in length, n_{seg} would be 154,651. We can now compare earlier electromagnetic launch (EML) approaches to the VPSL approach.

With a linear motor, the peak power supplied is $P_{peak} = m_0 a v_{ex}/\epsilon = 69\ GW$ (~35 Hoover Dams). However, it is the cost of conditioning power at P_{peak} levels that makes the linear motor impractical to implement, as each segment handles power levels of $P_{segment} = P_{peak} * i_{seg}/(n_{seg} - 1)$ where i_{seg} is the segment index. Integrating over length (l) yields $P_{total} = 0.5 P_{peak} n_{seg} = 0.5(69\text{GW})(154{,}651) = 5{,}358{,}714$ GW of power handling capacity for the system. It is most likely this metric, not physical length, that ultimately stalled earlier space EML efforts.

The proposed VPSL system, on the other hand, converts electricity into kinetic energy gradually; its energy conversion power is $P_{peak} = 0.5 m_a v_{ex}^2 / t_{bl} / \epsilon = 2\ GW$. So, VPSL requires 34X less power to operate. But with VPSL, $P_{segment} = P_{peak} / n_{seg}$ so $P_{total} = P_{peak} = 2$ GW. By reducing power conditioning hardware from $5{,}358{,}714\ GW$ to $2\ GW$ (a factor of 2.7 million) VPSL overcomes the economic barrier that stalled previous space EML systems.

While comparing architectures using sample numbers is useful for illustrating the benefit of v^2 cost scaling over v^3 scaling, a deeper analysis of a mission-focused architecture will reveal that in addition to the power used to spin up the screws and flywheels, several other systems draw power including vacuum pumps, solenoids that activate the clutches, the electromagnets in the grappler pads of the adaptive nut (see Figure 8), and the lift fans that support a component called the "Elevated Evacuated Tube" (EET). However, before proceeding with quantitative power analysis, we must first describe a specific implementation of VPSL technology in more detail.

V. A Specific Implementation of VPSL

A. Assumptions

This paper analyzes an implementation of a Variable Pitch Screw launch system for a 22-year-long Mars human outpost space program. Therefore, the launcher is only used for a few days or weeks during each Mars transfer window. Between windows, components such as the EET are stowed, and power systems are allocated to support the needs of the local community. The system is human-rated but assumes a fit crew that is well supported by custom-contoured lie-flat acceleration couches or water beds.

B. Orbital Mechanics

Determining the required exit velocity for a mass driver involves applying fundamental principles of orbital mechanics to account for the gravitational interactions of Earth, the Sun, and the target destination. For a mission to Mars, the velocity requirements are derived from the energy needed to escape Earth's gravity well and enter the transfer orbit to Mars. Below is the methodology:

1. **Orbital Speeds of Earth and Mars:**
   Using the Sun's gravitational parameter (μ_{Sun}), the orbital speeds of Earth and Mars are calculated as:

$$v_{Earth} = \sqrt{\frac{\mu_{Sun}}{r_{EarthOrbit}}},\ v_{Mars} = \sqrt{\frac{\mu_{Sun}}{r_{MarsOrbit}}} \tag{12}$$

2. **Hohmann Transfer Orbit:**
   The semi-major axis (a) of the transfer orbit is the average of the Earth's and Mars' orbital radii:

$$a_{transfer} = \frac{r_{EarthOrbit} + r_{MarsOrbit}}{2} \tag{13}$$

   The perihelion and aphelion speeds of the transfer orbit ($v_{perihelion}$ and $v_{\text{apohelion}}$) are calculated using the conservation of energy.

3. **Excess Velocity at Earth ($v_{EarthExcess}$):**
   The velocity needed to leave Earth's orbit ($v_{perihelion}$) minus Earth's orbital velocity gives the excess velocity:

$$v_{EarthExcess} = v_{perihelion} - v_{Earth} \tag{14}$$

This excess velocity depends on the specific transfer window and ranges between 2,830 m/s and 4,030 m/s, based on detailed mission analyses.

4. **Hyperbolic Escape Trajectory:**
   The hyperbolic escape velocity at the Earth's surface is calculated, accounting for the altitude of the mass driver and the Earth's rotation. The velocity components include:

   - Earth's rotational velocity contribution ($v_{rotation}$)
   - Escape velocity from Earth's gravity well
   - Excess velocity for Mars transfer

   The resulting exit velocity is derived as:

$$v_{exit} = \sqrt{\frac{2\mu_{Earth}}{r_{Earth} + h} + \frac{\mu_{Earth}}{|a|}} - v_{Rotation} \tag{15}$$

where 'h' is the altitude of the mass driver, and 'a' is the semi-major axis of the hyperbolic trajectory.

Practical Adjustments:

While theoretical calculations provide a baseline v_{exit}, real-world factors such as orbital eccentricity, inclination, and Earth's rotational alignment necessitate adjustments. Empirical data from NASA's mission planning documents refine these calculations, providing exit velocities optimized for specific launch windows.

C. Architecture

The proposed system (see Figure 7) has three main sections: a 773 km long submerged acceleration section (Figure 6), a 75 km long underground ramp, and a 102 km long aeronautically elevated section (Figure 8). All three sections are housed within an evacuated tube with an airlock at each end. It accelerates vehicles with an initial mass of 27,940 kg and a payload mass of 17,140 kg to 11,123 m/s relative to the Earth's surface. These vehicles, traveling eastward, exit the elevated evacuated tube into the rarified atmosphere at an altitude of 15 km.

The fundamental operating principles of the screws, rail, and magnetic coupling without mechanical contact were covered in the "Space Launch" section of [19]; however, since then, the design has evolved. The spacecraft is still mounted on a launch sled, but now the vehicle and the sled are propelled by a separate component called an "adaptive nut", whereas previously the functionality of the adaptive nut was integrated into the launch sled. The adaptive nut, launch sled, and spacecraft together comprise a "launch train" (see Figure 8).

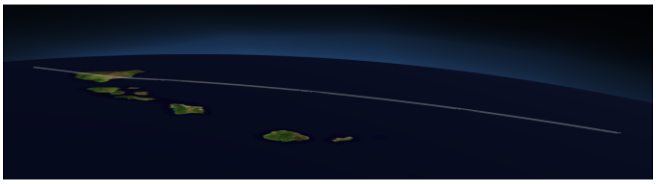

Figure 6: Launcher's scale compared to the Hawaiian Islands.

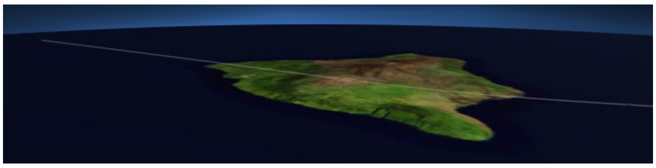

Figure 7: Ramp and aeronautically elevated evacuated tube.

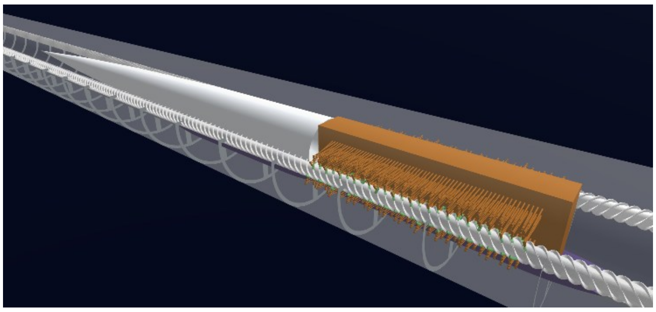

Figure 8: A launched vehicle (white) being accelerated by an adaptive nut (orange) that couples to the variable pitch screws.

A later section, entitled *Linear Active Magnetic Bearings (AMBs),* will revisit some of the material from the previous article and provide updates to reflect recent developments.

Favorable economic conditions for launch assist infrastructure and the aerodynamic drag aspects were covered in [16].

D. Virtual Prototyping Efforts

An implementation of the VPSL architecture, in the form of a digital twin[20], is available on GitHub[21] and was used to estimate both capital and operating costs. The digital twin simulates the complete system at architectural scale, capturing the kinematics of all major components, including the guideway, evacuated tube, variable-pitch screws, and the grappling mechanisms that interface with the screw flights. It models the launch train's acceleration profile and simulates the vehicle's trajectory through the rarefied upper atmosphere, incorporating thrust, aerodynamic drag, and relevant orbital mechanics.

Models of the major structural components – including the screws, brackets, guideway, and tube – are used to directly estimate the quantity of material required for construction. These estimates serve as inputs to a detailed cost model used to project capital expenditures. The cost model also computes energy usage throughout the launch process to support the estimation of operating costs.

Significant advances in the accessibility of advanced computer rendering have made it increasingly feasible to construct high-fidelity simulations of complex physical systems. These tools not only enable dynamic modeling but also support visual verification of system behavior, ensuring that the simulated mechanics align with the designer's intent. Leveraging these capabilities, the present digital twin – comprising over 27,000 lines of code – is likely the most complete and high-fidelity model of a non-rocket launch system developed to date.

A breakdown of the resulting cost estimates is provided in Table 3.

