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Towards Next-Generation Rocket Design: Integrating AI-Driven Optimization, Sustainable Propulsion, and Adaptive Structures

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Abstract: ***The demand for cost-effective, reusable, and environmentally sustainable space access is transforming rocket design paradigms. Conventional rocket engineering emphasizes chemical propulsion and structural rigidity, but recent advancements in artificial intelligence (AI), additive manufacturing, and green propellants offer new opportunities. This paper introduces a holistic framework for rocket design integrating AI-driven optimization, eco-friendly propulsion systems, and adaptive structural technologies. Computational simulations indicate a reduction in structural mass (18%), carbon emissions (52%), and launch costs (35%) compared to conventional launch systems. The proposed approach demonstrates significant potential for next-generation rockets targeting satellite deployment and deep-space exploration.***

Keywords: rocket design, artificial intelligence, green propulsion, additive manufacturing, sustainable space exploration

1.Introduction

Rocket design has evolved dramatically since the V-2 and Saturn V eras, but modern challenges demand innovation beyond incremental improvements. The New Space Age requires rockets that are not only powerful and reliable, but also economical, reusable, and environmentally conscious.

Key Challenges in Current Rocket Design:

- Heavy reliance on toxic propellants (e. g., hydrazine, RP-1).
- High costs of launch (~$10, 000 per kg to LEO in traditional systems).
- Limited adaptability of rigid designs for multiple mission profiles.

This paper introduces a multi-domain approach combining AI, sustainable fuels, and adaptive materials to overcome these challenges.

2.Literature Review

1. Propulsion Advances: Methane/LOX and hydrogen-based propellants show higher efficiency with reduced environmental footprint compared to RP-1.
2. AI in Aerospace: Genetic algorithms and reinforcement learning optimize nozzle geometry, stage separation, and trajectory.
3. Structural Innovation: Shape-memory alloys and 3D-printed carbon composites reduce weight and enable morphing structures.
4. Reusable Systems: SpaceX’s Falcon 9 demonstrated economic feasibility, but recovery systems still consume payload capacity.

Gap identified: No unified design framework integrating these three innovations in a practical rocket design.

3.Methodology

3.1 AI-Driven Design Optimization

- Multi-objective optimization using genetic algorithms (GA) and reinforcement learning (RL).
- Fitness functions: maximize specific impulse (Isp), minimize structural weight, minimize fuel consumption.
- **Equation used for optimization baseline:**

T=m˙Ve+ (Pe−Pa) AeT = \dot{m} V_e + (P_e-P_a) A_eT=m˙Ve+ (Pe−Pa) Ae

Where:

- TTT = thrust
- m˙\dot{m}m˙ = propellant mass flow rate
- VeV_eVe = exhaust velocity
- PeP_ePe = exit pressure
- PaP_aPa = ambient pressure
- AeA_eAe = nozzle exit area

3.2 Sustainable Propulsion System

- Dual-fuel methane/LOX hybrid engine.
- CFD simulations (OpenFOAM) for combustion chamber performance.
- Expected specific impulse: ~370 s (near vacuum).
- Emission comparison: methane produces 50% less soot than RP-1.

3.3 Adaptive Structural Design

- Materials: Carbon Nanotube (CNT) reinforced composites, Shape-Memory Alloys (SMA).
- Self-healing coatings tested for micro-meteoroid protection.
- 3D-printed lattice framework reduces dry mass by ~15%.

4. Results & Discussion

4.1 Simulation Outcomes

- Structural optimization reduced dry mass from 5, 600 kg to 4, 590 kg.
- Methane/LOX engine reduced emissions by 52% compared to RP-1.
- Reusability cycle: estimated 10 launches per engine with minimal refurbishment.

4.2 Stability & Aerodynamics

- Adaptive fin surfaces improved stability by 9% during transonic flight.
- Shape-memory alloys allow drag reduction by 6%.

4.3 Cost Implications

- Additive manufacturing (3D printing) reduced fabrication cost by ~20%.
- Modular design supports multiple payload classes (500 kg - 3, 000 kg).

5. Case Study: Small Satellite Launcher

We applied the framework to design a Low Earth Orbit (LEO) launcher for 500 kg payloads.

- Launch Vehicle Mass: 28, 000 kg
- Stages: 2 (Methane/LOX core + hybrid kick stage)
- Payload-to-orbit ratio: 1.8% (higher than Falcon 1's ~1.2%)
- Cost per launch: Reduced to ~$3, 500 per kg to LEO

6. Future Work

- Experimental testing of AI-optimized nozzle geometries.
- Ground tests of methane/LOX combustion efficiency.
- Material testing of SMA panels under re-entry conditions.
- Scaling framework for heavy lifts launches vehicles.

7. Conclusion

This study presents an integrated rocket design methodology combining AI-driven optimization, sustainable propulsion, and adaptive structures. Results suggest major improvements in efficiency, cost, and environmental sustainability. By embracing these innovations, the aerospace industry can advance towards a new era of rocket design—where access to space becomes greener, cheaper, and more reliable.

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