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Comprehensive Review of Studies on Magnetic Launchers

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Abstract

Magnetic launchers provide safer, faster, and lower-friction alternatives to traditional chemical-fuel systems by using innovative principles such as superconducting magnetic levitation, linear motors, and pulsed electromagnetic fields in thrust generation and the control of moving parts. However, magnetic launchers still have not overcome current issues such as efficiency and energy demand, heat management and wear, and control and optimization. This review study aims to present the recent developments—such as magnetic-field optimization, energy-recovery circuits, and artificial-intelligence-based efficiency estimation or control—together with their technical details, by analyzing the current state of different types of magnetic launchers (Maglev Launchers, Coilguns, and Railguns) from 2019 to 2025. In line with this aim, each academic study conducted after 2019 has been compiled and analyzed in terms of launcher type, magnetic-launcher support system, technical characteristics, launch distance, energy consumption, obtained velocity, prominent findings, and additional notes.

Keywords

Coilgun, Rail-Gun, Maglev

1. Introduction

In recent years, the rapidly increasing requirements for energy efficiency, sustainability, and control precision in defense, space, transportation, and unmanned aerial vehicle (UAV) technologies have brought magnetic launch technologies to the forefront as alternatives to traditional chemical propulsion systems. Magnetic launchers are systems capable of accelerating objects to high velocities through electromagnetic force generation without the need for physical contact. In this respect, magnetic launchers reduce losses in energy conversion for high-precision engineering applications and allow integration with renewable energy sources. Numerous studies conducted between 2019 and 2025 demonstrate that this technology has achieved significant advancements in electromagnetic coil (coilgun), rail (railgun), and superconducting magnetic levitation (maglev) systems.

This review study examines the systems described in different articles in a comparative manner in terms of technical parameters, performance efficiencies, and structural innovations. For example, high-temperature magnetic levitation systems developed using YBaCuO (YBCO)-based superconductors and Halbach array configurations have formed the basis of low-friction linear launch solutions [1]. In the same period, electromagnetic coil launchers powered by photovoltaic panels offered an innovative alternative for military and portable applications through off-grid energy generation [2]. Furthermore, it has been shown that multi-stage coilgun systems are superior to single-coil structures in terms of both efficiency (up to 32.7%) and velocity (above 150 m/s) [3].

In this review, energy efficiency determined as a function of consumed energy and achieved velocity is defined as a common performance metric to ensure an equitable comparison across systems. Within the scope of this study, efficiency is characterized as the ratio of the total electrical energy drawn by the system to the kinetic energy of the projectile at muzzle exit. The total consumed electrical energy encompasses capacitor charging, power electronics losses, ohmic losses in conductors/coils/rails, switching losses, and the power consumption of necessary cooling and auxiliary systems. This methodology explicates thermal losses and duty cycles in pulse-power intensive systems, such as coilguns and railguns, while preventing the overestimation of performance data by integrating the energy overhead of cryogenic infrastructure into the analysis of superconducting maglev-based solutions. Consequently, diverse launcher systems can be compared within a consistent framework, evaluated not merely on “high velocity”, but also on energy conversion efficacy and sustainable operational conditions.

In this context, the examinations conducted reveal the efforts of different research groups to find solutions in areas such as energy density, thermal endurance, electromagnetic induction (EMI) reduction, cooling continuity, and artificial-intelligence-supported control algorithms [4]. However, despite all these studies, there are still significant limitations in terms of structural, thermal, and energy management during the transition of magnetic launchers from laboratory scale to industrial scale [5] [6]. Therefore, compiling the articles published in the 2019-2025 period is of great importance for jointly evaluating the current state of the technology, the engineering challenges, and its future directions.

The articles compiled in this study cover a wide technological diversity, ranging from electromagnetic coilguns to superconducting maglev systems, from solar-powered launchers to reluctance-based linear motors. In the selection of the articles, the review of the relevant study in the Web of Science (WoS) and the inclusion of criteria such as launcher type, magnetic launcher support system, launch distance, energy consumption, and achieved velocity were taken into consideration. Through this study, it is aimed to reveal the technical evolution, performance limitations, and development potentials of magnetic launcher systems in the specified period, thereby establishing a scientific basis for the development of future high-velocity, low-cost, and environmentally friendly launch technologies.

2. Comprehensive Review of Magnetic Launcher Studies after 2019

In this study, recent research conducted on “magnetic launchers” from 2019 to 2025 has been reviewed, and for each study, the launcher type, magnetic launcher support system, technical characteristics, launch distance, energy consumption, achieved velocity, prominent findings, and additional notes have been identified and presented in **Table 1**.

Table 1. Compilation table of articles on magnetic launchers after 2019.

Launcher Type	Magnetic Launcher Support System	Technical Characteristics	Launch Distance	Energy Consumption	Achieved Velocity	Prominent Findings	Additional Notes	Ref.
Linear-motor-supported magnetic levitation (Maglev) launch system Fixed-magnet guideway + HTS (high-temperature superconductor)-supported carriage system A laboratory-scale linear rail system capable of launching on inclined surfaces	Multi-surface superconducting magnetic bearing 4 HTS (YBaCuO) superconductor stacks (2 in the right, 2 in the left cryostat) Permanent magnets: optimized using a Halbach array configuration Linear DC servo motor (Omron-R88L-EC-GW-0309) integrated into the carriage Cooling: open liquid-nitrogen cryostat system (0.92 L volume, ≈ 30 minutes of levitation time)	Rail length: 1600 mm, effective stroke: 1300 mm Resistance to lateral forces increased on the carriage through multi-surface interaction Magnet dimensions: Center: 20 × 10 × 20 mm Edges: 20 × 20 × 20 mm Vertical and horizontal flux components balanced due to Halbach configuration•	Total rail length: 1600 mm Maximum carriage travel distance: 1300 mm	Direct energy consumption is not specified; however: A PLC-controlled servo drive has been used Position information has been precisely monitored using an optical encoder In the SCADA-controlled system, position, velocity, acceleration, and jerk values can be input	Test velocities: 800 mm/s (initial tests) 2200 mm/s (maximum achievable velocity) Initial acceleration: 2500 mm/s^2 Deceleration: 15,000 mm/s^2 Jerk: 100,000 mm/s^3	Multi-surface interaction increased the lift force by 44.25% compared to single-surface systems. The system provides low friction and stable levitation. Hysteresis effects (permanent displacement after loading/unloading) were observed, and linear behavior was disturbed. Displacement amplitude decreases at high velocities indicating suitability for high-velocity applications. Although laboratory-scale, the system offers a scalable solution for Maglev trains, model aircraft launch, and even space launch systems.	The launcher angle can be adjusted using a hydraulic platform. The limited operating duration (30 min) of the superconducting cooling system was observed due to the open cryostat; however, it has been indicated that it can be extended to 30+ hours using vacuum systems. The sensor system employed front/rear position sensors and lateral laser displacement measurements.	[1]

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Electromagnetic launcher (coil launcher) Air-core coil driven by a direct current pulse	Energy source: Photovoltaic solar panels (a total 5 kW panel system was proposed) The energy is boosted to 200 V using a boost converter and stored in a capacitor bank. The stored energy is discharged through an air-core coil during launch with a 1000 A direct current pulse.	No magnetic rail. Launcher coil: air-core, wound with 245.33 m of No. 4 AWG copper wire (~488 turns). Coil specifications: Length: 0.316 m Radius: 0.08 m Area: 0.02 m^2 Coil inductance≈20mH Resistance: 0.2 Ω	It is a short-to-medium range system intended for military use, designed to launch a 1-kg projectile to a distance of 1 km.	Energy stored in the capacitor bank: 800 J (joules) + 220 W (heat loss) ≈ 11,000 J total. Launch duration: ~1 second Boost converter efficiency: 85% Total system power requirement: 1500 W from solar, but the recommended panel power is 5 kW (to compensate for efficiency losses and charging duration).	Launch exit velocity: 140 m/s	The system's ability to operate solely on solar energy makes this study unique. Compared to conventional superconducting systems: it offers a cheaper, portable, low-cost, and simpler design. Heat is a significant issue: the coil is exposed to 200,000 W of heat in 1 second, with a cooling duration of 17.4 minutes. Forced air convection (fan) was used for cooling. To achieve shorter cooling times, fan power must be increased, which in turn raises energy requirements. Since coil insulation is limited to 80˚C, the system's maximum temperature is restricted to 75˚C.	The boost converter and the launch coil were fully simulated using LTSpice, while the thermal behavior of the system was analyzed through ANSYS APDL. Since the system can operate solely on photovoltaic panels, the proposed design is suitable for military mobile operations. MPPT (Maximum Power Point Tracking) was not implemented, although it was recommended for future iterations of the system. Recommendation: System performance may be further enhanced by employing low-resistance conductors, superconducting winding materials, and a liquid-cooled thermal management architecture.	[2]

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Three-coil Toroidally-Coupled Reconnection Electromagnetic Launcher (TCREL) The system is based on the Toroidal Reconnection Electromagnetic Launcher (TREL) architecture.	Three coaxially arranged driving coils The coils are powered by a pulse capacitor bank, delivering high-current pulses (peak current: 5587 A) A dual-metal-plate armature is used in the TCREL system, whereas the conventional REL employs a single-plate armature.	Coil structure: TCREL: Three-coil configuration (each stage contains three coils) REL: Two-coil configuration (each stage contains two coils) Insulation and mechanical reinforcement: Coils are encapsulated with epoxy resin, providing a deformation-resistant structure. The inductance gradient (dL/dx) and the inter-coil magnetic interactions are optimized in the design.	The distance has not been specified.	Initial voltages: REL: 1494 V TCREL: 2500 V The capacitors were tested at different voltage levels (ranging from 1494-2500 V).	Muzzle exit velocities after launch: REL: 122.6 m/s TCREL: 148.4 m/s TREL (multi-module structure): 157.5 m/s TREL achieved the highest velocity thanks to its multi-stage configuration.	Efficiency: REL: 8.248% TCREL: 15.818% TREL: 32.717% (highest) Structural strength: TCREL > REL TREL > TCREL Current and force: TCREL has ~100 A higher current than REL → this nearly doubles the force.	Magnetic flux lines spread outward in the TCREL configuration, whereas in the TREL design they concentrate toward the center → this increases thrust efficiency. Stress analyses (deformation cloud plots) indicate that the TREL configuration is the most stable and mechanically robust structure. The TCREL system is faster and more efficient than the REL design, and it can also be modularly converted into the TREL architecture. Simulations were performed using Maxwell and MATLAB, and validated through LCR bridge measurements.	[3]