Table 3: Cost Model Parameters

Description	***Value[1]***
Accelerator Length	773 km
Ramp Length	75 km
Elevated Evacuated Tube Length	102 km
Brackets Cost of Materials	0.351 B USD
Rails Cost of Materials	1.533 B USD
Screws Cost of Materials	1.850 B USD
Tube Wall Cost of Materials	1.736 B USD
Tube Liner Cost of Materials	2.590 M USD
Total Materials Cost	5.472 B USD
Total Materials Cost Per Meter	7,076 USD/m
Screw Motors Cost	1.546 B USD
Accelerator Total Cost	12.490 B USD
Accelerator Cost Per Meter	16,153 USD/m
Ramp Tube Wall Cost of Materials	0.169 B USD
Ramp Brackets Cost of Materials	34.265 M USD
Ramp Rails Cost of Materials	0.150 B USD
Ramp Tunneling Cost	3.625 B USD
Ramp Total Materials Cost	0.534 B USD
Ramp Total Cost	4.693 B USD
Ramp Total Cost Per Meter	62,180 USD/m
Elevated Evacuated Tube Tube Mass	13,853,002 kg
Elevated Evacuated Tube Buoyancy Per Meter	53 kg/m

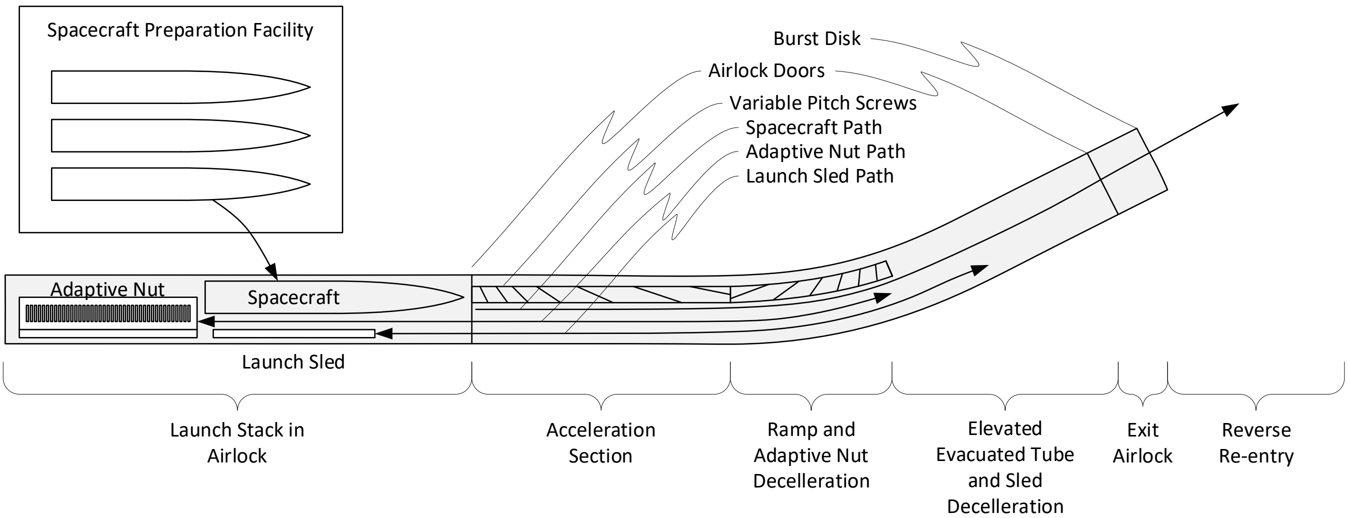

Figure 9: System Architecture Diagram illustrating main components, sections, and travel paths. Not to scale.

Aeronautic Lift Total Capital Cost	2.886 B USD
Aeronautic Lift Capital Cost Per Kg of Payload	208.333 USD/kg
Elevated Evacuated Tube Tube Cost	11.738 B USD
Elevated Evacuated Tube Tube Cost Per Meter	115,018 USD/m
Elevated Evacuated Tube Total Cost	14.624 B USD
Elevated Evacuated Tube Total Cost Per Meter	143,299 USD/m
Capital Cost of Vacuum Pumps	0.121 B USD
Energy Cost of Initially Pulling Vacuum	1.027 M USD
System Total Capital Cost	31.807 B USD
Interior Volume of Evacuated Tubes	60,487,269 m3
Pump Down Time	23.1 days
Cost of Aeronautic Lift	1.151 B USD
Exit Airlock Pump Down Time	10.1 min
Operating Cost of Pulling Vacuum Inside Airlock	312 USD
Total Energy Cost Per Launch	35,260 USD
Total Energy Cost For All Launches	19.746 M USD
Launch Vehicle Cost	7.799 M USD
Total Capital Costs	31.928 B USD
Total Operating Costs	4.387 B USD
Total Payload Landed on Mars	9,412,167 kg
Cost Per Kg of Payload Landed on Mars	3,858 USD
Tube Liner Cost of Materials	2.590 M 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.

E. Physical Prototyping Efforts

To support the development of the VPSL architecture, we have established a phased prototyping roadmap involving a series of physical builds at progressively larger scales. Each prototype is designed to test increasingly complex aspects of the system, with the smaller-scale builds serving to identify and resolve engineering challenges before they are incorporated into the next iteration. This staged approach allows for incremental validation of critical subsystems while managing cost and technical risk.

Figure 10: Screws of the first physical prototype of the VPSL system.

We are currently developing the first and smallest-scale prototype (see Figure 10). It features a 6-foot-long guideway and is primarily focused on the synchronized driving of segmented screws. Each screw contains an internal brushless DC (BLDC) motor, and we are developing custom motor controllers to enable precise coordination. At this scale, mechanical coupling is used between the adaptive nut and the screw flights, rather than electromagnetic coupling, to simplify the design and allow for more rapid iteration. The early prototype is proving valuable in uncovering practical issues related to motor integration, such as heat dissipation through the thin screw support brackets and the cost and complexity of the drive electronics. These lessons will directly inform the design of future prototypes, where magnetically coupled drive systems (akin to linear active magnetic bearings) will be introduced to more closely replicate the intended operational configuration.

F. Linear Active Magnetic Bearings (AMBs)

The magnetic coupling system is one of the core technologies of VPSL. It is used to couple the sled and adaptive nut to the guideway and to couple the adaptive nut's grapplers to the screw flights. The term “Linear Active Magnetic Bearing” or “Linear AMB” was chosen to differentiate these coupling mechanisms from Linear Motors, which are used in other types of mass drivers such as the Electromagnetic Aircraft Launch System (EMALS) installed on modern aircraft carriers [22]. A linear active magnetic bearing (AMB), similar to its rotary counterpart, uses a combination of electromagnets, position sensors, and closed-loop control to actively maintain a non-contacting, stable gap between two objects, called a Primary and Secondary, along a linear axis. In the case of the coupling between the adaptive nut and the screw flights, the Primary is the adaptive nut's grappler pads, the Secondary is the screw flights, and the “linear axis” is technically helically shaped. Within the Primary, electromagnets are oriented in a homopolar configuration to minimize changing magnetic fields within the Secondary and thus magnetic friction. This approach, which is also widely used in flywheel energy storage systems, is covered in more depth in [19]. To reduce power consumption, permanent-magnet-biased electromagnets [23] or electropermanent magnets [24] may be considered as alternatives to the use of standard electromagnets in the Primary.

In a recent article published in Space Settlement Progress, we highlighted technologies that push the boundaries of magnetic levitation and described our initial steps toward exploring high-speed, low-friction magnetic systems – efforts that include expert consultation, preliminary design work, and plans for advanced simulation and experimental validation [25]. A significant amount of theoretical work was done on even higher speed electromagnetic levitation for energy storage in the 1980s by John R. Hull and Malvern K. Iles [26].

In the embodiment that we analyzed, these grapplers employ electromagnetic pads that magnetically interact with the screw flights, transferring kinetic energy to the sled without any physical contact. In the terminology of screws, each screw has multiple “starts” (for example, the screws shown in Figure 11 and Figure 12 have 4 starts). When grapplers engage with a screw flight, they always do so in a symmetric configuration – such as in opposing pairs or triangular arrangements – ensuring that the resulting forces are balanced. This minimizes net loads on the screw's bearings and support structures, preserving mechanical stability during operation.

This system functions similarly to a magnetic worm gear, eliminating the need for traditional linear electric motors. The design avoids the complexity of rapidly switching electromagnets, enhancing efficiency and simplifying power electronics.

In general, magnetic gearing and levitation systems can employ a range of techniques, including both active and passive control, configurations based on magnetic attraction or repulsion, and implementations using conventional electromagnetic coils as well as more advanced technologies such as high-temperature superconductors and cryogenic systems. In keeping with our design philosophy – to prioritize technologies with a proven track record in the industry, minimize system cost, and avoid reliance on scarce or specialized materials – we chose to evaluate the feasibility and cost of a configuration based on magnetic attraction using conventional electromagnets. This approach aligns with established "heritage" technologies such as, for example, active magnetic bearings (AMBs) [23] and certain electromagnetically levitated systems, including the German-developed Shanghai Maglev Train [27]. That said, we are not opposed to incorporating alternative and potentially more advanced techniques where they demonstrate clear advantages in performance, cost-effectiveness, or suitability for specific subsystems.

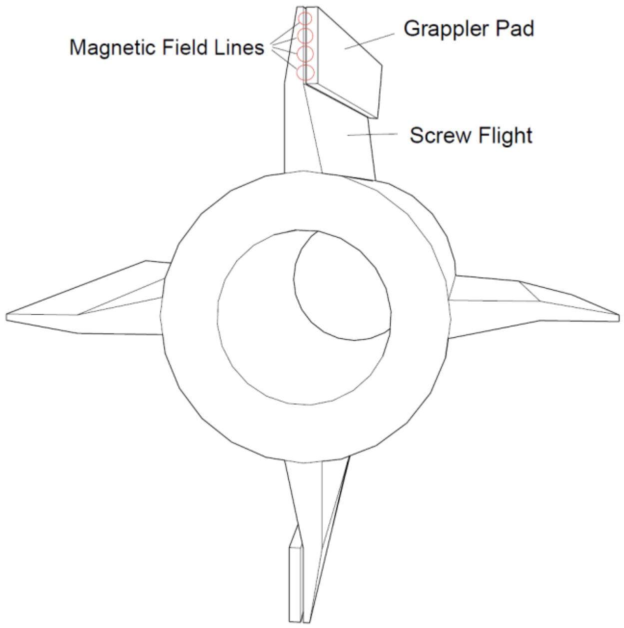

Figure 11: Illustration of screw flights (four starts) and grappler pads showing orientation of the magnetic field lines.

When a grappler pad is engaged, sensors in the grappler pads will continuously monitor the gap between the grappler pads and the screw flights, and the magnetic field strength is actively regulated to maintain a stable separation. This control system counteracts the substantial forces exerted by the grappler's actuators, which would otherwise pull the pads away from the screw flights.

When a grappler pad needs to be repositioned, the electromagnets are switched off to reduce the mechanical load on the actuators, allowing them to move more freely.

Figure 11 illustrates how magnetic field lines loop through the screw flights and grappler pads when the pad is engaged, crossing the small "air gap" (technically a vacuum gap) between them.

The grappler pads create a magnetic field that loops through the Secondaries – the ferromagnetic material of the screw flights. Any given point on the screw flights will experience a change in magnetic field strength as the sled passes by. Therefore, it is important to employ industry-standard techniques to minimize the degree to which the changing magnetic fields induce eddy currents and cause energy loss through magnetic friction. The use of magnetic shielding, such as laminates, is an example of one such commonly employed technique. Additionally, within a strip of grappler pads (see Figure 12) the individual pads can be energized to create a magnetic field that will ramp up gradually, reach a peak, and then taper off to reduce the rate of change in magnetic field strength from the perspective of a point in the screw flights. For example, if at the peak speed of 11,123 m/s, we sinusoidally ease-in and ease-out the grappler pad strip field strength over a distance of 2 meters at the start and end of each grappler pad strip, these easing functions would have a frequency of …

$$\frac{4\ m}{11123\ m/s} = 0.00036\ s$$

If we use the Steinmetz equation

$$P_t = C_m B_m^{\alpha} f^{\beta} \tag{16}$$

With parameters for 3% Si electrical steel obtained from [28] where the exponent α of flux density is set to 1.71, the exponent β of frequency is set to 1.36, and the material constant C_m is set to $7.3 \times 10^{-3}\ W/kg$, and if we assume a peak magnetic field strength of 1.52 Tesla, a frequency of one over 0.00036 s, then we arrive at a value P_t of 772 W/kg in the parts of the screw flights parts that are interacting with grappler pad strips where easing is occurring. However, electrical steel has low yield stress compared to what is needed for this application. A more accurate analysis would require Steinmetz parameters for a material that strikes a better trade-off between being having high yield strength and being magnetically optimized. If we assume a material with poor magnetic properties (e.g. α=2.1 and β=3.0), then P_t would peak at 0.3 GW/kg. To put this in perspective, the launch sled gains energy through momentum transfer at a peak rate of 34 GW. Significant energy savings are clearly possible through optimizing the tradeoff between high mechanical strength and good magnetic properties in the tips of the screw flights. This is an aspect of the design where further study is needed.

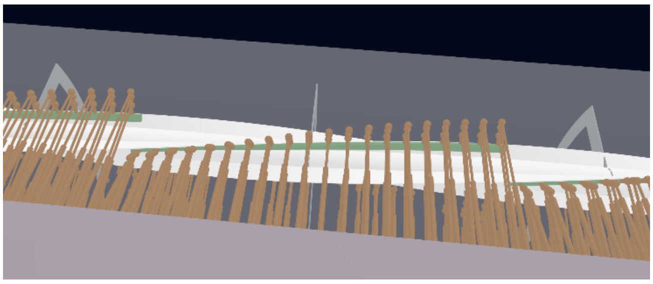

Figure 12: A strip of grappler pads coupling with a screw flight as seen from a camera mounted on top of the adaptive nut.

While the screw's flight tips (the secondaries) are made from steel with both strength and good magnetic properties, the rest of the screw should be made from steel with good mechanical properties relative to its cost - for instance, A514 (T-1 high-strength) with a yield strength of 690 MPa. By metallurgically bonding these two steels, it should be possible to enhance the magnetic properties at the screw flight tips where there is less stress (see Figure 13) while maximizing structural strength towards the center.

Figure 13 shows the results of a simple stress simulation for a muzzle-end screw segment with eight starts (sets of flights). The simulation estimates the maximum tip speed given a set of input parameters. In this case an engineering factor of 1.5 was applied. The inner radius is 0.15 m and the radius to the tips of the screw flights is 0.5 m. The theoretical maximum tip speed is estimated to be 530 m/s.

Applying an engineering factor of 1.25 raises the maximum to 581 m/s, and reducing the factor to 1.0 increases it further to 649 m/s. With stronger but more expensive steels such as Maraging steel, our simulations suggest that tip speeds in the range of 1000 m/s should be possible, although such materials would add considerably to the cost. Naturally, after detailed cost and performance trade studies, the tip speeds in an optimized design could end up being lower. However, the purpose of this simulation was to provide a back-of-the-envelope preliminary estimate of what tip speeds might be achievable in theory.

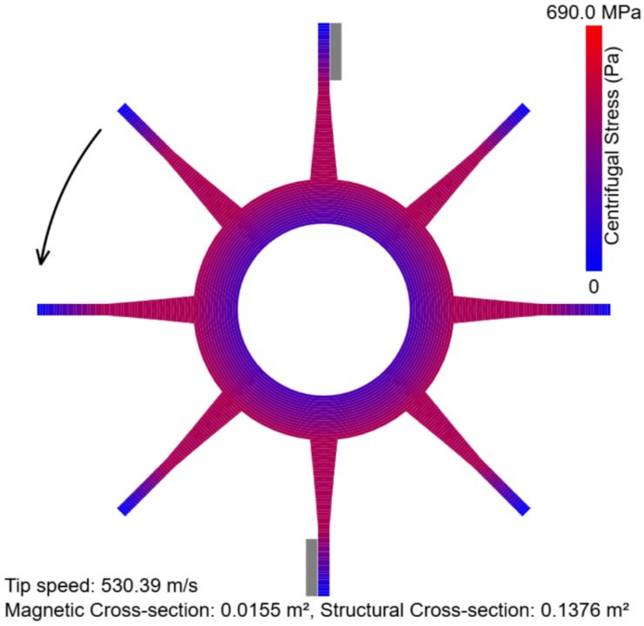

Figure 13: Fast 2D Stress simulation in a screw with eight starts.

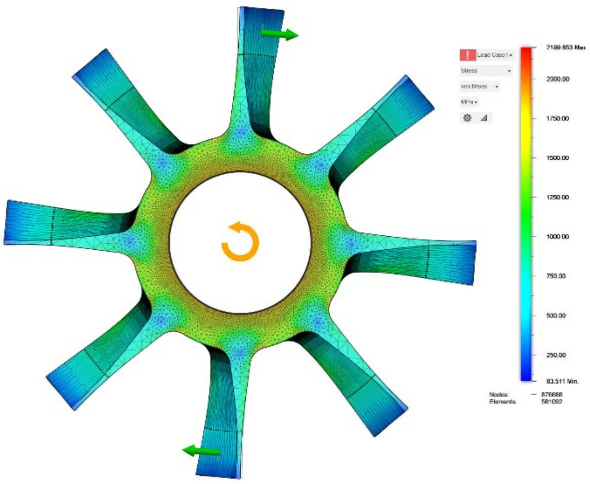

Figure 14: Fusion360 Stress simulation of screw with centrifugal and lateral loads.

We also investigated how the load from the grapplers coupling with the screw flight tips would create stresses within the screw flights (see Figure 14). We observed that significant deflection occurred, which can in theory be compensated for through grappler pad placement, by activating the clutches in the flywheels is a manner that will advance the screw flights by an angle designed to counter the deflection angle, or a combination of both. We also confirmed that the additional lateral loads fall well within the stress limits of the design. Figure 15 shows the lateral load-induced stresses only, and reveals that these stresses (up to 161 MPa) are small compared to the stresses caused by centrifugal forces (~1500 MPa).

Our investigation revealed that the centrifugal loads cause some deformation in the shape of the screw to occur between the rest state and the operational state of the screw. More design work is planned to ensure that the screws geometry is within design tolerances when in operation.

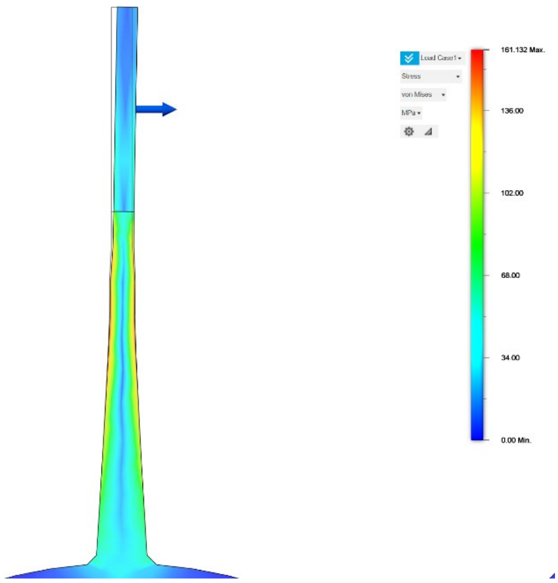

Figure 15: Stress on a screw flight in the absence of centrifugal forces.

G. Grappler Actuation and Control

A central challenge in the design of the VPSL system lies in the precise positioning and dynamic control of the grappler pads relative to the screw flights. These grapplers must operate with high precision to maintain the small vacuum gap required for efficient magnetic coupling, while also adapting to the helical geometry of the screw.