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Alternating-current (AC) electromagnetic launcher system Grid-connected single-coil system enabling sequential (serial) firing Single-coil coilgun architecture experimentally tested	Projectile acceleration via AC-powered magnetic field Capacitor-free system, allowing continuous firing with AC Triac switching system coupled with a TMS320F28335 DSP microcontroller Phase-Locked Loop (PLL) for grid synchronization Projectile position is estimated sensorlessly based on the coil current difference Artificial Neural Network (Time-Delay MLNN) predicts projectile position with 94.67% accuracy	Coil structure: Single-phase, powered by AC. No additional sensors are required. Current variations are monitored by the microcontroller to perform position estimation. Artificial intelligence algorithm: Two-hidden-layer MLNN, predicting projectile position using historical current data. Real-time processing: integrated with the embedded system.	The exact launch distance is not specified; however, the system is laboratory-scale and based on short-range experimental tests.	Since it is capacitor-less, it operates directly from the mains supply. A 220/12 V, 1 kVA transformer is used to provide a low-voltage, high-current configuration. The ACS712-30A current sensor and the LV25-P voltage sensor were used for measurement.	The velocity value is not directly provided. To control the projectile velocity, the coil energization timing is precisely adjusted. The initial velocity is maximized by cutting off the energy at the moment when the current differences reverse direction.	A sensorless projectile-position estimation algorithm was developed. With the MLNN: –Position-zone prediction accuracy: 94.67% –The acceleration region and the central position of the projectile are successfully classified. The recoil-force issue is largely mitigated using this method. The system is scalable to multi-stage coilgun architectures. Serial firing with an AC power source is possible (no capacitor-charging delay). ANN outputs are used to optimize triac firing (trigger) timing.	The firing angle was experimentally tested at different phases, such as 75° and 90°. A total of 60 launch tests were conducted, and classification was performed based on current-difference patterns. MLNN training was carried out using the Levenberg-Marquardt algorithm. Data processing: normalized current-difference signals were used to create a time-series dataset for training.	[4]

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For rail (conductive) systems, this is not a direct launch system, but a study focused on the optimization of the launcher component.	Copper + AISI 4340 steel composite structure	Composite type: Copper on top and steel at the bottom – dual-layer structure Current applied: 25,000 A (pulsed peak current) Rail geometry: Symmetric U-type, 5 mm projectile contact width Rail length: 100 mm (for the simulation model)	No direct launch was performed. Conductivity within the rail, temperature distribution, and electromagnetic field intensity were analyzed.	The exact energy consumption has not been provided.	Velocity data is not available.	Composite rail materials resistant to electrical and thermal stresses in rail electromagnetic launcher systems have been proposed. ANSYS Workbench – electromagnetic + thermal analysis Important data regarding thermal stress were reported: heating in the copper rail exceeds 500 °C, whereas the composite rail structure reduces this value to below 300 °C.	Within the rail, the magnetic field intensity reaches up to 1.35 T in copper, whereas in the composite it is more evenly distributed. The contact surface between the projectile and the rail experiences less damage, thereby increasing the system's lifespan. Analysis method: 3D coupled electromagnetic and thermal solution (ANSYS Maxwell + Thermal Solver) The study is significant for improving rails, which are the most wear-prone and costly components in rail electromagnetic launcher systems.	[5]

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Reluctance-type electromagnetic launcher (REL) based on the minimum reluctance principle Single-coil (single-stage) configuration It operates on the principle of generating a pulsed magnetic field to accelerate a ferromagnetic projectile.	Pulsed power supply: supported by a bridge-type capacitor circuit Main components: 1 capacitor (800 µF, 1200 V initial voltage) 2 IGBT switches 4 fast-recovery diodes 1 current-limiting inductor	System components: Ferromagnetic projectile Drive coil (Lcoil) and its resistance (Rcoil) Single-coil (single-stage) structure Gap between projectile and coil: 3.5 mm Projectile height = drive coil height (for maximum thrust efficiency) Initial position P: Distance between the projectile's front end and the coil's front edge = 20 mm	The net travel distance is not specified. Motion simulations were conducted over the 0-10 ms interval.	Initial capacitor energy: ≈576 J With the improved circuit: – Residual current is recovered as energy – Charging time is reduced – Energy efficiency is increased	The velocity value is not specified.	Improved circuit: – Reduces residual current in the drive coil to zero – Recovered energy is used for the next cycle – Launch efficiency is significantly increased	Simulation tools used: Finite Element Analysis (FEA) and a custom-developed SPICE-style circuit model Advantage of performing both charging and discharging cycles with a single capacitor in the circuit Proposed for applicability in low-cost reluctance launcher systems The residual current recovery feature suppresses the counterforce behind the projectile	[6]
It is a launch system supported by magnetic levitation and a linear motor.	High-temperature superconductors (YBCO) and neodymium magnets (NdFeB) are used for magnetic levitation. A HIWIN LMC-A6 linear motor is employed for launching.	Rails: A total of 6 modules, each containing 192 magnets, providing an overall length of 5760 mm. Magnets: NdFeB magnets measuring 15 × 15 × 5 mm. Superconductors: YBCO cylinders with a critical temperature of 92 K (21 mm diameter, 8 mm height). Motor: Maximum velocity of 5 m/s and maximum acceleration of 100 m/s^2. Launch Carriage: 0.8 kg aluminum frame, with a total system mass of 8 kg. VR Integration: Full simulation and analysis capability using Unity and Oculus Quest 2.	Depends on initial conditions: – In an unactuated system: ~85 m track length required. – With 3 N thrust and 0.043 rad yaw angle: only ~14.5 m of track is sufficient.	No specific numerical values are provided; however, a constant linear-motor thrust of 60 N is assumed. Liquid nitrogen is used for cooling the superconductors.	Take-off velocity: in the unactuated condition 58.5 m/s, and with low thrust and an appropriate angle 24-28 m/s. The UAV completes take-off within 0.95-2.7 s.	The most critical factors in the UAV's take-off are the presence of thrust and the pitch angle. A small initial pitch angle combined with a low level of thrust significantly reduces the required take-off distance and velocity. VR support enables better comprehension of simulations in engineering analyses. The system is modular in structure and can therefore be applied to different types of UAVs. Since the superconducting system can generate lift even at low velocities, take-off and landing are safer compared to conventional systems.	This system was developed as an EU-supported test platform within the GABRIEL Project. Simulations were prepared in MATLAB, and the results were transferred to a VR environment using Unity. UAV control algorithms have not yet been integrated into the simulation; manual control and synchronization were assumed. Although the system is designed for micro-class UAVs, the modeling framework is scalable to larger systems.	[7]

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Electromagnetic launcher (coilgun) A single-coil, linear-exit system designed for ferromagnetic projectiles An aircraft-mounted launch ramp intended for deploying micro/nano satellites into space.	Magnetic flux is increased by reducing reluctance through an iron-yoked magnetic circuit. A capacitor bank (2 × 2500 μF, 450 V) transfers high energy to the coil in a short time. The system includes an SCR-thyristor launch circuit and a microcontroller-based triggering and velocity measurement unit.	Coil specifications: Length: 20 mm Number of turns: 100 Inner diameter: 15 mm Wire: Dual-strand winding using 2 × 0.8 mm diameter wire Resistance: 0.125 Ω Iron yoke: Made of soft iron; 4 mm and 6.6 mm variants were tested. Capacitor capacity: 5000 μF (total) Supply voltage: Between 60 and 140 V	The system is designed for short-range experimental measurements. The actual launch distance is not specified; however, it is intended to be suitable for low-altitude in-space launches of microsatellites.	For a 5 mF capacitor charged to 100 V: 25 J of stored energy. The energy efficiency (η) was measured by determining how much of this electrical energy is converted into kinetic energy.	Maximum exit velocity: 14.9 m/s (at 140 V) Velocity measurement: conducted using two optical sensors spaced 10 mm apart. Efficiency: 2.78 % (with iron yoke system) The iron yoke increased velocity by 17 % and efficiency by 36 %.	The iron yoke completes the magnetic circuit around the coil, increasing magnetic flux lines. It also increases the inductance variation, thereby enhancing the launch force. Projectiles made of non-ferromagnetic materials (e.g., copper or aluminum) show almost no movement; the presence of magnetic dipoles is critical for projectile propulsion. Higher velocities were achieved at the same voltage, making the system more efficient and energy-saving. From an application perspective, flying launch ramps aim to deploy satellites from the upper layers of the atmosphere.	•Magnetic flux lines were visualized using FEMM4.2 simulations. Higher performance at the same voltage was achieved through the reluctance reduction strategy. A single-coil structure was employed, aiming for a compact and optimized design rather than multi-stage systems.	[8]

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Synchronous Induction Coil Launcher (SICL) Designed for the electromagnetic launch of high-mass projectiles using a multi-stage coil system. Pulsed current is employed for the launch.	The system consists of drive coils and an armature. The armature is an aluminum cylindrical structure, and the magnetic field interactions have been analyzed in detail. Three-dimensional magnetic field modeling was performed using the Biot-Savart law and the principle of magnetic superposition. The drive coils are wound with Litz wire, which allows for high current density and uniform current distribution.	Drive coil: Coil voltage: 3500 V Peak current: ~33 kA Coil composition: Litz wire, cross-sectional area 56.25 mm² Length: approximately 10 mm per applicable segment. Magnetic field values: Axial magnetic field in single-stage system: 8.69 T Radial component: 1.45 T The magnetic field is symmetric without the armature; adding the armature distorts the field, making it asymmetric.	Not specified, but the system has typically been tested experimentally in a laboratory environment. Intended application: long-range electromagnetic launch of high-mass payloads (e.g., missile defense, microsatellites).	Capacitor bank voltage: 3500 V Peak current: approximately 30-33 kA The stored energy is likely on the order of several kilojoules, although no explicit numerical value is provided.	The article does not specify the projectile's launch velocity. The primary focus is on magnetic field distribution and modeling. However, indirectly, a high magnetic field implies high force and thus the potential for high launch velocity.	The magnetic field simulations closely match the numerical model calculated in MATLAB. When the armature is added, counter-eddy currents slow down the rise and fall rates of the magnetic field. Using two coil stages distorts the field distribution due to field superposition, reducing overall symmetry. The skin effect causes the magnetic field to concentrate near the surface at high frequencies, which is particularly significant in aluminum armatures.	Measurements were carried out using one-dimensional Hall probes and validated through simulation. In tests where the armature position was kept fixed, the measurements and the modeling showed good agreement. It is recommended that electronic components be placed close to the armature head to avoid being affected by the magnetic field. The influence of the metal enclosure reduces the magnetic field due to counter-eddy currents.	[9]