While we have not yet constructed a full-scale physical prototype of the grappler assembly, we have taken important steps toward de-risking the design and validating its feasibility. Our current validation approach is based on a high-fidelity digital twin that incorporates the kinematics and control logic of the grappler system. This environment has allowed us to simulate actuator motion, analyze mechanical clearance tolerances, and assess control behavior under various operating conditions. Although this represents a form of virtual prototyping rather than traditional experimental testing, it provides a critical foundation for early-stage feasibility assessment.

The dynamic behavior of the grappler system is illustrated in the supplementary video submitted with this article. In the video, grapplers are colored red when they are switched on and green when switched off. To enhance clarity, the playback speed has been reduced to half of real time, and timestamps were added during encoding to facilitate reference to specific events. Only acceleration using the variable pitch screws is shown. The purpose of the video is to demonstrate the basic mechatronic feasibility of the system; further work is ongoing to refine and optimize the motion control algorithms, improve the grappler actuator and pad design, and model additional screws for adaptive nut deceleration.

The simulation also demonstrates how VPSL circumvents one of the major cost and complexity barriers associated with coil gun systems – namely, the need for rapid, high-frequency electromagnetic switching. In VPSL, switching frequency is below 1 Hz as switching occurs only when grapplers are repositioned, rather than continuously along the launch path, significantly reducing the demands on power electronics and helping to resolve one of the scalability bottlenecks associated with high-speed electromagnetic propulsion systems.

Although electromagnetic switching occurs only during grappler repositioning, the system must also support occasional rapid adjustments in magnetic field strength during engagement to maintain the desired separation between the grappler pads and the screw flights. As such, the electromagnetic design must balance inductance and current-handling capability to allow both stable holding force and responsive control bandwidth.

Our simulations indicate that, during engagement with the screw flights, grappler pads undergo only gradual movement to remain synchronized with the helical geometry – motion that falls well within the performance envelope of commercially available actuators. In contrast, when disengaged, grapplers must reposition quickly to minimize downtime. We observed that the actuation challenge becomes progressively easier as the launch train accelerates, since higher velocities reduce both the repositioning frequency and required motion amplitudes.

This observation has led to a refined control strategy in which only a subset of grapplers – those near the midpoint of the adaptive nut – are active during the initial phase of acceleration. As the launch train gains speed and actuator demands decrease, additional grapplers are progressively brought online, with full engagement occurring relatively early in the launch sequence. This staged engagement strategy helps manage early-stage control complexity.

We also concluded that increasing the number of screw starts (the number of independent helical threads engaged by the grapplers) as the launch train accelerates is preferable to maintaining a constant number throughout the acceleration section. This reduces motion congestion at the start of the launch and lowers the required grappler stroke range at higher speeds, making precise control easier.

H. Capital Costs

1) Submerged Floating Tube

This component resembles the submerged floating tube depicted in Figure 16 where steel tension anchors secured to the sea floor hold a buoyant concrete tube a few tens of meters below the water’s surface.

Figure 16:Rendering of a floating tube bridge proposed for crossing Sulafjorden (a fjord) as part of Norway’s E39 coastal highway project.

The VPSL’s submerged floating tube is a single reinforced concrete tube 773 km long by 10 m in diameter with an interior volume of 60,790,000 m^3 and a surface area of approximately 24,320,000 m^2. Comparable civil engineering projects include: a) the Fehmarn Belt Fixed Link which is an immersed tube tunnel is 10 m high by 41.2 m wide by 17,600 m in length with an interior volume of 7,251,200 m3, and b) the cumulative surface area of wind turbine towers worldwide, which is estimated to exceed 120,000,000 m^2 across hundreds of thousands of turbines (for example, a single turbine with a 100 m tall steel tower and a 4 m diameter has a surface area of approximately 1,256 m^2), so producing the submerged tube is a project on the scale of producing just the masts for 20% of the world’s wind turbines.

The concrete tube forms the structural shell of an underwater tunnel. Inside it, a slightly smaller ribbed steel tube maintains the vacuum environment required for operation.

2) Ramp - Civil Engineering

Creating a relatively straight but gradually skyward-curving corridor through mountainous terrain will require a mix of civil engineering techniques tailored to the specific challenges of the terrain, including steep slopes, valleys, ridges, and rock formations. Below-grade techniques include trenching, deep cuttings, and tunneling. Above-grade techniques include earthworks, viaducts, and bridging. There are specialized tools designed to optimize the route and estimate the preconstruction cost and environmental impact of constructing a transportation corridor, such as roads or railways, based on a defined path. These include ArcGIS Pro by Esri, CostOS by Nomitech, Softree Optimal by Softree Technical Systems, ConWize by ConWize Ltd., and GEstimator by Manu Varkey. These tools combine geological, hydrological, and geotechnical data from geological surveys, soil surveys, and hazard maps to do comprehensive feasibility studies for infrastructure projects, such as optimizing routes for railways, roads, or pipelines.

For this implementation, we assumed the entire ramp would be within a tunnel. The cost of constructing tunnels is heavily influenced by their diameter, with a general scaling relationship based on tunnel radius. According to data from the study “*Cost Overruns in Tunnelling Projects…”*[29], Figure 4a, the estimated cost for tunneling is approximately £60 million per kilometer for an 18-meter diameter tunnel. Converting this to US dollars at an exchange rate of £1 = $1.31, the cost per meter for a tunnel is calculated as:

$$Cost_{USDperMeter} = d_{Tunnel} \times \frac{60{,}000}{18} \times 1.31 \qquad (17)$$

3) Evacuated Tube

The evacuated tube was assumed to be constructed by spiral welding stainless steel, the same technique that was used to create the evacuated tubes used for the LIGO observatories, and a technique that has been used to make towers for wind turbines. The technical viability of the spiral welding technique for maintaining long vacuum in stainless steel tubes has been well-established by the work at the LIGO observatories. Each observatory has 8 km of evacuated beam tubes. They have been able to maintain the vacuum inside these tubes at one trillionth of an atmosphere for almost 25 years, according to Dr. Michael Landry, Head of the LIGO Hanford Observatory.

4) Elevated Portion of Evacuated Tube

The Elevated Evacuated Tube is designed to hold a vacuum while being supported in the atmosphere. Airliner fuselages are also designed to support about 1 psi (6895 Pa) of negative pressure, albeit with a number of additional structural requirements that make airliner fuselages more complicated. The evacuated tube will be required to support a negative pressure equal to the ambient pressure at its altitude, as its interior will be pumped down to an estimated 5 Pa. For this implementation, we assumed that the cost-per-meter of elevated evacuated tube would be similar to the cost-per-meter of airliner fuselages.

a) Cost Estimation Using Aerospace Manufacturing Data:

The cost of manufacturing the elevated evacuated tube can be roughly estimated using data from Spirit AeroSystems, a leading aerospace manufacturer. In 2023, Spirit AeroSystems produced 1,418 airplane fuselages for Boeing and Airbus, totaling over 52,000 meters of fuselage. With a net revenue of $6 billion for that period, the cost of producing a meter of fuselage is approximately $115,000.

Extrapolating this to a 122-km aeronautically supported tube gives a projected upper-bound cost of approximately $14 billion. While aircraft fuselages are significantly more complex than a bare evacuated tube, this serves as a reasonable upper-bound estimate for budgeting.

a) Aeronautic Support for the Tube

A variety of techniques for supporting an elevated evacuated tube have been discussed in the literature, but for this implementation, we will assume it is supported aeronautically using electrically powered fans, which also provide station-keeping through gimbaled thrust mechanisms. These fans are powered directly by electricity supplied from the ground, eliminating the need for onboard batteries and reducing operational costs.

Heritage technologies for lift and control include helicopters, electric vertical take-off and landing (eVTOL) aircraft, and multirotor drones. Among these, agricultural drones offer one of the best cost efficiencies.

Payload mass is calculated by subtracting dry mass (not including batteries) from maximum takeoff mass. An XAGV40, which has a maximum takeoff mass of 44 kg, a dry mass of 20 kg, and costs $5000, has a payload mass of 24 kg and an estimated cost-per-kg-lifted of $208.

Based on these considerations, the elevated evacuated tube is estimated to cost 16.6 billion.

5) Airlocks

There are airlocks at both ends of the evacuated tube. The first airlock is engineered to be just large enough to accommodate the vehicle and the adaptive nut. The second airlock is engineered to accommodate the vehicle exiting the system at high speed. Therefore, the second airlock is much longer and includes a door that closes quickly behind the departing vehicle, a burst disk at the end of the tube that the spacecraft breaks through, and a mechanism that installs a new burst disk after every launch. Airlock capital cost was excluded from the estimate due to its minimal expected impact on overall system cost. However, airlock operational costs were modeled.

6) Maglev Track

The maglev track for the Variable Pitch Screw Launcher (VPSL) is a T-shaped passive guideway designed for simplicity and cost-efficiency. It contains no active electromagnetic components, as all levitation and control systems are housed in the launch sled and the adaptive nut. Both components glide along the track using electromagnetic suspension (interacting directly with the ferromagnetic guideway) or electrodynamic suspension (interacting with passive conductive elements embedded in the guideway).

This design minimizes the per-meter cost of the track, as it consists primarily of structural materials like steel or reinforced concrete and embedded conductive strips. By concentrating active systems in the sled and adaptive nut, the track remains low-cost, easy to maintain, and scalable for long lengths.

7) Mass Driver

The mass driver component of the VPSL system includes screws, motors to drive the screws, brackets and magnetic bearings to support the screws, flywheels and flywheel brakes. For this analysis, we assumed that there are two mass drivers: one that accelerates the adaptive nut, launch sled, and vehicle, and a second that decelerates only the adaptive nut to bring it to a stop before it reaches the elevated evacuated tube section, and which also recovers some of its kinetic energy.

8) Adaptive Nut and Launch Sled

The adaptive nut (see Figure 8) is a moving component of the Variable Pitch Screw Launcher (VPSL) that travels along the maglev track. Its primary function is to push the sled, which carries the launch vehicle, down the track. The adaptive nut uses a system of actuators, referred to as “grapplers,” which engage with the screw flights to achieve acceleration. These were covered in more detail in an earlier section.

At the end of the mass driver section, where the ramp begins, the adaptive nut disengages from the sled. It decelerates on the ramp using a second set of screws designed specifically for this purpose, recovering its kinetic energy during the process. Meanwhile, the sled and launch vehicle continue to coast up the ramp at high speed. After coming to a complete stop, the adaptive nut can either be set aside for another launch or returned to the starting point for reuse.

The launch sled itself is a lightweight component that detaches from the vehicle after entering the elevated evacuated tube. It comes to a stop within the tube by braking against the track while the vehicle continues on its ballistic trajectory within the evacuated environment.

The costs of the adaptive nut and launch sled were excluded from this analysis, as preliminary back-of-the-envelope estimates indicated that their contribution would be negligible relative to the overall system cost.

9) Initial Evacuation of the Tube

The process of creating a vacuum in the evacuated tubes is a critical step in preparing the Variable Pitch Screw Launcher (VPSL) for operation. This involves removing air from the large interior volume of the system using high-performance vacuum pumps. Below is an overview of the process and associated costs:

1. Vacuum Pump Specifications:
   - Each vacuum pump has a power rating of 3.7 kW and a pumping speed of 108 m^3/h.
   - The ultimate achievable pressure for each pump is 0.375 Pa.

- The unit cost of a vacuum pump is approximately USD 12,129.

2. Interior Volume:
   The total interior volume of the evacuated tubes, including the mass driver tube, ramp tube, and elevated evacuated tube, is estimated to be 61,642,250 m³.

3. Pumping Duration:
   With 10,000 vacuum pumps in operation, the time required to achieve the target interior pressure is approximately 36 days, based on the relationship:

$$t_{pump} = \frac{V}{S} \ln\left(\frac{P_{Outside}}{P_{Inside}}\right) \quad (18)$$

   Where 'V' is the volume of the tubes, 'S' is the total pumping speed, and '$P_{Outside}$' and 'P_{Inside}' are the initial and final pressures, respectively.

The total capital cost for 10,000 vacuum pumps is USD 121 million, and the cost of operating them to pull the initial vacuum is estimated at USD 1 million, assuming wholesale electricity costs and the system's power requirements. The $1 million cost will also need to be paid if the system needs to be unsealed for maintenance or if the tube is punctured, necessitating repair.

10) Electricity Grid Upgrades

Upgrades to the electric grid may be required, depending on the location of the system. However, given the system's projected 20+ year operational lifespan, it is assumed that the cost of these upgrades would be amortized and effectively covered through the ongoing cost of electricity purchased for the system.

11) Summary of Capital Costs

Table 4 provides a summary of the main drivers of the system's capital cost.

Table 4: Summary of capital costs

Item	Capital Cost (billions USD)
Vacuum Pumps	0.121
Mass Driver	12.067
Ramp	4.511
Elevated Tube Cost	13.334
Aeronautic Lifters Cost	3.279
Total	33.312

12) Powering the Launcher

While each launch requires significant energy to accelerate the launch train to the required exit velocity, the energy demand is offset, in part, by regenerative braking applied to the adaptive nut during deceleration. Below are key considerations:

1. Energy Requirements:

The kinetic energy required per launch is calculated as:

$$E_{kinetic} = \frac{1}{2} m_a v^2 \quad (19)$$

…where 'm_a' is the accelerated mass, or the mass of the launch train - that is, the combined mass of the launch vehicle, payload, propellant, adaptive nut, and launch sled, and 'v' is the velocity at the end of the acceleration section.

The regenerative braking system recovers a portion of this energy from the adaptive nut during deceleration.

$$E_{recovered} = \frac{1}{2} m_{an} v^2 \quad (20)$$

…where 'm_{an}' is the mass of just the adaptive nut, and 'v' is the velocity at the end of the acceleration section.

2. Energy Consumption per Launch:

Similar to the acceleration screws and flywheels, the deceleration screws and flywheels transfer momentum. The adaptive nut's momentum is used to speed up flywheels inside the deceleration screws. Between launches, these flywheels are slowed down again with generators to produce electricity that is then used to speed up the flywheels inside the acceleration screws.

The total energy consumed for each launch accounts for the efficiency of the acceleration and deceleration systems:

$$E_{total} = \frac{E_{kinetic}}{\eta_{acceleration}} - E_{recovered} \cdot \eta_{deceleration} \quad (21)$$

…where '$\eta_{acceleration}$' and '$\eta_{deceleration}$' are the efficiencies of the respective systems, which we estimated to be 0.8.

For a typical launch, the mass driving energy requirement is approximately 2.52×10^{12} joules (2.52 TJ), corresponding to an energy cost of USD 34,948 per launch. If we assume 40 minutes between launches, then the power requirement to "recharge" the screws will be 2.52 TJ/2400s = 1.05 GW. At 0.05 USD/kWh, the energy cost is USD 35,000.

13) Powering the Elevated Evacuated Tube's Lift Fans

The elevated evacuated tube system requires aeronautic lift to counteract the force of gravity and maintain the tube's position. The cost of generating this lift is determined by the force of gravity acting on the tube, the duration of the Mars transfer window, and the specific cost (cost-per-kg lifted) of aeronautic lift.

The Mars transfer season duration is assumed to be 14 days, or 14·24·3600=1,209,600 seconds. For each season, the cost of aeronautic lift is:

$$Cost_{season} = F_{lift} \cdot t_{season} \cdot CostPerN/s \quad (22)$$

where the cost of generating lift aeronautically is 7×10^{-7} USD/N/s [19]. The cost per launch season works out to be 0.131B USD. However, this cost could be reduced significantly if, during the launch season, the elevated evacuated tube was stowed between launch windows.

The power draw of the lift fans is estimated to be significant at 6.849 GW. A high-voltage DC cable will carry this power from a power plant on the ground to the lift fans.

14) Cycling the Airlocks

Both airlocks need to be pumped down to a vacuum before each launch. The second airlock is much longer than the first, but it is also located at a higher altitude where the atmosphere is thinner. The energy cost to cycle the airlocks was calculated to be 1,081 USD per launch.

15) Engaging the Clutches

During a launch, electromagnetic clutches activate to transfer momentum from and to the flywheels. We surveyed a number of commercially available electromagnetic clutches to determine that they typically require roughly 1 W of power per Nm of torque generated. The peak torque on the acceleration screws, which occurs when the launch train is at the end of the acceleration section, is 3,034 Nm per millimeter of screw. As the adaptive nut is estimated to be 74 m in length, the peak power used by the clutches of both screws is estimated at 0.121 GW.

To put the 3,034 Nm per millimeter of screw value in perspective, if a mountain bike's front disk break were able to achieve this level of torque, it would be able to decelerate a 100 kg rider (including bike) at 10 Gs. This is an aspect of the design where additional mechanical engineering work should be done to further derisk the architecture.

16) Powering the Grappler Pads

The grappler pads experience a peak force near the end of the acceleration section of 54.6 MN, or 184 N/cm^2. Let's assume that the grappler pads are basic electromagnets (that is, no superconductors and no permanent magnet biasing). A sampling of commercially available maglocks (typically 12 or 24 volts) shows that the power required to generate a holding force is on the order of 1.25 mW/N. Using this power-force relationship, we can estimate that the grappler power consumption will peak near the end of the acceleration section at 69 kW. However, this estimate will be optimistic because maglocks typically do not have an air gap, whereas the grappler pads will. The exact value in practice will depend on how small an air gap is achievable. More engineering work will be required to establish that accurately. However, our initial rough estimate of the power required for the grappler pads shows it to be many orders of magnitude less than other components of the system.

The energy needed to power the grappler pads through the acceleration and deceleration phases is estimated to be on the order of 1.5 kWh. For reference, the capacity of an electric car battery ranges from 40 to 120 kWh.

17) Summary of Power Requirements

Table 5 summarized the power requirements of several of the VPSL sub-systems. While these values should be considered early estimates, they should help others to determine where additional R&D work would likely have the most impact.

Table 5: Power requirements of VPSL Sub-systems

VPSL Sub-System	Power Draw (GW)
Screws and Flywheels	1.05
EET Lift Fans	6.85
Airlock Pumps	0.037
Electromagnetic Clutches	0.121
Grappler Pads	0.000069

18) Launched Vehicles

Where a typical spacecraft has many complex systems that must operate close to their failure point with minimal redundancy to save weight, a spacecraft launched by a mass driver can be engineered far more conservatively. The primary reason for this is that the per-kg cost of accelerating the spacecraft is low because the system costs are almost entirely made up of fixed costs and operational costs that are not significantly affected by spacecraft mass. In addition, there is some benefit to adding extra mass to a mass-driver-launched spacecraft. The extra mass can help to ensure that: a) the spacecraft will withstand the dynamic pressure at the speed and altitude at which it exits the elevated evacuated tube, b) the spacecraft will not decelerate too quickly should its rocket engine fail to light when it exits the elevated evacuated tube, c) crews will be adequately shielded from space radiation during their long journey between planets, and d) upon arrival there will ample feedstock for manufacturing structures and equipment in-situ.

The vehicle needs Environmental Control and Life Support (ECLS), communication, navigation, and power generation systems. It needs at least one rocket engine that is used to: a) counter aerodynamic drag as the vehicle exits the Earth's atmosphere, b) course correct during the interplanetary journey, and c) decelerate the spacecraft at the final stage of Entry, Descent, and Landing (EDL).