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Multi-Pole Field Electromagnetic Launcher (MFEML) Structure generating radial launch force with a spiral sling coil and multiple acceleration coils Multi-stage linear system designed to propel large-mass projectiles at high velocities	Spiral cylindrical sling coil: Provides the initial motion (initial velocity: 0.05 m/s). Acceleration coils (8 units): Sequentially triggered to provide the main acceleration (maximum velocity: 78.19 m/s). Each coil is triggered by a capacitor bank. A magnetic equivalent circuit model has been developed. Separate formulas have been presented for magnetic reluctances and magnetic flux lines.	Sling coil: Cylindrical structure, 2 mm × 16 mm, 30 turns, multilayer winding, Charging: 200 µF, 40 kV. Acceleration coil: Rectangular cross-section, 8 units, Inner dimensions: 18 × 18 mm, outer dimensions: 28.5 × 28.5 mm, length: 10.55 mm, 50 turns, Charging: 400 µF, 50 kV.	• A long-range launch capability is targeted through the use of a multistage structure.	•For the sliding coil: 160 J For the acceleration coil: 500 J	Muzzle velocity: 78.19 m/s (octapole system) Hexapole: 61 m/s, decapole: 84.22 m/s	•Reluctance distribution and inductance formulas dependent on projectile position have been derived in detail. The force generated by each coil has been calculated according to position. Flux leakage and current layer thicknesses have been considered to obtain more accurate results. The spiral catapult coil generates the force required for initial movement (initial thrust: 60 kN). Total force: 100 kN MFEML demonstrates that it can be an alternative to chemical and hydraulic systems due to its high force and velocity capacity. The effect of different pole numbers (6, 8, 10) on system performance has been tested.	The model has been validated using FEA (Finite Element Analysis). The developed method realistically accounts for details such as coil shape, reluctance, and flux density. The proposed inductance formulas can be adapted for any arbitrary coil shape and size. Thanks to electrical equivalent circuit analyses, theoretical and design simulations can be performed synchronously.	[10]

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Launcher with a high-temperature superconductor passive magnetic suspension system Linear motor-assisted magnetic levitation catapult system Contactless launch solution optimized for UAV takeoff and landing	YBCO superconductors (cooled with liquid nitrogen) Magnetic levitation achieved using the Meissner effect and flux pinning phenomenon Magnetic rails + launch platform + linear motor + launch carriage with duralumin frame System vibrations and moments passively balanced by levitation forces	Launch carriage lift gap: ~6.6 mm equilibrium point, maximum lift 17.3 mm Mass of the launch carriage: Not specified, but analyses conducted for masses liftable by the superconductors Motor: Linear motor, carriage moved with constant 20 N force for 1 second Superconductors: Enhanced flux pinning effect achieved when cooled at 3 mm magnetic field distance	In the simulation: 2-second motion duration, The carriage travels a total distance of 14.2 meters	Direct energy consumption is not provided numerically. However, the system uses a linear motor moving with constant force, and its energy can be controlled.	The carriage reached a maximum velocity of 14 m/s and was then decelerated. The UAV leaves the carriage at a velocity of 24 m/s after 2.2 seconds. Launch distance: 28 meters (windless scenario).	Vibration damping is low but controlled (typical for the current system). A constant acceleration can be applied to the UAV, ensuring a smooth takeoff. The Meissner effect and flux pinning passively balance external disturbances and load imbalances. In lateral slip conditions, the system oscillates but tends to hold the UAV at the center. Wind effects have been analyzed: headwind reduces the launch distance, tailwind increases it. Simulations have validated the design for safe UAV takeoff and landing.	This study presents a detailed dynamic and aerodynamic analysis of the previously examined GABRIEL system. The mathematical model is represented as a six-degree-of-freedom system and simulated in MATLAB. Both longitudinal and lateral motions have been investigated. UAV model: Micro UAV Bullit (1.27 kg, 0.84 m wingspan). The separation velocity from the launch cart, launch forces, and wind effects have been incorporated into the simulation.	[11]

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ermanent-magnet (PM) coilgun A projectile made of a neodymium magnet (N52 grade) is used instead of a ferromagnetic slug Single-coil, upward-launch configuration	The energized coil generates a magnetic field and pushes the PM (neodymium-magnet) projectile The PM itself serves as the magnetic source As the projectile reaches the coil's center, the coil reverses its excitation polarity, converting pull into push and increasing acceleration Static electromagnetic simulations were performed using Ansys Maxwell	PM projectile: Neodymium N52 Density: 7.45 g/cm^3 Mass: 40.1 g Volume: ~5.38 cm^3 Coil: 25 mm length, 1000 turns Current: 4 A Polarity reversal applied at the coil center Force: Maximum ~22 - 25 N Provides 4 - 5 times higher force compared to a ferromagnetic projectile	Launch distance of a single 50 mm (5 cm) coil	Excitation energy: approximately 0.825 J After subtracting gravitational energy: kinetic energy ≈ 0.805 J	PM projectile: v = 6.3 m/s Ferromagnetic projectile in the same system: v = 2.8 m/s	Higher force and velocity were achieved by using permanent magnets (PM). If synchronized coils are implemented in a multi-stage structure, the velocity and force can be further increased. High performance in a compact package makes the system suitable for mobile platforms, mini-launchers, and space-launch applications. PM projectiles are both lighter and more energetic than ferromagnetic ones. The cost-to-performance ratio can be better, as the required energy input is lower.	Modeling was performed using both theoretical formulas and electromagnetic simulation. Force-distance curves were used to calculate the net force area applied to the projectile (0.825 J). Polarity reversal during projectile travel is critical; proper synchronization significantly improves performance.	[12]
Solar-powered electromagnetic coil launcher Based on a boost converter, capacitor bank, and air-core coil system	Energy source: Solar panels with a total capacity of 5 kW Energy from the sun → boost converter → 200 V capacitor bank Charged capacitor → discharges into the coil at 1000 A Coil: Air-core, No.4 AWG wire (245.33 m length), 0.2 Ω resistance, 20 mH inductance	•Coil current: 1000 A (1-second shot) Coil voltage: 200 V Energy conversion: Target potential energy: 1 kg × 9.8 m/s^2 × 1000 m = 9800 J Total energy requirement (including losses): ~11,000 J Boost converter: 85% efficiency, operates between 96 - 200 V Forced air cooling system with fan: added for thermal management	Vertical launch target: 1000 m The simulation was modeled to meet this target A vertical launch system designed to propel a single projectile to an altitude of 1 km	Total energy requirement supplied by solar panels: ~11,000 J Charging time: Depends on solar irradiance, average ~160 seconds Fan power is also supplied from this energy → cooling system limit: 1.5 kW total system power	Required launch velocity: ≈140 m/s	This system proposes a portable launcher that operates solely on solar energy, independent of the grid. Overheating is the most critical design issue: the coil faces 200,000 W of heat generation in 1 second. Maximum allowable coil temperature: 75˚C Cooling time: 17.4 minutes (with air fan system, h = 73 W/m^{2}K) The developed system is simple and low-cost, capable of operating in harsh environments such as deserts. Standard copper wire is used instead of superconductors. The boost converter design was simulated in LTspice, and the system logic follows three stages: charge – standby – launch.	Thermal analysis: Validated using Ansys APDL and an analytical model. Solved under fixed temperature and convection boundary conditions. A nonlinear relationship exists between the heat transfer coefficient and fan velocity. Future recommendations: Improvement suggestions include using superconducting wire, fluid cooling, and a hybrid solar + wind system. An MPPT algorithm and soft-switched converters could enhance overall system efficiency.	[13]

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Electromagnetic catapult type launch system System used: Dual-sided superconducting magnet linear synchronous motor (SCLSM).	Iron-core and air-core SCLSM structure: Superconducting magnets (SCM): 4 units Iron-core structure → used for magnetic field guidance and leakage flux suppression Ring windings (armature winding) employed → provides high winding density and low torque ripple	Pole pitch (τ): 1.04 m SCM specifications: Current: 210 A Number of turns: 2340 turns Length: 0.94 m Height: 0.48 m Thickness: 25.4 mm Armature: Current: 2000 A Number of turns: 10 turns Height: 0.42 m Width: 0.5 m	Launch distance not specified	Detailed energy data not provided	Total electromagnetic force with four SCMs: 64.8 kN (thrust force) Thrust density: 109.83 kN/m³ A similar system at Holloman Air Force Base, USA, achieved a launch velocity of 186.9 m/s	The iron-core system compared to the air-core system: - 2 times higher magnetic flux density - More uniform field distribution Leakage flux density: - Average gap flux: 1.84 T - Leakage flux: 0.30 T → leakage ratio ≈ 16.3% Optimum air gap: 30 mm → 65.12 kN maximum thrust Armature width and height significantly affect performance: - Width = 360 mm → highest thrust density - Height ≈ 0.38-0.40 m → optimal Saturation does not reduce system energy efficiency, as the iron core is used solely for magnetic field guidance	Simulations: ANSYS Maxwell + Finite Element Method Superconducting magnets have been successfully used in both Japanese Maglev trains and U.S. rocket sled tests Moving-magnet motor configuration is more stable than moving-coil designs and does not require cable connections Application areas: aircraft launches, space support systems, high-velocity rail testing, Maglev platforms	[14]

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Permanent magnet (PM) linear synchronous electromagnetic launcher AC-powered linear machine structure designed to achieve high thrust during launch	•Inverted U-type structure: Armature positioned between two permanent magnets (PM) Wing-type structure: PM is movable, stator armature on both sides Coil types: -Distributed winding -Concentrated winding - Ring winding	PM (Neodymium magnet) + AC-excited coil combination Coil current: 150 A (in the experimental prototype) Leakage magnetic field magnitude varies with winding type: - Distributed winding: highest EMI - Concentrated winding: lowest EMI PM magnetic field is static, AC coil field varies over time Inverted U structure stands out as the design with the least environmental magnetic leakage	Launch distance not specified	Exact energy value is not specified However, 150 A current in the coils indicates that the system is relatively high-powered	Velocity data is not provided	Electromagnetic interference (EMI) can cause deviations in sensitive components such as UAV compasses. Suppressing stray magnetic fields is critical, especially in UAV systems. Inverted U structure with concentrated winding → lowest stray field. Analytical model validated with 3D finite element analysis. Beyond 600 mm, stray field drops below 100 μT → safe zone for UAV systems.	EMI suppression methods were proposed: - Semi-enclosed shielding systems - Body covering with high-permeability metal plates (silicon steel) Increasing material thickness results in stronger EMI attenuation In the prototype system, stray fields from both PM and coil sources were measured separately, yielding values close to the analytical model Control strategy used: structure compatible with MTPA (Maximum Torque per Ampere) UAV navigation sensors should be positioned at least 600 mm away from the launcher	[15]