The spacecraft also needs a long, narrow, and regeneratively cooled nosecone that is designed to minimize aerodynamic drag as the vehicle exits the elevated evacuated tube and travels upward through the residual atmosphere.

For this implementation, the cost of each launch vehicle was roughly estimated to be $7.8 million USD; however, this should be considered a placeholder value until a more accurate estimate can be made.

19) Summary of Operating Costs

Table 6 provides a summary of the main drivers of the system's operating cost. These costs are for the entire program lifetime of 10 Mars transfer windows with 56 launches per window.

Table 6: Summary of Operating Costs

Item	Operating Cost (billions USD)
Power for Mass Driver	0.014
Power for Lift Fans	1.307
Launch Vehicles	4.37
Total	5.691

20) Cost-Per-Kilogram Versus Delta-V

Each vehicle's mass at launch is 27,940 kg, and it can place 17,140 kg on the surface of Mars. The effective payload could be higher if cannibalizing the vehicle to create feedstock for manufacturing other equipment were factored in. By dividing the capital and operating costs by the total payload delivered to Mars, the fully considered cost per kilogram is calculated to be USD 3,858, assuming an airspeed of 11,123 m/s at the launcher's exit.

Using the cost model within the digital twin, we varied the airspeed and accounted for differences in aerodynamic and gravity drag between mass drivers and rockets to produce the cost curve (dark blue) shown in (Figure 17) for the variable pitch screw mass driver. The estimated "equivalent delta-v" required to land on the surface of Mars is 16,616 m/s. Equivalent delta-v is a measure of how much delta-v a rocket-based system would need for the mission. It accounts for the mass allocated to entry, descent, and landing (EDL) systems to level the playing field when comparing missions to airless moons versus planets with atmospheres (see [18] for a more complete definition of equivalent delta-v). The curve fit to the empirical data from Figure 4 suggests that a state-of-the-art rocket-based launch and EDL system would result in a cost of nearly $5 million per kilogram delivered to the Martian surface. However, this estimate is highly sensitive to how the overall program cost of past programs, such as Mars 2020, is allocated between payload and transportation-related expenses.

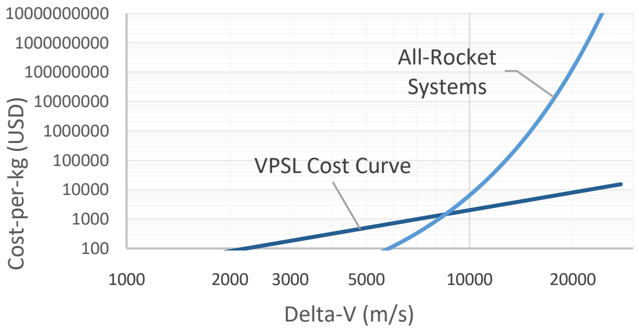

Figure 17: Cost curve for Variable Pitch Screw Launcher (dark blue) versus empirical curve fit for all-rocket systems (light blue).

Nonetheless, even under less conservative assumptions, the VPSL system still achieves a cost-per-kilogram to Mars roughly three orders of magnitude lower than that of chemical rocket-based systems. Given that decades of development have already established the limited rate at which incremental improvements will reduce the cost of chemical rocket-based launch, this comparison underscores the potentially transformative gains that may be achieved by breaking with legacy paradigms and adopting an infrastructure-based approach to launch.

21) Discussion

The cost section illustrates how we calculated the cost of launching payloads to Mars using a variable pitch screw mass driver. The actual calculations are implemented in code, which is more detailed than the summary presented here. That code is available online (see [20]), though it may evolve over time and may not remain in strict sync with this article.

The real challenge in presenting a cost estimate for a novel system isn't just performing the analysis – it's getting people to engage with it seriously and critique it on its actual merits. In practice, it's far easier to dismiss new estimates by leaning on a widely held belief: that large, complex engineering projects routinely run over budget and under-deliver. This skepticism, while not unfounded, often stems from highly visible failures that attract media attention and reinforce public distrust in cost projections – even when those failures result from management decisions rather than flaws in the original technical analysis.

We've made every effort to ground our estimates in well-established numbers derived from heritage technologies and analogous infrastructure projects. However, we recognize that any complex cost analysis – especially for an unfamiliar concept – can be difficult to distinguish from past efforts that ultimately proved too optimistic.

Professionals who assess cost estimates for accuracy typically look for a combination of factors, including:

- Clear lineage to historical costs and benchmarks
- Sensitivity analysis that explores key cost drivers
- Transparency in assumptions and scope boundaries
- Scalability and lifecycle modeling
- Risk identification and contingency planning

We encourage readers to examine not only the assumptions we've made but also the methodology and structure of the model itself. The goal is not to suggest that our estimate represents the final word on the capital cost of VPSL infrastructure, nor to deny the possibility of cost overruns occurring once construction begins. Rather, we aim to establish a conservative, transparent, and fact-checkable baseline – one that can serve as a starting point for more in-depth analysis and informed discussion. As the field develops, innovations may emerge that reduce costs relative to this baseline. Thus, our baseline can serve as a benchmark that will allow contributors to demonstrate how their innovations lead to tangible improvements. Conversely, others may identify additional cost elements that we have overlooked or underestimated. Over time, this process of iterative refinement can help build broader confidence in the model's estimates and predictive value.

We also hope to see other engineers with relevant expertise independently develop their own cost estimates for this architecture or similar architectures and compare them to ours. We fully expect discrepancies – differences in assumptions, modeling choices, and interpretation are inevitable – but through comparison across multiple estimates, we aim to demonstrate that our methodology is not prone to systemic underestimation. Over time, we hope this process will establish that our approach yields results that are accurate to within 10–20% rather than being optimistic by, for example, an order of magnitude or more.

I. Sustainability

Beyond being cost-effective, the Variable-Pitch Screw Launcher (VPSL) offers a sustainable alternative to all-rocket systems by largely eliminating reliance on resource-intensive and environmentally harmful chemical propellants. Its design allows for energy-efficient operations through regenerative braking and renewable energy sources can power it – even somewhat intermittent sources thanks to its spinning screws which behave somewhat like a spinning reserve. These factors combine to make the VPSL a scalable, reusable, and environmentally conscious solution for future space exploration.

J. Environmental Impact

The Variable Pitch Screw Launcher (VPSL) architecture includes both underwater and underground components, and while these features are intended to minimize environmental interference during operation, it is important to also address potential impacts during construction and over the system's lifecycle.

Marine Construction:

The underwater portion of the system will not be assembled in situ but rather fabricated on land in a controlled factory environment and then gradually extended into the ocean. This "extrusion" process limits construction-related disturbances in the marine environment. The system will be stabilized using tensioned mooring lines anchored to the seafloor. These moorings have a minimal ecological footprint and are designed to avoid significant disruption of benthic habitats, much like established practices in offshore renewable energy infrastructure.

Operational Noise and Mechanical Disturbance:

During operation, the VPSL system is designed to be exceptionally quiet. The spinning screws are mounted on magnetic bearings and operate within a vacuum-sealed enclosure, eliminating air friction and mechanical contact that might otherwise generate noise. Likewise, the adaptive nut and launch sled are magnetically levitated and guided, so there is no physical interaction with the rails or screw flights. Although these components travel at very high speeds, their motion does not produce acoustic disturbances, frictional heating, or mechanical wear, making the system effectively silent and low-maintenance under normal operating conditions.

Electromagnetic Containment:

All magnetic fields used in the propulsion, guidance, and coupling systems are contained within electrical machines or structural elements. As with conventional electric motors, magnetic fields are strong but highly localized. There is no significant external electromagnetic radiation expected from the system during operation, and shielding designs follow well-established practices to ensure safety and environmental compatibility.

Geological Considerations:

The ramp section of the VPSL requires tunneling into the Earth, which is a standard civil engineering practice. Geological surveys and appropriate tunneling methods will be employed to ensure that the process avoids unstable formations and minimizes impact on surrounding geological structures. Tunnel construction risks are well understood and can be managed with existing technologies and regulatory safeguards.

In summary, the VPSL is designed to minimize both construction and operational environmental impact. While any large infrastructure project demands careful planning and monitoring, the technologies employed here are inherently low-emission, low-disturbance, and based on engineering principles that have been successfully applied in other environmentally sensitive contexts.

K. Public Feedback and Critiques

On May 23, 2024, the concept of a Variable Pitch Screw Launcher (VPSL) was presented at the International Space Development Conference and later shared publicly via YouTube, where it received over 125,000 views and a large volume of viewer feedback. To analyze this feedback, we used ChatGPT-4o to extract and summarize recurring themes of concern – categorized under “Concern,” “Key Challenges,” and “Representative Quote” – to which we provide a structured “Response.”

While the article itself establishes technical feasibility and cost estimates using appropriate engineering and cost modeling techniques, we recognize that these analyses – though rigorous – may not be accessible or persuasive to readers unfamiliar with infrastructure-based launch systems. Public skepticism often stems from deeply held assumptions about what launch technologies “should” look like, shaped by decades of dominance by chemical rockets. Rather than dismissing these concerns, we view them as important perspectives that deserve thoughtful responses. Addressing these critiques head-on is part of our broader effort to improve the clarity, accessibility, and credibility of emerging launch concepts like VPSL, especially when the full technical detail may be overlooked due to length or complexity. The concerns viewers shared were:

1) Vacuum Tube Challenges:

Concern: Many commenters doubted the practicality of building and maintaining a vacuum tube long enough for the Variable Pitch Screw Launcher (VPSL). They compared it to Elon Musk’s Hyperloop, suggesting similar challenges such as vacuum integrity, construction costs, and operation under dynamic conditions.

Key Challenges:

- Creating a vacuum tube spanning multiple miles.
- Designing fast-acting doors that can maintain vacuum integrity while allowing objects to exit.

Representative Quote: "This seems like another Hyperloop-style idea, where the vacuum tube is a cost and engineering nightmare waiting to happen."

Response: The Hyperloop concept is faced with several challenges. It needs to be close to populated areas to be close to customers, and it needs to compete with other forms of transportation, which are relatively economical when compared with rockets that are designed to transport people to Mars. Hyperloops need to be designed to let potentially millions of people enter and exit the system every day. So, when people suggest that it could be costly or challenging to maintain a vacuum within an evacuated tube transport system, they may have a point.

There are significant differences between the evacuated tubes in the VPSL system and the evacuated tubes in a Hyperloop-style transit system. The VPSL tubes can be manufactured in a controlled factory environment using a continuous spiral welding technique, inspected, and then gradually extended into the ocean or up into the ramp tunnel. Because there’s no need to transport and then weld tunnel segments in the field, this method makes it easier to achieve reliable, leak-free joints. As mentioned earlier, the LIGO beam tubes, which are made out of spiral-welded stainless steel [30] (see Figure 18), have maintained a vacuum of 1 trillionth of an atmosphere for over 25 years. As much of the system is under the ocean, underground, or elevated at a high altitude, it is less likely to be accidentally or maliciously punctured by, for example, a stray bullet.

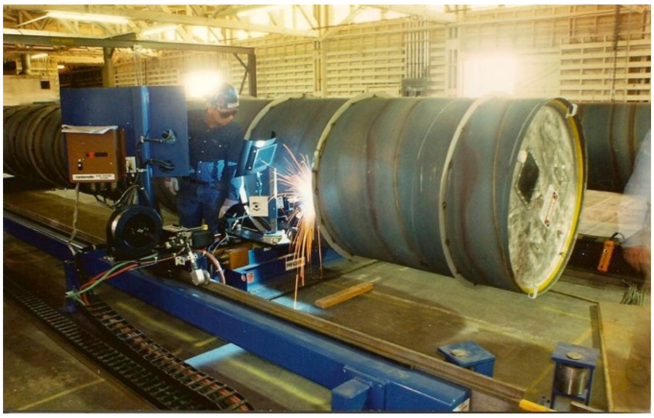

Figure 18: A segment of LIGO’s beam tube being assembled. Support rings are welded to the spiral-welded tube to increase the structural integrity of the 3 mm thick steel. (Credit: Caltech/MIT/LIGO Lab)

Vehicles are expected to enter and exit the system through the airlocks only about 560 times over the entire operational life of the launcher, and the system requires just two sets of doors. As a result, the cost of engineering and maintaining these doors to ensure vacuum integrity will represent only a tiny fraction of the system's total cost. Unlike proposals such as Hyperloop – where some have raised concerns that the operational challenges of maintaining airlock seal reliability under repeated use may have been underestimated – this aspect of the VPSL architecture is unlikely to pose a significant challenge to the system's overall economic viability.

Thermal expansion should not pose a significant problem because the vacuum tubes are either in a relatively stable thermal environment – either submerged in the ocean or inside a tunnel – or because the section of the tube is free floating – which is the case for the section in the ocean and the elevated evacuated tube. The section inside the ramp tunnel can employ metal bellows expansion joints to prevent the buildup of stress (see Figure 19).

Figure 19: Metal bellows expansion joint and reinforcement ribs on display at the LIGO facility in Washington.

While constructing nearly 1,000 kilometers of tubing may seem daunting, it is well within the capabilities of existing manufacturing facilities, such as those producing wind turbine towers. For instance, the United States has a domestic wind turbine tower manufacturing capacity of approximately 11 gigawatts per year, with each tower typically measuring around 100 meters in height. This translates to the production of roughly 1,100 kilometers of tower sections annually. Therefore, leveraging similar manufacturing processes and capacities, producing the required tubing length is a feasible endeavor.

2) Material Requirements:

Concern: Commenters expressed skepticism about the materials required for the VPSL, particularly in achieving high strength, heat resistance, and electromagnetic properties while remaining cost-effective.

Key Challenges:

- The structural materials for the tube and screws may need to withstand high speeds, heat, and magnetic forces, which could require novel or experimental materials.
- Availability of such materials in the required quantities is uncertain.

Representative Quote: "What materials are supposed to handle these speeds, forces, and temperatures? Are they even real?"

Response: The variable pitch screw launcher is primarily made out of steel. The elevated evacuated tube portion will be made out of aero-grade aluminum. The submerged floating tube would be made from steel-reinforced concrete. The materials used are well-understood and widely utilized, with conservative engineering factors applied compared to those required for rocket systems. Consequently, the system is intentionally designed to avoid exposing materials to elevated mechanical stresses or thermal loads, thereby ensuring low rates of wear and metal fatigue over time.

3) Eddy Current Issues:

Concern: Some commenters noted that the interaction between the spinning screws and electromagnetic systems might generate eddy currents, leading to energy losses and heat buildup. This could compromise the system's efficiency and safety.

Key Challenges:

- Designing a system that minimizes energy losses due to eddy currents.
- Mitigating thermal effects from electromagnetic interactions.

Representative Quote: "The eddy currents alone would probably make this an energy sink, not a launcher."

Response: Some of the components will be required to travel through magnetic fields at speeds as high as 11,128 m/s near the end of the launcher. No one would argue that it's possible to travel through a gravitational field at these speeds, so the question then becomes, what is different between a gravitational field and a magnetic field? The key difference that is most relevant to the question is field uniformity. If a magnetic field is sufficiently uniform in the direction of travel, then the object that is traveling through the magnetic field will not experience changing magnetic field strength, and it is the changes in magnetic field strength that cause eddy currents to flow. Therefore, the challenge is to design the system so that the magnetic fields are as uniform as possible and change as slowly as possible.

For example, at the highest speeds, the grapplers on the adaptive nut form a continuous spiral. The magnetic field generated by the grappler pads will be "homopolar" so that from the perspective of the screw threads it won't change polarity from one grappler pad to the next. The magnetic field strength will slowly ramp up, reach a peak, and then ramp down.

However, this is certainly an area where more engineering work could be done to properly quantify the magnitudes of the interactions and to assess whether any additional measures well-known in the art are needed. For example, to mitigate energy losses, metal components interacting with magnetic fields can be laminated, reducing eddy current formation by limiting the cross-sectional area of conductive paths.

4) Fast-Acting Components:

Concern: Skepticism arose about the feasibility of fast-acting components like electromagnetic pads and other mechanisms required to adjust and maintain the trajectory of a payload in real time.

Key Challenges:

- Synchronizing electromagnetic fields and mechanical components at the speeds required.
- Ensuring reliability under operational conditions.

Representative Quote: "How do you make components that can handle microsecond precision at such high speeds?"

Response: At the lowest speeds, near the start of the launcher, the grappler pads need to be moved fairly quickly and frequently to deal with the changing geometry of the screw, but at higher speeds the speed of grappler actuation slows down considerably. Magnetic bearings use a similar technology in that they measure the distance across an airgap and adjust the strength of a magnetic field in real time to maintain it. These systems can respond very quickly – in milliseconds – to counter perturbations. Robotics and simulation tools like nVidia's Isaac, which model robotic actuators, can be used to ensure that the engineering of the adaptive nut stays inside the capabilities already well-established within the robotics and magnetic-bearing industries.

5) Comparisons to Existing Concepts:

Concern: Some commenters drew parallels between the VPSL and existing concepts like SpinLaunch. They noted that SpinLaunch faces challenges related to scaling and achieving required speeds, suggesting that VPSL may encounter similar issues.

Key Challenges:

- Scaling the concept beyond prototypes.
- Overcoming practical hurdles seen in similar projects.

Representative Quote: "This sounds like SpinLaunch 2.0 but with screws. The same problems will probably crop up."

Response: While both SpinLaunch and VPSL aim to reduce reliance on chemical rockets through mechanical acceleration, the two approaches differ significantly in both physics and engineering challenges.

SpinLaunch relies on a rotating arm to impart velocity to a payload, but the speed at the end of that arm is fundamentally constrained by the tensile strength of known materials – limiting achievable velocities to a very small fraction of what is required for orbital or interplanetary missions. Furthermore, the payload experiences extreme g-forces during acceleration, restricting the technology's usefulness to small, ruggedized payloads that can be heavily g-hardened. VPSL avoids these constraints by relying on a screw-based linear drive. While the screw's rim speed remains within the bounds of current material science, the helical nature of the system enables the launch train – comprising the adaptive nut, sled, and spacecraft – to travel at many times the screw's rim speed. This allows it to reach orbital or even escape velocities. Additionally, the architecture's length can be increased to reduce required acceleration, enabling much lower g-loading and expanding its potential to include human-rated missions and sensitive payloads.

Both SpinLaunch and VPSL accelerate their internal mechanisms and payloads in vacuum environments to avoid energy losses and aerodynamic stresses during the acceleration phase. The key difference lies in what happens after acceleration. VPSL uses an elevated evacuated tube to provide a low-resistance flight corridor extending up to approximately 15 km in altitude. This significantly reduces the atmospheric density the vehicle encounters after exiting the launcher. In contrast, SpinLaunch exits into the atmosphere at the altitude of the ground-based launcher, where air density is much higher. As a result, the payload must endure far greater aerodynamic forces and heating immediately after launch. VPSL's approach mitigates these effects, reducing thermal stress on the vehicle, improving energy efficiency, and enabling flight conditions more compatible with sensitive or crewed missions.