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Electromagnetic launching system (EMLS) TPMLL (Tubular Permanent Magnet Linear Launcher), i.e., tubular permanent magnet linear launcher	Moving part: - Outer section: 5 permanent magnets + 5 ferromagnetic rings - Inner section: Aluminum tube Stator: - Consists of 3 small stator segments forming an outer casing - Each segment contains 2 stator teeth, one yoke, and bread-type circular windings - Between segments: 2 non-ferromagnetic rings Air gap: between stator and moving part Structure: entirely tubular and circularly symmetric	Magnet type: NdFeB (Neodymium) Stator material: Silicon steel (50W470) Excitation current: 10 A Coil turns: 30 Stroke length: −6 mm to +6 mm Stator outer diameter: 63 mm (fixed) Laminate carrier thickness: 67.5 mm (fixed) Three main parameters analyzed in optimization: - Permanent magnet width - Permanent magnet thickness - Stator yoke thickness	No specific launch distance is provided; this is a laboratory-scale prototype.	Power consumption is not directly specified.	No velocity value is provided	Sensitivity analysis showed that three parameters (magnet width, magnet thickness, stator yoke thickness) are the most critical. According to these three parameters: - Increase in average force (T) - Decrease in ripple coefficient (c) - Decrease in copper loss/thrust ratio (k) Optimum values: -Permanent magnet width: 10 mm -Permanent magnet thickness: 4 mm -Stator yoke thickness: 3.6 mm	Optimization algorithm used: fuzzy optimization iteration + weight determination algorithm Software used: FLUX (2D finite element analysis) Three-objective optimization: maximize thrust, minimize ripple, minimize copper loss	[16]
Linear displacement converted into rotational motion.	Magnetic launcher + ferromagnetic circuit + rotating NdFeB magnets + coil combination. (Rotational motion is used for electricity generation based on changes in magnetic flux.)	Central Magnet: Ø8.2 mm × 2.1 mm NdFeB magnet Magnetic Launchers: 4.8 mm × 4.8 mm × 2 mm NdFeB Coil (Prototype): 1250 turns, L = 20 mH, Rs = 150 Ω Coil (Industrial): 1000 turns, L = 12.8 mH, Rs = 120 Ω Wire Diameter: 80 µm copper wire Ferromagnetic Circuit: 4 × 500 µm FeSi3% layers Total Volume: 3.5 cm^3 (30.5 mm × 21 mm × 5.5 mm)	Displacement is short but sufficient for energy conversion.	Prototype → Produced Energy: 1.235 mJ Energy Density: 350 $\mu\text{J/cm}^3$ Industrial → Produced Energy: 750-1000 µJ Energy Density: 214-285 $\mu\text{J/cm}^3$ Input Mechanical Energy: 2.21 mJ Efficiency η_{EH} ≈ 56%	Oscillation frequency after rotation: 70 Hz Approximately 1.235 mJ of energy is transferred within 60 ms	High energy output is achieved through a magnet placed directly inside the coil and guided magnetic flux. It can generate energy during both forward and backward movements, thus operating symmetrically.	The device behavior has been thoroughly simulated using MATLAB/Simulink and finite element modeling, and experimentally validated. The developed system is suitable for battery-free autonomous switches that convert button movement into electricity. It has been commercialized (by Legrand®).	[17]

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A multi-stage coilgun, with each stage controlled by a coil and a capacitor.	Staged coils: Each powered independently by its own capacitor. Magnetic sensors: Detect the projectile's position and trigger the next coil. Control system: Each coil is sequentially triggered with precise timing to provide successive thrust.	Coil design: – Length: 35 mm – Inner diameter: 12 mm – Outer diameter: 36 mm – Number of turns: 700 Projectile: – Material: Iron (ferromagnetic) – Length: 45 mm – Diameter: 10 mm Capacitor: – Capacitance: 4700 μF – Voltage: 450 V Magnetic field: – Up to ~1 T at the coil center Software used: – COMSOL Multiphysics (magnetic field + force analysis)	Single-coil analysis: – Effective launch region ≈ 35 mm (approximately equal to the coil length) Multi-stage launcher: – Each stage is assumed to have similar dimensions to the single-coil module (≈35 mm active acceleration length)	For each stage: approximately 476 J.	According to the simulation data: The projectile exit velocity with a single coil is approximately 40-50 m/s. With a multi-stage configuration, the goal is to increase this value to above 100 m/s.	Magnetic force-time graphs: -The direction of the force changes according to the position of the projectile within the coil (first attracting, then decelerating). Optimal positioning: -The next coil should be activated before the projectile reaches the center of the coil. Verification through simulation: -Force-time and velocity-time curves are consistent with physical expectations. Importance of timing: -Delayed triggering → loss of velocity - Early triggering → the next coil becomes active before sufficient acceleration occurs → low efficiency - It is emphasized that the launching system should operate together with precise control algorithms.	The authors propose this model particularly for laboratory-type prototype coilguns. As application areas, the precise launching of small-mass objects, magnetic weapon prototypes, and experiment sets intended for educational purposes are listed. The model has been validated through highly detailed COMSOL simulations, providing robust electromagnetic force and energy analyses.	[18]
A staged-coil electromagnetic launcher (coilgun) provides linear acceleration by applying impulsive magnetic force to a metal projectile using low voltage.	Advanced current-shaping circuit: Each coil is triggered with a dedicated discharge module, achieving a longer-duration and controlled current profile. IGBT-controlled triggering system: Timed by a microcontroller Each stage consists of an independent capacitor + coil + IGBT + snubber circuit.	Number of coils: 3 Number of turns per coil: 600 Wire diameter: 0.9 mm Coil resistance (each): 0.5-0.8 Ω Coil inductance: 750 μH Capacitor capacity / voltage: 1,000 μF / 50 V Total stage length: ~300 mm (each coil ≈ 10 cm)	-	Energy per stage: 1.25 J	Output velocity achieved with 3 stages ≈ 22.75 m/s	Smoother current-time profile More stable acceleration Current spikes between stages are prevented, reducing energy loss	Analysis was performed using both an experimental prototype and SPICE-based circuit simulation. The design is particularly suitable for safe, low-voltage coilgun systems intended for educational and laboratory purposes.	[19]

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Linear launcher motor (LM) Piston-like linear motion driven electromagnetically (aiming to replace conventional internal combustion engine pistons)	Solenoid (coil)-based electromagnetic drive system Soft-steel AISI 1008 yoke and piston body	Number of coil turns: 400 Coil wire diameter: 4.1 mm Coil height: 39.75 mm Coil length: 224.5 mm Piston diameter: 80 mm Piston length: 121.2 mm Yoke and piston material: AISI 1008 soft steel	Maximum displacement (piston motion): 75 mm	Energy calculations have not been provided	Unloaded: ~6.1 m/s Loaded (100 A): 2.5 m/s	Compared to piston systems, linear launcher motors have: -Less mechanical friction -Fewer moving parts -Lower maintenance requirements JMAG was used for 2D magnetic analysis It was used together with MATLAB/Simulink for dynamic and static performance evaluation The applicability of this system in low-power transportation systems, such as light electric vehicles, has been emphasized	Application target: In-vehicle electromagnetic linear actuator as an alternative to ICE motors Particularly suitable for compact and low-cost applications Has the potential to eliminate up to 35% energy losses present in mechanical piston-based motor systems	[20]
No direct launching system has been introduced The fundamentals of magnetic launcher systems have been explained in detail	The fundamental supporting elements on which magnetic systems are based have been explained	Focus has been placed on the technical material properties	In this theoretical study, no measured launch distance is provided	A conceptual framework regarding energy transfer has been presented	It does not include any velocity or dynamic results	The flux density-field relationship in coil systems has been explained theoretically	Supporting theoretical content	[21]
Series-connected augmented four-pole railgun model	Series-connected augmented system: There is a series connection between the main and auxiliary rails. The auxiliary rails are mounted outside the main rails.	Number of rails: 8 (4 main + 4 auxiliary) The auxiliary rails are placed to increase magnetic flux density and provide electromagnetic shielding. Armature: Square cross-section, optimized by trimming the corners. Material: Copper and aluminum are used for both the rails and the armature. Rail structure parameters: 1200 mm × 1200 mm × 2500 mm	Distance is not specified; it is a short range test setup	Not specified	The projectile exit velocity is not directly provided. Total electromagnetic thrust of the unaugmented launcher: 28,710 N Total electromagnetic thrust of the augmented launcher: 63,853 N	The C type current distribution transmitted the electromagnetic force to the armature more efficiently. The augmented system produced approximately 3.7-4.8 times greater electromagnetic force.	It is proposed for the electromagnetic launching of heavy smart munitions. The research is supported by both numerical analysis and the finite element method (FEM).	[22]

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The focus of the article is not a direct launching process; instead, it is the development of a magnetic field measurement apparatus integrated into the projectile within a railgun system.	Measurement technology used in the system: B-dot probe (detects magnetic flux variation) FPGA-controlled data acquisition and recording to local FRAM memory Electromagnetic shielding (copper, aluminum, magnetic, and hybrid mate	B-dot probe: 4 turns, 64 mm^2 coil area FPGA: Cyclone I EP1C3T100CN8 ADC chip: AD9280 (8-bit, 32 MSPS, 95 mW) Memory: FRAM FM25L256, 256 KB, 20 MHz Housing size: 19 mm × 39 mm (cross-section), 40 mm (length) Voltage regulation: 7.4 V → 3.3 V and 1.5 V outputs via battery module Data processing: MATLAB	No projectile firing was performed	The in-projectile sensor system has very low power consumption (approximately 100 mW).	A low-velocity static measurement was performed.	The projectile-mounted measurement device developed is capable of accurately measuring the in-bore magnetic field of the electromagnetic rail system.	This study concerns the characterization of railgun systems using an in-munition sensor. It provides critical data for modeling factors such as corrosion damage, electromagnetic interference, and armature current.	[23]
Electrodynamic launcher of the railgun type.	MASEL-type modular augmented electromagnetic launcher (Modular Augmented Stage Electromagnetic Launcher) A structure supported by eight magnetization loops (16 magnetization rails) The magnetization rails are added to the conventional rails to increase magnetic flux density	Main rails: 2, conventional rails carrying current Magnetization loops: 8 loops → total of 16 magnetization rails Armature mass: 72 grams Current type: I(t), time-varying current Modeling methods: Maxwell’s equations + vector potential + finite difference method Numerical implementation: COMSOL + “dummy armature” method	Not explicitly stated, but calculations were performed along the launch channel used for the MASEL launcher Numerical modeling indicates that the armature traveled 33 mm (for t = 0.2 ms)	The energy value is not provided directly.	Calculated exit velocity: 394.3 m/s Full-scale experiment velocity: 376.9 m/s	The magnetization rails nearly double the magnetic field intensity. Under the same current, the magnetization-assisted structure produces a higher Lorentz force than the conventional structure. Thanks to the magnetization rails, similar velocities can be achieved under conditions where a conventional railgun would require twice the current. Acceleration data obtained from numerical modeling strongly agree with experimental results. The “dummy armature method” operates approximately 1000 times faster than other methods while providing comparable accuracy.	The “dummy armature” method provides high-accuracy solutions with low computational resources. This study offers a robust computational framework for optimizing magnetization-assisted rail systems.	[24]

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The electromagnetic launcher (EML) is based on the principle of propulsion by magnetic force through a solenoid structure.	The design and optimization were carried out based on solenoid-based electromagnets.	Solenoid-type electromagnet: Plugnut, coil, core, cap, and yoke Material combinations: SS430 (steel), copper, CRS (cold-rolled steel), PVC, aluminum, NdFe35 (neodymium magnet) Force-current relation: – Target force: 1960 N –Required current: Approximately 167.6 A	Load mass: 200 kg, lifted over a distance of 50 m	At 30˚ inclination: 49,000 J (min) At 90˚ inclination: 98,000 J (max)	No velocity value is provided	Type-1 solenoid produced 2193.2 N of force, representing the most cost-effective design. Type-2 solenoid produced 2115.7 N of force. Optimal combination: - Plugnut: SS430 - Coil: Copper - Core: SS430 - Cap & Yoke: CRS Advantages of the solenoid-type electromagnet, such as high efficiency, low cost, reduced heating tendency, and easy selection with Python, are emphasized. In this study, a real launch system is not constructed; only the selection, design, and evaluation of the electromagnet are performed.	The launcher system has not been physically tested and is limited to theoretical and software-based modeling. All designs were tested with 2D and 3D modeling using ANSYS Maxwell software. The selection algorithm is implemented in Python, recommending the optimal electromagnet combination based on user-provided inputs such as distance, force, current, and material.	[25]
The electromagnetic launcher (EML) operates by triggering electromagnets through contactless energy transfer to achieve propulsion.	An inductively coupled electromagnetic launcher operating with a wireless power transfer (WPT) system Transmitter coils – placed along the track Receiver coil – connected to the moving carrier (armature) Power is transferred via magnetic field variation	Launch coils: One transmitter coil per segment On the carrier: 2.5 cm diameter receiver coil Coil material: Enameled copper wire (AWG24) Transmission distance: 1.5 - 2 cm (between transmitter and receiver) Launcher rails: Mechanical rail system; not magnetic rails Control: Arduino Mega 2560 with IR sensor-based position feedback for triggering	Tested on a track approximately 120 cm long	Total energy consumption is not explicitly provided	The article does not provide a precise numerical exit velocity. The system appears to be designed primarily for demonstration and proof-of-concept purposes rather than achieving high projectile velocities.	Wireless power transfer is one of the first methods applied in launch systems. IR sensor-based position detection combined with Arduino-controlled triggering offers a low-cost and modular design. WPT efficiency between segments was measured to be approximately 70-80%.	This system is a laboratory-level prototype, not intended for defense applications or heavy-load launching. Because the receiver coil on the carrier is small, WPT efficiency can drop rapidly — indicating a need for improvement in future designs.	[26]

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Electromagnetic Launch (EML) — Coilgun.	Operates with a projectile that includes a permanent magnet (Neodymium N52). An electromagnetic acceleration system based on a coil (solenoid) launcher.	Coil Structure: Each coil consists of approximately 200 turns and is driven with a current of 2 A. Coil Configuration: One or two coils are placed inside a glass tube, and the coil polarities can be reversed. Projectile: An N52-grade neodymium permanent magnet is used as the projectile. Mass: 40.1 grams Dimensions: Diameter ≈ 19 mm, length ≈ 30 mm	Single-coil setup: 50 mm Dual-coil setup: 50 mm spacing between the coils + additional separation	Energy transfer obtained from simulation: - Single coil: 0.086 J - Dual coil: 0.17 J	Single-coil system: Simulation: 2 m/s, Experimental: 1.5 m/s Dual-coil system: Simulation: 2.9 m/s, Experimental: 3.0 m/s	The PM (permanent magnet) projectile achieved approximately 10 times higher velocity compared to a ferromagnetic projectile. PM projectiles are more efficient because they can be accelerated by both attractive and repulsive forces. Experimental data closely matched simulation results. The prototype system was implemented using low-cost Arduino, optical sensors, and an L293N driver.	Friction losses during launch were not included in the simulation. The scalability of the developed system has been demonstrated, providing a basis for more advanced systems.	[27]
Electromagnetic rail launcher (EML) Complete system modeling powered by an air-core compulator (alternator-type energy source)	Compulator-type power supply: Used to generate high-current pulses for electromagnetic launch applications. Magnetic-field generation: Provided through the conductive launcher rails. Comprehensive physics modeling: Includes friction, Velocity Skin Effect (VSE), and eddy currents. Rails: Conductive metallic rails (typically aluminum or copper). Projectile: Conductive, equipped with a sliding contact (armature).	Rail structure: Straight, parallel-rail configuration, 3D modeled in the simulation environment. Power source: Air-core compulator (including rotor and stator). Simulation environment: EN4EM (Electromagnetic Numerical for EML) — proprietary software developed by the authors. Modeling scope: Electromagnetic field, thermal effects, friction forces, eddy currents, Velocity Skin Effect (VSE), material stresses. Operating frequency: Compulator output frequency modeled up to approximately 300 Hz. Sliding contacts: Modeled in detail, including contact loss and friction effects.	A 1-meter track simulation was conducted through modeling. Rail length and projectile dimensions are not explicitly provided; however, the system is stated to be suitable for full-scale military applications.	The exact energy value is not provided numerically; however, the compulator's output current is modeled in the range of several hundred kiloamperes. Using the EN4EM software, the entire system is solved based on energy-momentum balance principles.	Weak interaction model: 1450 m/s Strong interaction model: Approximately 1300 m/s	The EN4EM software is a comprehensive 3D analysis tool developed for electromagnetic rail launcher systems. The inclusion of friction, eddy currents, the Velocity Skin Effect (VSE), and thermal phenomena in the model enables more realistic and physically consistent velocity predictions. The time-varying output current of the compulsator has a pronounced influence on the launch profile and the resulting electromagnetic propulsion force. Modeling the magnetic field distributions at the rail-projectile interface provides critical insights into the projectile's centering behavior, stability, and contact quality.	This study is one of the rare works that focuses on a full-system analysis, encompassing the entire process from energy generation to projectile exit, rather than examining only the coil or rail components. High-fidelity modeling has been conducted for military applications, including hypersonic projectiles and missile platforms. The specific material properties of the rails and the projectile are not explicitly stated in the study.	[28]

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Coilgun (Coil-Based Electromagnetic Launcher) A coilgun system that has been enhanced and modified to generate very high-intensity pulsed magnetic fields.	A Modified AC Magnet (MBM) configuration is employed. To concentrate and direct the magnetic field, the system incorporates disk-shaped electromagnetic shields (constructed from segmented aluminum) and a superconducting cryogenic environment (liquid nitrogen or liquid helium). The magnetic field is designed to reach its peak value and decay within a very short time interval.	Rails: No conventional rails are used; the projectile travels along the launch channel without physical contact. Coil Type: Very large-diameter pulsed coils (designated MBM1, MBM2, …). Coil-Projectile Ratio: The inner diameter of each coil is approximately $D_c \approx 10 \times D_p$ (projectile diameter). Shields: Segmented, disk-shaped aluminum shields employed for eddy-current control. Cooling: The disk shields are cooled with liquid nitrogen or helium, enhancing their electrical conductivity. Projectile: Equipped with a diode-based cylindrical winding, which is excited during each MBM stage transition. Propulsion Mechanism: A bidirectional force system termed the Push-Pull Electromagnetic Launcher (PPEL).	Although a precise distance is not specified, the system is modular in nature, and therefore, a theoretically unlimited number of MBM units can be integrated. It is indicated that the system may be employed in applications such as satellite launch systems or long-range artillery projectiles.	No numerical value is given, but: The coils used have a large diameter → energy transfer $\propto Dc^2$.	The velocity is not precisely specified; however: magnetic field intensity reaches up to 100 Tesla. Magnetic pressure: 40,000 atmospheres (~4 GPa). With these values, it is projected that projectiles could reach high velocities on the order of 2 - 2.5 km per second.	The PPEL system differs from classical railguns and coilguns in that it uses both pushing and pulling forces simultaneously, resulting in more efficient acceleration. Because the projectile moves without contact, there are no frictional losses or energy disturbances caused by mechanical contact. The disk-shield system allows the magnetic field to be guided and concentrated into a narrow region. If the system is cooled to a superconducting state, $\mu r \rightarrow 0$, creating a diamagnetic environment that maximizes field focusing on the projectile. Thanks to its high energy density, it is suitable for missions such as orbital impact operations ("Space Sniper").	The coil inside the projectile is energized only during the moment of passage, minimizing energy loss. By directing eddy currents, excessive magnetic field compression is prevented. Its modular architecture makes the system scalable and suitable for multiple applications.	[29]

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Railgun-based electromagnetic launcher.	The launcher operates using a pulsed power supply (PPS) A modular capacitor-based PPS system with a total capacity of 4 MJ has been developed. The PPS is configured to be compact, portable, and capable of delivering high pulse currents.	Rails: Copper alloy, square cross-section of 25 mm × 25 mm, length of 3 meters. Barrel structure: Glass-reinforced composite material, supported with steel bolts for mechanical integrity. Armature: C-type aluminum alloy, fixed and conductive. No permanent magnets or coil-based field generation are used; the magnetic field is produced solely by the PPS.	No specific range is stated; total barrel length is 3 meters.	Experiment A: 850 kJ PPS energy was used. Experiment B: 992 kJ PPS energy was used. PPS modules have a capacity of 250 kJ and can be scaled modularly up to 4 MJ.	Experiment A: 42 g / 850 kJ / 2778 m/s / 2590 m/s (Simulation). Experiment B: 130 g / 992 kJ / 1560 m/s / 1480 m/s (Simulation).	A 3D Finite Element (FE) model provided detailed electromagnetic and mechanical analyses covering both the launcher and the PPS. Velocity Skin Effect (VSE) was included in the model as the key parameter influencing current distribution in the rails and armature at high velocities. A time-dependent analysis was conducted on the components of the launcher resistance (AC resistance, back EMF, VSE resistance), demonstrating that VSE becomes dominant at high velocities. Magnetic flux density up to 22.5 T was achieved.	Instead of a moving armature, the model used a fixed armature with externally defined velocity and displacement to reduce computational load.	[30]