Therefore, SpinLaunch can, at best, only slightly reduce the delta-V that a rocket system will need to travel to a destination such as Mars – at least until stronger materials are invented. The variable pitch screw launch has the potential to almost entirely eliminate the delta-v that the rest of the system needs to supply with rocket propulsion. However, both SpinLaunch and the VPSL technology are differentiated from other mass driver architectures in a key way – they avoid being heavily reliant on power conversion hardware whose cost scales with velocity cubed.

6) Scaling the Prototype:

Concern: Commenters questioned the scalability of the VPSL from small-scale prototypes to full-scale systems capable of launching significant payloads. Issues with maintaining consistent performance at higher speeds and larger sizes were highlighted.

Key Challenges:

- Maintaining magnetic field strength and consistency across longer systems.
- Handling larger payloads without degrading system performance.

Representative Quote: "It's easy to show a small prototype. Scaling it up to something useful is the real challenge."

Response: Scaling a small-scale prototype to a full-scale system is a challenge that many innovative technologies face. Failures in scalability can often be attributed to several factors, including:

Investor Confidence: Investors may lose confidence in a project if milestones are unclear or if intermediate results do not align with expectations. This often results in funding shortfalls that hinder the transition to larger-scale implementations.

Fundamental Physics Challenges: In some cases, the physical principles that enable small-scale systems do not translate well to larger systems. For example, forces, energy losses, or material stresses can grow nonlinearly with size, leading to unforeseen limitations.

Flawed Cost Projections: Early-stage projections of costs per unit often fail to account for diminishing returns, rising complexity, or additional infrastructure requirements at scale. This can result in systems that are technically feasible but economically impractical.

Inadequate Financial Planning: Scaling typically requires substantial upfront investment over long time horizons. Without a well-developed financial plan or diversified funding sources, projects can stagnate at intermediate stages of development.

The VPSL technology is being developed and refined using a combination of physical prototypes and simulated “digital twin” prototypes. There is a roadmap for both, which should serve to keep the project on track and help maintain investor confidence in the team’s ability to correctly set and consistently hit its milestones. The following article provides additional information: [25].

7) Cost and Energy Efficiency:
Concern: Many doubted the claimed cost and energy efficiency of the VPSL. They argued that the capital investment and operational costs might outweigh any long-term savings over rockets or other alternatives.

Key Challenges:

- High upfront costs for construction and materials.
- Potentially high operational energy requirements due to inefficiencies.

Representative Quote: "If it’s so cheap, why isn’t anyone building it? Sounds like the usual case of underestimating real-world costs."

Response: One of the reasons why this article was written was to better establish and communicate the cost and energy efficiency and to increase the number of subject matter experts who can review and either validate or invalidate its findings. Perhaps an equally valid question is “Something similar to this was proposed before called ‘StarTram’. Why didn’t anyone build that?” The reasons are that StarTram had many components that were subject to velocity-cubed scaling, and StarTram was proposed as an alternative and lower-cost way to place payloads into low-earth orbit at a time when we had already implemented solutions to that problem, such as the Space Shuttle. We do not have already-implemented solutions to the problem of how we can affordably establish a human presence on Mars.

8) Choice of Hawaii's Big Island:
Concern: Some commenters raised issues with the decision to depict the launcher ramp on Hawaii's Big Island.

Key Challenges:

- Environmental impacts and the potential for strong opposition from local communities.
- The cultural significance of the island and its volcanic terrain may complicate construction.
- Perceived lack of realism in siting such infrastructure near a populated and culturally sensitive area.

Representative Quote: "Why would you even think of putting something like this on Hawaii? The environmental and cultural backlash would be massive."

Response: Hawaii’s Big Island offers several advantageous features that make it an attractive conceptual example for siting the Variable Pitch Screw Launcher (VPSL):

- High Elevation: The island’s volcanic peaks provide natural high-elevation terrain, which can be tunneled through or built upon to support the upward curving ramp.
- Gentle Slope: The island’s terrain includes relatively gradual inclines that are well-suited for the construction of a launch ramp.
- Low Latitude: Its proximity to the equator allows for a significant velocity boost from Earth’s rotation, making launches to interplanetary destinations more energy-efficient.
- Proximity to Water: The surrounding ocean enables the longest part of the system – the evacuated tube containing the mass driver - to be installed in the ocean to avoid terrain-leveling and right-of-way costs.
- Empty Downrange Area: The vast Pacific Ocean provides a safe area downrange of the launcher, minimizing risks to populated areas or critical infrastructure.

Usefulness as a Familiar Example

The Hawaiian Islands are widely recognized, making them an effective reference point for visualizing the scale and scope of the launcher. Using the Big Island as a conceptual example helps audiences grasp the design’s physical requirements and geographic considerations during early discussions. This familiarity enhances the ability to communicate complex ideas to a broader audience, including stakeholders, policymakers, and the general public.

Understanding Community Concerns

Hawaii’s Big Island is home to a culturally rich and environmentally conscious community. The history of opposition to large-scale projects, such as the Mauna Kea observatories and a proposed SpinLaunch facility, highlights the need to address concerns proactively. Key issues include:

- Environmental Protection: Preserving the island’s unique ecosystems and natural beauty.
- Cultural Heritage: Respecting sacred sites and ensuring that construction aligns with the values of the local population.
- Community Involvement: Ensuring transparency and collaboration during all planning stages to build trust and support.

The lessons learned from these previous projects provide valuable insights into how to engage with the community respectfully and productively.

Potential Benefits for the Community

A carefully designed proposal for the VPSL could offer significant benefits to the local community, including:

- Infrastructure Improvements: The construction of the launcher could drive upgrades to local power grids, transportation networks, and communication systems.
- Economic Opportunities: Increased revenue from tourism, the creation of many local high-tech jobs for Hawaiians, and the potential for global recognition as a premier spaceport.
- Cultural Legacy: Emphasizing the Big Island’s pivotal role in enabling humanity’s journey to the stars. The project could include initiatives to honor and integrate Hawaiian culture, ensuring that its contributions are remembered far into the future.

Flexibility in Site Selection

While Hawaii's Big Island provides an ideal conceptual example, the VPSL could be sited in other locations with similar characteristics. Potential alternatives include:

- Other Islands or Coastal Areas: Locations with high elevation, low latitude, and access to large bodies of water.
- Deserts Located Near Mountains: Remote areas with minimal environmental and cultural disruption, where flat terrain can be artificially created and where a ramp can be constructed by tunneling up through a mountain.

This flexibility ensures that the VPSL concept is adaptable to a variety of geographic and community contexts.

Minimizing Disruption

The design of the VPSL can be tailored to minimize its impact on the local environment and community:

- Subterranean Ramp: Placing the majority of the ramp underground to reduce visual and environmental effects.
- Stowable Elevated Evacuated Tube: The elevated evacuated tube could be deployed only when there is a suitable launch window for interplanetary travel and then stowed between launch windows. This would reduce its visual impact and prevent it from interfering with air traffic most of the time.
- Cultural Sensitivity: Conducting extensive consultations with local leaders, cultural experts, and environmental organizations to identify and avoid culturally significant areas.
- Sustainable Design: Incorporating renewable energy sources and eco-friendly construction practices to align with environmental priorities.

Conclusion to Response

Hawaii's Big Island serves as a compelling conceptual example for the VPSL due to its unique geographic advantages and the insights it provides into community concerns and engagement strategies. While the island offers many benefits, the project's success will depend on careful planning, transparent communication, and a commitment to respecting local values. By addressing these considerations early, the VPSL can serve as a model for how innovative infrastructure projects can harmonize with their surrounding environments and communities.

L. Additional Concerns

In addition to feedback from people who commented on the YouTube video, Atlantis Project team members and other subject matter experts more familiar with the concept contributed additional topics that would benefit from further research. These include:

- The complexity associated with the changing geometry of the magnetic pads and their corresponding interface to the screw flights.
- Dissipation of heat from the motors within the screws.
- Engineering the many flywheels, flywheel brakes, and flywheel motors with sufficient reliability so that downtime for repairs can be avoided or engineering them so that repairs and maintenance can be performed easily.
- Additional loss mechanisms. Aside from eddy currents and hysteresis losses, are there any additional losses that would come into play at these speeds? For example, one source said, "…magnetic materials consist of domains which are separated from each other by walls. A change in the magnetic field can cause a shift of the walls, which results in losses. These losses are called additional losses or excess losses."
- Optimizing the trade between the altitude at the high end of the elevated evacuated tube and the robustness of the vehicle's thermal protection system.
- Whether to use electrodynamic, electromagnetic, (or both) suspension techniques at the interface between the screw flights and the grappler pads.

These concerns will not be addressed here, but the team is certainly interested in working with others who have subject-matter expertise relevant to any of these topics.

VI. Conclusions

The Variable-Pitch Screw Launcher (VPSL) offers a transformative approach to addressing the economic and operational challenges of space exploration. By leveraging quadratic scaling of capital costs with exit velocity and avoiding the exponential and cubic cost growth of traditional launch systems, the VPSL provides a viable pathway to enable interplanetary missions within the budgetary constraints of space agencies.

As with any novel idea, there is inherent uncertainty in determining whether its potential has been accurately characterized by its proponents. However, the VPSL concept is supported by a detailed digital twin (which simulates kinematic behavior and spacecraft flight profiles) and a comprehensive cost model built on conservative assumptions, such as using airliner fuselage cost-per-meter data to estimate elevated evacuated tube costs. These tools ensure transparency and provide a robust framework for independent validation. This approach invites experts across relevant fields to engage with the data and independently verify the conclusions presented in this work.

Our analysis suggests that the VPSL, or a similarly conceived infrastructure-based launch system, represents a critical step forward in making human exploration beyond low Earth orbit economically viable. Whether for missions to the Moon, Mars, or other destinations, such systems have the potential to reshape the economic landscape of spaceflight and usher in a more sustainable era of interplanetary exploration.

VII. References

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