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Electromagnetic Launching (EML) Four-rail railgun generating a quadrupole magnetic field (CFREL and the enhanced ECFREL types).	Quadrupole Magnetic Field Structure Improved magnetic field shielding through a primary + auxiliary rail configuration Reduction of magnetic interference and field leakage at the armature center	• Main Rail (copper + steel composite): Copper (400×15×40), Steel (400×5×40) Auxiliary Rail: Copper (400×20×40) Copper: High conductivity (5.8×10^7 S/m) -Steel: High hardness and wear resistance -Aluminum Armature: Lightweight and high conductivity (3.8×10^7 S/m) Launch Coils: Instead of a dedicated coil structure, the magnetic field is generated by passing a 500 kA current at 2 kHz through the rails Skin effect and eddy currents were taken into account Hollow, quadrupole-structured armatüre The armature contains four drainage springs to guide current flow and increase conductivity Dimensions: 80 × 80 × 40 mm -Structure: Extended rear tail for improved contact efficiency	Simulation-based study → no specific launch distance provided The analyzed launch section was modeled up to approximately 180 mm	Current amplitude: 500 kA, frequency: 2 kHz Net energy consumption not specified; thermal ablation and energy efficiency were analyzed	ECFREL (proposed): Fx (kN): 0.953 / Fy (kN): 1.568 / Fz (kN): 89.465 / Total Force (kN): 89.484 CFREL (baseline): Fx (kN): 1.032 / Fy (kN): 2.562 / Fz (kN): 40.044 / Total Force (kN): 40.139 No explicit velocity value given, but thrust was reported to have increased significantly	Current density at the armature-rail interface was reduced by 10.1% Magnetic shielding capacity increased by a factor of 2.42 in ECFREL Electromagnetic force nearly doubled Structural deformation was prevented by reducing Y- and Z-axis forces on the armature	High-accuracy electromagnetic analysis was conducted using the Finite Element Method (FEM) Weaknesses of CFREL (high current density, narrow shielding region, low thrust) were successfully mitigated with ECFREL For future work, compactification and field optimization are recommended due to the large structural volume	[31]

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Reluctance-type electromagnetic coil launcher.	Reverse-force suppression was implemented using a dumping resistor. Reverse-force suppression was examined via two methods: the open-circuit method (more effective but risky) and the resistor-damping method (safer and more suitable for engineering applications).	Coil: 400 turns, copper wire, 50 mm length, 20 mm thickness Armature: Q235 steel, hollow cylindrical structure, 15 mm length, 18 mm diameter, 40 g Capacitor: 340 μF - 780 V → ~103.5 J stored energy Dumping Resistor: 5-ohm resistor connected Modeling: 2D axisymmetric finite element analysis using Ansoft Maxwell	According to simulation data, the projectile was propelled forward by 240 mm.	Energy was discharged in a controlled manner using the dumping resistor Approximate energy: 103.5 J	Single-stage classical reluctance launcher: 13.9 m/s Reverse-force suppressed by open-circuit method: ~20 m/s Two-stage launcher with resistor: 29.8 m/s	The open-circuit method suppresses reverse force effectively but is unsafe Final projectile velocity is 114% higher with the resistor-based method Experimental and simulation results show strong agreement	This method is suitable for compact, low-cost, portable electromagnetic launchers In electronic circuit design, resistor-based damping is recommended over open-circuit switching Losses such as eddy currents and velocity skin effect (VSE) were not considered in the simulations	[32]
Induction-type electromagnetic launcher (MFEL - Multipole Field Electromagnetic Launcher).	Dual-layer, multipole magnetic-field structure. The inner and outer layers each consist of six saddle-shaped coils placed with a 30° angular offset.	Coil Type: Saddle-shaped, 12 coils in total (six inner, six outer) Coil Wire: 1.5 mm enamelled copper wire Coil Inductance: Inner: 49.686 μH, Outer: 56.22 μH Coil Resistance: Inner: 145.498 mΩ, Outer: 168.678 mΩ Armature: Slotless, hollow cylindrical aluminium sleeve (2A12 alloy) Support Structure: Cylindrical fiberglass tube with heavy-nylon base Capacitor Bank: 400 μF capacitor, charged up to 2500 V Circuit: Each layer is driven by its own capacitor bank, discharged simultaneously	Travel distance is not specified, but the armature motion was tested in a single stage.	Voltage: 2500 V Energy: 1.25 J (single layer), 2.5 J (dual layer)	Voltage: 2500 V - Linear velocity: 3.37 m/s - Rotational speed: 40.97 rpm Voltage: 20 kV (simulation) - Linear velocity: 183.79 m/s - Rotational speed: 3666.17 rpm	The new structure enables simultaneous linear and rotational motion. The rotational motion provides gyroscopic stabilization, helping the projectile maintain its trajectory. The dual-layer configuration produces higher linear and angular velocities compared to the single-layer design. The SDMFEL design can be integrated with other launcher systems.	The experimental system is operated using an FPGA-based data acquisition and control platform. Simulation and experimental results are generally consistent, although some discrepancies arise due to factors such as friction and mechanical deformation. Suggested improvements include the use of higher voltages, reducing circuit resistance, and improving manufacturing quality.	[33]

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Railgun (electromagnetic rail-type launcher) Magnetic-field-constrained architecture.	Magnetic-field confinement achieved using permanent magnets. This system aims to prevent uncontrolled spreading of the magnetic field and to enable the generation of a highly efficient and well-targeted Lorentz force.	Rail Material: High-conductivity metal (assumed copper) Magnets: Neodymium (NdFeB) permanent magnets arranged in various configurations Simulation Tools: Ansys Maxwell 2D and 3D electromagnetic simulations Rail Widths: 4 mm, 5 mm, 6 mm Rail Gaps: 20 mm, 30 mm, 40 mm Current Application: DC current applied through the launcher coils	Llaunch distance is provided, as the study focuses on simulating magnetic-field and force distributions rather than projectile motion.	No energy assessment is included, since the work is an optimization-oriented design study.	No launch or velocity data are reported.	Increasing rail width (4 mm → 6 mm) leads to stronger magnetic-field generation. Decreasing the gap between rails (40 mm → 20 mm) results in a more concentrated and centrally focused magnetic field. The highest Lorentz force and most effective field profile are obtained with rails 6 mm wide and spaced 20 mm apart. This configuration provides both efficient energy utilization and precise generation of targeted launch force.	The paper presents only magnetic-field distribution and electromagnetic-force simulations. It serves as a preliminary analysis for design optimization. The configuration is potentially suitable for military or precision-guided munition-launch systems requiring controlled electromagnetic force.	[34]
Electromagnetic launcher - DSLIM (Double-Sided Linear Induction Motor).	Multi-layer secondary plate structure (copper + aluminum); secondary topology optimized to increase terminal velocity.	Launcher dimensions: 600 mm; Payload: 4 kg (drone); Power: 4 kW, 3-phase AC supply. DSLIM test setup includes adjustable air gap - 10 mm Al plate or 3 mm Cu + 2×1 mm Al composite.	Motor length: 600 mm	Power: 4 kW (3-phase AC supply)	Terminal velocity with conventional plate = X m/s (numerical value not provided). Terminal velocity increase with three-layer optimized plate: 28.37%. Total increase compared to conventional topology (including optimization): 36.21% + 5.68% = 41.89%.	Behaves similarly to the deep bar effect, providing optimum torque during launch. Results validated through 3D FEM simulations and experimental testing.	Launcher focuses on terminal velocity against a fixed payload, with power factor and force ripple as secondary considerations. Experimental deviations exist due to high friction.	[35]

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Electromagnetic Launcher (Coilgun / Reluctance type).	Capacitor bank, thyristor triggering, PIC16f877A-controlled velocity and voltage measurement circuit.	Coil inner diameter: 15 mm Four different coil lengths: 15 mm, 20 mm, 50 mm, 100 mm Capacitor bank: 5000 µF - 450 VDC Power supplies: 2 × 12 V, 5 V, 6 V, 500 V DC	Measurement range: 10 mm (for velocity measurement); projectile length: 20 mm (ferromagnetic) .	Maximum charging voltage: 230 V (tested with parallel and series configurations).	Maximum velocities: – 20 mm coil, parallel connection, 200 V: 14.87 m/s – Conical coil, 230 V: 9.22 m/s – Straight coil, 230 V: 2.87 m/s	The 20 mm coil achieved the highest velocity and maximum efficiency (3.01%). The conical coil is significantly more efficient than the straight coil; it reduces deceleration forces. Parallel winding method provides higher velocity compared to series winding. Inductance variation (ΔL = 60-64 µH) is directly correlated with the maximum velocity.	The entire system was physically constructed. Velocity measurements were performed between two light gates (10 mm apart). Magnetic flux lines were simulated using FEMM 4.2. The conical coil reduced projectile lag effects and improved overall performance.	[36]
Modular Augmented Staged Electromagnetic Launcher.	Independent power feed unit (PFU) for each segment Equal-length segment design Coil and rail geometry optimized to increase magnetic coupling Advanced electromagnetic modeling based on 3D FEM was used	Rail width: 5 mm • Distance between rails: 9 mm Number of coil turns: 8 (optimum) Total number of segments: 14-16 (variants tested) Current: Up to 67.9 kA in the main circuit Load: Simulated with properties similar to real ammunition Modeling: Comparative analyses using 3D FEM and time-domain solvers	Launch length not explicitly given, but analyses were conducted using fixed segment lengths Velocity distribution analyses were performed through simulation depending on the segment configuration	Different segmentation strategies were tested with constant total energy input Each segment's PFU (Power Feed Unit) is independently controlled Energy, efficiency losses, and system stability were evaluated, though values were not presented directly in joules	With synchronous segmentation: 1.8 km/s With equal-length segmentation and optimization: 2.272 km/s Improvement: approximately 41.9% increase in velocity	Equal-length segment design delivered higher performance than synchronous segmentation Precise design of coil turn count and rail geometry played a critical role in velocity improvement As the number of segments increases, terminal velocity rises; however, the optimum is between 14 and 16 FEM analyses show consistency with physical test results	Provides a guiding model for high-velocity projectile systems and railgun applications Independence of driver segments ensures system stability	[37]
Two-Stage Reluctance Coil Launcher (an electromagnetic system accelerating a ferromagnetic armature using coil current).	IGBT-based dual energy recovery circuits: - Type 1: Stores residual energy in a capacitor for use in the next shot. - Type 2: Transfers energy from the previous stage instantly to the next stage.	Capacitor: 820 µF Voltage: 406 V (Type 1), 600/406 V (Type 2) Armature: 45# carbon steel, 25.6 g Coil: Copper Switch: IGBT (650 V, 480 A)	Two-stage configuration Stage 1 IGBT duration: 2 ms Stage 2 duration: 0.8 ms Trigger delay: 2 ms	Initial energy: 135 - 213 J Type 1: 10 J energy recovery, 10.36% efficiency Type 2: 36.5 J energy recovery, 10.49 - 12.26% efficiency	Classical: 27.5 m/s (7.16%) Type 1: 33.1 m/s (10.36%) Type 2: 41.8 m/s (10.5 - 12.3%)	Classical: 27.5 m/s (7.16%) Type 1: 33.1 m/s (10.36%) Type 2: 41.8 m/s (10.5 - 12.3%)	Energy recovery reduces drag, improving velocity and efficiency. Simulation and experimental results are consistent (stable over 400 tests). ±0.02 ms IGBT error is negligible.	[38]

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Inductive-type Electromagnetic Launcher (IEL) with a ring-shaped, dual-fin armature structure.	• Fixed-core + coil configuration. The magnetic field is generated by coil current, providing thrust via the Lorentz force. Analyzed using FEMM and ANSYS.	Voltage: 100-500 V DC Current: 80 A Maximum magnetic flux density: 0.039 T Coil: 48 mm height, 42.75 mm width Armature: 27 mm height, 50 mm width, 90 mm length Air gap: 2 mm	• Armature has a 600 mm long dual-fin structure. Launch motion is linear, accelerated by Lorentz force.	Simulated at 100-500 V. - Resistances: R_1 = 0.1 Ω, R_2 = 100 Ω, R_3 = 5000 Ω. -Capacitors: 0.0004 µF and 0.1 µF.	At 500 V, generates 156 N force and 2 m/s velocity; under the same conditions, output velocity can scale up to 425 m/s.	Magnetic flux density analysis observed flow along 10 flux tubes. Self and mutual inductances were calculated using the magnetic circuit model. Simulation indicates suitability of the model for high-velocity applications.	The model is applicable to compact, high-velocity systems. Thrust increases linearly with voltage (65 N → 156 N). Velocity increase is proportional to energy efficiency.	[39]
Four-stage Synchronous Induction Coil Launcher (SICL); two energy directions were compared: PP (current in the same direction) and PN (current in opposite direction).	The objective was to increase armature velocity by manipulating coil current directions (PP-PN). Analysis was performed using FEM (ANSYS Maxwell 2022R2). Each coil was triggered with individual timing.	Four-stage coil system Coil inner radius: 43 mm Length: 20 mm, 40 turns, copper wire Armature: Aluminum, 50 g, 20 mm length Capacitor: 0.6 mF (stages 1 - 2, 1 kV) / 0.266 mF (stages 3-4, 1.5 kV)	Stage gaps tested: D = 5 mm and D = 15 mm. Optimal triggering position and duration were individually determined for each stage.	300 J input energy applied per stage. In PN configuration, energy loss is reduced due to flyback diodes. In PP, induced currents are limited because currents are in the same direction.	For D = 5 mm, PP is faster. For D = 15 mm, PN is faster. In PN, braking force is low, achieving exit velocities up to 70-80 m/s.	Coil current direction and stage spacing determine launch efficiency. PP is more efficient at short distances, PN at longer distances. Induced current direction governs acceleration and braking.	Current direction selection must consider system geometry. Diode placement and mutual inductance affect the system. Simulation results are consistent with theoretical models.	[40]
Flat-coil type electromagnetic launcher. Three models were compared: APAS (Aluminum Plate Armature) ICAS (Inductive Coil Armature) DFAS (Direct-Fed Armature)	Analysis based on FEM and numerical simulations. Thrust is generated through coil-current interaction. DFAS employs direct-contact feeding, whereas the others use inductive feeding.	DFAS peak current: 21.1 kA ICAS peak current: 28.3 kA APAS peak current: 28.0 kA Magnetic induction (peak): 4.7 T (DFAS) - 0.008 T (APAS) Voltage: 1-1.5 kV Material: Aluminum alloy	The model is intended for low-mass projectiles. Motion occurs in the 0-51 m/s range over a short distance (<1 m). Current direction and armature type determine acceleration.	DFAS: 29.7% APAS: 24.4% ICAS: 13.4% DFAS achieves higher efficiency with lower current.	DFAS: 51 m/s APAS: 46.2 m/s ICAS: 34.2 m/s	DFAS demonstrates the highest efficiency. APAS is the safest in terms of electromagnetic shielding. ICAS is unstable under high flux. Flat structure allows for volume savings.	Maximum stress in all systems < 42.5 MPa. APAS shielding performance is limited to 0.008 T. The requirement for sliding contacts in DFAS may pose engineering challenges. APAS is simpler, more cost-effective, and practically applicable.	[41]

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Multi-stage Electromagnetic Coil Launcher (EMCL); multi-phase system with GFRP insulating structure.	• Three-phase, six-coil configuration with GFRP-insulated body. Coils are T2 copper with a phenolic epoxy resin matrix reinforced with glass fiber. Thermal, electromagnetic, and structural fields are integrated into a FEM model.	Coils: 6 units (A1, A2, B1, B2, C1, C2) Current: 70 kA peak (three-phase pulse) Magnetic field: 19 T (maximum) Temperature rise: 293 → 301 K (over 3 ms) Material: GFRP + epoxy Model: 2D axisymmetric, 4-node elements	Acceleration duration ≈ 3.5 ms; diameter: 120 mm; multi-stage phase sequence (A-B-C). Stress and deformation analyses conducted axially and radially.	Three-stage pulsed current applied in each phase; maximum 70 kA sustained over 3 ms. Local energy density limited by 17-19 T field.	Experimental velocity data not provided; focus is on insulating deformation rather than projectile velocity. Performance degradation observed under stress.	Primary damage mechanisms: stress exceedance and accumulation of plastic deformation. Temperature increase is low (~10 K), so thermal degradation is negligible. Weak regions of GFRP: inner wall and inter-phase partitions. Short-circuit currents accelerate crack formation.	Service life of GFRP is limited; current design is inadequate for long-term use. Fiber orientation should align with electromagnetic loading. Proposed improvement: radial/axial "disconnect-type" design. Insulating and mechanical performance should be optimized concurrently.	[42]
Electromagnetic Railgun (EM Railgun) - analysis of conductive/magnetic shielding effects for the casing and internal system.	2D axisymmetric model; shield materials: copper, aluminum (conductive); low-carbon steel, permalloy (magnetic). Simulation results are compared with experiments.	Input current: double exponential pulse, 2694 A peak, decays over 23.4 ms Magnetic field: 3.6 T (without shielding) Shield thickness: 5 mm Material properties: copper (6×10^7 S/m), aluminum (3.77×10^7 S/m), steel (8.4×10^6 S/m), permalloy (1.7×10^6 S/m)	Analysis conducted at measurement points (P1-P9) along the core; firing duration ≈ 0-20 ms; casing length 400 mm	1 MJ pulse power system; 3.2 mF capacitor bank; voltage range 0 - 25 kV; current peak 2694 A	Velocity measurement not performed - focus is on magnetic field variation. Simulation and experimental curves show good agreement (max difference ≈ 0.1 T)	Copper shield reduces peak field by 19.7% (1.91 dB) Aluminum: 11.4% (1.05 dB) Steel: 3.6% (0.32 dB) Permalloy: 0.1% (0.1 dB) Multi-layer shields (outer conductive + inner magnetic) achieved the best results, with attenuation up to 61 dB Shield delays the peak of the magnetic field and increases the pulse width	Most efficient configuration: highly conductive material at the rear, high-permeability material at the front Measured delay in dynamic firing test: 7.2 ms Shielded structure exhibits smoother and lower-noise magnetic field variation.	[43]
Hybrid armature electromagnetic coil launcher. Combination of reluctance and induction type coil systems.	Ferromagnetic + conductive (aluminum) armature combined. Ferromagnetic tip aligned with the end of the coil, conductive tip aligned with the coil center. Simulation and experimental validation performed.	Diameters: 11.8 mm, 18.4 mm, 50 mm Ferromagnetic: 45# steel Conductive: aluminum Capacitor: 1 - 3 kV Current: 8 - 70 kA range Model: 2D axisymmetric FEM	11.8 mm: single stage 18.4 mm: 7 stages 50 mm: single stage Stage spacing optimized (D = 5 - 15 mm)	11.8 mm: 1000 V 18.4 mm, 7-stage: 1 kV 50 mm: 1000-3000 V Energy efficiency: 2 - 9% • Input energy: ~1 - 2 MJ	11.8 mm: 16-17 m/s 18.4 mm: 53-58 m/s 50 mm: 16.6-52.1 m/sm/s	Small diameter (11.8 mm): pure ferromagnetic armature more efficient (4.9%) Medium diameter (18.4 mm): hybrid achieves best efficiency, 9.12% (↑4%) Large diameter (50 mm): 2000 V → 7.87% efficiency (↑5%), 3000 V → efficiency decreases due to magnetic saturation	Hybrid structure increases efficiency, but effectiveness decreases at high voltage Efficiency improvement is limited by diameter Simulation and experiment show good agreement For practical applications, diameter-based hybrid selection is recommended	[44]

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Electromagnetic railgun - efficiency estimation improved with Artificial Neural Network (BP) and Particle Swarm Optimization (PSO).	Three-layer PSO-BP neural network (4 input, 9 hidden, 1 output neurons). Data obtained from experimental results. PSO optimizes network weights to reduce error.	Input variables: Rail spacing (14 - 22 mm), Rail height (14 - 20 mm), Curvature height (0 - 2 mm), Rail thickness (6 - 10 mm) Learning rate: 0.05 Training: 1000 iterations	Cross-section optimized through parameter variation: 14-22 mm range. Experimentally, efficiency was measured, not velocity.	BP and PSO-BP models trained over 1000 epochs. Energy variations were not directly measured, but neural network errors: BP MAE = 0.70%, PSO-BP MAE = 0.28%	Neural network predicts efficiency, not launch velocity. Launch velocity was not used experimentally.	Efficiency increase per parameter: - Rail spacing ↑ → +0.71%/mm - Rail height ↑ → +0.61%/mm - Curvature height ↑ → +1.10%/mm - Rail thickness ↑ → −0.19%/mm Parameter influence order: Curvature height > Rail spacing > Rail height > Rail thickness PSO-BP model prediction accuracy: 99.1%	PSO-BP method can predict electromagnetic launcher efficiency with high accuracy. Average absolute error reduced by 59%. AI-based prediction models are applicable in design optimization.	[45]
Electromagnetic (EM) Space Launcher – analysis of railgun, coilgun, and linear motor-based systems for space-launch applications. Includes both Earth-based and Moon-based scenarios.	Different systems compared: -Railgun -Coilgun (Lunatron, Mass Driver) -Linear synchronous motor (LSM) Energy storage options: capacitors, inductors, MHD or MFCG systems.	Energy requirement: 100 MJ/kg (for 8 km/s, with 32% efficiency). Achieved velocities: 5 km/s (railgun), 1 km/s (coilgun). Pulsed-power system cost: ≈500,000 $/MJ. Target: <10,000 $/MJ (50× cost reduction).	For LEO, 7.8 km/s is required, but 9 km/s is targeted to compensate for atmosphere + gravity. Escape velocity: 11.2 km/s. On the Moon, required velocities: 1.65-2.38 km/s (easily achievable).	Launching a 1-kg payload to 8 km/s requires 100 MJ input energy. Electricity cost: 2.8 $/kg (4× cheaper than chemical fuel). However, pulsed-power hardware is expensive.	Laboratory railguns: 5 km/s Coilguns: 1 km/s Lunar environment target: 2.38 km/s (feasible).	EM launch is highly efficient in terms of propellant, but system cost is high. Absence of atmosphere on the Moon allows exceeding material and velocity limits more easily. Major limiting factors: cost and power density. “MagLifter” and “Startram” concepts are discussed as examples.	Earth-based EM launch is limited by aerodynamic heating. Moon-based systems (LEMMA, Mass Driver) are feasible. For human transport, liquid-breathing support (to withstand high G-loads) has been proposed. EM systems are strategic for space defense and resource transport.	[46]
Three-phase modular linear-rotary switched reluctance launcher (MLRSRL). Hybrid structure capable of producing both rotational and linear motion.	Modular stator and rotor: 6 ferromagnetic rings Each ring has 6 U-shaped ferromagnetic blocks Three-phase windings are used for both linear and rotary power generation.	Material: 50DW470 silicon steel Average magnetic flux density: 1.6-1.8 T 3-phase, centralized winding configuration Stator/rotor air gap optimized Rotor: 20 mm module depth, 4 mm edge width	Linear motion range: 0-90 mm Rotary structure: 12/10 poles Phase gaps: 5-15 mm	Average current: 7-9 A (CCC control) Voltage: ~1 kV Energy model: FEM + Simulink, including magnetic saturation	Average torque: 42.7 Nm Average thrust: 145.5 Nm Torque ripple: 68.8% Thrust ripple: 64.5%	Modular design shortens the magnetic path, increasing torque density by 38% and thrust density by 44%. Manufacturing cost reduced by 31%. Optimal parameters: α = 27°, β = 29°, h_1 = 20 mm, h_2 = 4 mm.	3D magnetic flux distribution in the air gap has been optimized. Saturation analysis and sensitivity testing achieved maximum performance. Lighter and more efficient compared to conventional LRSRL.	[47]

3. Findings

3.1. The Evolution of Magnetic Launch Technologies

Studies published between 2019 and 2025 indicate that a significant transformation has occurred in magnetic launch systems. The systems developed during this period can generally be classified as electromagnetic (coil-gun), rail-based (railgun), linear-motor-supported (linear launcher), and superconducting maglev-based approaches. Initially limited to laboratory-scale prototypes, these systems have in recent years approached an applicable level in various fields such as unmanned aerial vehicle (UAV) launch, micro-satellite launch, defense systems, and space technologies. In particular, high-lift and low-friction systems developed using superconducting materials (YBCO, YBaCuO) and neodymium magnets (NdFeB) provide a safer, more repeatable, and energy-efficient alternative compared to conventional mechanical or chemical launch solutions.

Coilgun: With the capability to accelerate a 1 kg payload to a muzzle velocity of 140 m/s, this offers a suitable architecture for scenarios prioritizing portability and cost advantages.

Railgun: Distinct from other systems due to its speed potential, velocities reaching levels of ~394 m/s have been reported in model/experiment comparisons. This structure stands out as the most rational choice for scenarios targeting high-speed and high-mass outputs.

Magnetic Levitation: Operating on linear motor and magnetic levitation principles, this system focuses on lower but highly controlled velocities, such as 2.2 m/s. This velocity profile presents a strong argument for platform integrations requiring system stability, repeatability, and precise acceleration control.

3.2. Technical Barriers in Experimental Stages: Thermal Management and Operational Duration

Nearly all studies in the literature indicate that these technologies are still in the experimental stage and involve various engineering limitations. For example, open cryostats with liquid nitrogen used in superconducting systems provide only 30 minutes of active levitation time, which constitutes a significant limitation for long-duration operations. Similarly, in electromagnetic launchers, heat accumulation weakens coil insulation under high current pulses and shortens the system's operational lifetime. Although some studies partially mitigate this issue through fan-assisted air-cooling systems, the increase in energy consumption and the resulting loss of efficiency become unavoidable.

3.3. Renewable Energy Integration and Power Management in Magnetic Launch Systems

When evaluated in terms of energy sources, renewable-energy-supported launcher systems powered by solar panels attracted significant attention in the 2020s. These systems provided approximately 11,000 J of energy generation using 5 kW solar panels, offering portable and off-grid solutions. However, the lack of MPPT (Maximum Power Point Tracking) algorithms in these systems reduced energy conversion efficiency and caused interruptions in consecutive shots due to the long cooling duration.

3.4. Performance Analysis of Multi-Stage Coil Systems and Synchronization Challenges

It has been observed that multi-stage coilgun systems in electromagnetic launchers exhibit a clear performance superiority over single-coil systems, and that 3 - 10 stage configurations can increase both velocity and efficiency by more than twofold. However, triggering timing and inter-coil synchronization still remain major problems; in cases of incorrect timing, the system generates a reverse force, thereby reducing the projectile's acceleration.

3.5. Intelligent Control Systems and AI Integration in Magnetic Launchers

Another trend that has become prominent in studies conducted after 2023 is the integration of intelligent control systems and artificial-intelligence-based position estimation algorithms (such as Time-Delay MLNN) into the launch process. Through these approaches, sensorless position detection and dynamic current adjustment have become possible, achieving accuracy rates above 94%. However, most of these models have remained limited to single-phase or small-scale experimental setups and have not yet reached a level capable of handling high-frequency electromagnetic induction (EMI) issues at an industrial scale.

3.6. Material Optimization and Thermal Endurance in Railgun Systems

Research conducted on rail-based systems (railguns), on the other hand, has focused on thermal endurance and material optimization. It has been determined that copper-steel composite rails improve heat distribution by 40 - 50% compared to conventional copper rails and extend rail lifetime. Nevertheless, although these systems can reach a magnetic field density of 1.35 T even under high current pulses (above 25,000 A), they still cannot be widely implemented due to the high-cost material requirements.

4. Conclusion and Recommendation

According to studies published between 2019 and 2025, magnetic launcher technologies have developed across a wide spectrum, including electromagnetic (coilgun), superconducting (maglev), linear-motor, and solar-powered hybrid systems. A prominent trend during this period is the increase of electromagnetic solutions aimed at high energy efficiency and modular design, as alternatives to conventional explosive or chemical propulsion. However, a review of the current literature indicates that most systems remain at the laboratory scale, and full optimization in fundamental areas such as energy density, cooling efficiency, synchronization algorithms, and material durability has not yet been achieved. In particular, short cooling durations and dependence on liquid nitrogen in superconducting systems, as well as heat accumulation and efficiency loss in electromagnetic launchers, represent the most critical limiting factors. Moreover, in applications requiring high velocity and acceleration, suppression of stray magnetic fields, armature geometry, and material selection remain engineering challenges that must be addressed. Although the literature suggests that magnetic launch technologies are moving toward a low-cost, environmentally friendly, and modular future, comprehensive solutions for energy density, thermal management, electromagnetic compatibility, and scalability have not yet been established. Overall, these findings indicate that magnetic launchers represent a promising technology for space, defense, and unmanned aerial vehicle applications, yet they are still maturing at an experimental level.

The thermal management performance of electromagnetic launchers has been studied in the literature at various levels of detail. In conventional fan-assisted systems, a one-second pulse generates a current thermal load of approximately 200 kW. This load is managed with 1.5 kW of cooling power and a total energy budget of ~11 kJ. Although the system maintains a temperature of 75˚C, a complete cool-down time of approximately 17.4 minutes is required. In contrast, YBCO superconductor-based architectures offer significant operational continuity. Operating time is ~30 minutes in an open cryostat and over 30 hours in a vacuum environment. However, direct energy consumption data for these systems is not presented in the literature. This lack of data prevents the derivation of common metrics such as "energy cost per shot" and an objective comparison between systems.

Review data indicate that electromagnetic launchers can be tailored to specific mission profiles based on their acceleration characteristics and energy infrastructure. In the UAV segment, HTS-based contactless maglev launchers emerge as the optimal solution due to their modularity and reduced takeoff distances, while for micro-satellite launches, the SCLSM architecture offers a more viable approach than currently immature airborne concepts, driven by its superior thrust capacity. In the defense sector, multi-stage reluctance (TREL/TCREL) configurations targeting high efficiency and velocity and high-force multi-pole coil (MFEML) structures constitute potent alternatives to conventional systems. Ultimately, the operational sustainability of these architectures is contingent upon the integration of composite material technologies to enhance the thermal-mechanical resilience of rail and conductor components.

Future research should focus on the industrial scalability and long-term thermal endurance of these systems. Firstly, closed-loop cooling systems and composite heat-distribution materials should be developed to reduce the cryogenic (low-temperature) requirements of high-temperature superconductors (HTS). In electromagnetic launchers, approaches such as energy recovery, current shaping algorithms, and artificial-intelligence-assisted trigger control can significantly enhance efficiency. Additionally, the integration of MPPT (Maximum Power Point Tracking)-based hybrid energy systems (solar and wind) can ensure energy continuity in portable systems. For rail and coil systems, next-generation high-permeability shielding materials and parametric optimization models should be employed to address material fatigue, stray-field attenuation, and EMI protection. Finally, since most current studies are limited to single-axis prototypes, the development of multi-axis and dynamic control-supported systems (e.g., VR-integrated test platforms) will accelerate the maturation of the technology in both academic and applied domains.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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