MARTIAN EXPLORATORY GUIDANCE AIRCRAFT (MEGA) ROCKET

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ABSTRACT

The Martian Exploratory Guidance Aircraft (MEGA) is a research proof-of-concept designed to evaluate the feasibility of rocket-launched gliders for extraterrestrial reconnaissance. This paper details Phase 1 of development: the integration of ArduPilot-based avionics and a custom ground-station command loop. While the platform's logic is designed for Martian deployment, current aerodynamics and testing are Earth-optimized to validate the control software. A critical assumption of this research is the GPS-to-Visual Odometry (VO) proxy, where Earth-based GPS navigation serves as a functional substitute for Martian localized vision-based navigation. Newly observed findings include the verification of a low-latency manual command injection system using Python on an M1 Mac and the implementation of dual-zone cooling for internal avionics. Phase 2 will focus on autonomous "Guided" missions, using computer vision to dynamically generate waypoints for geological investigation and landing zone identification.

INTRODUCTION

Motivation

The current imperative in planetary exploration necessitates the development of agile reconnaissance platforms capable of rapidly acquiring localized, high-resolution data. MEGA Rocket is designed to satisfy that imperative. As a rocket-launched surveillance drone, this system can be deployed and reached operational altitude in a matter of seconds. Once in the air, it performs controlled flight and gathers data using a suite of internal sensors. It uses onboard computer vision processing to identify then investigate points of interest as well as safe landing sites.

Problem Statement

Current terrestrial drone systems successfully perform surveillance and mapping tasks. However, these copter-style platforms function poorly in the significantly thinner Martian atmosphere. The objective of this project is to provide astronauts with the same high-fidelity terrain mapping capabilities available on Earth. On Mars, the low atmospheric density and challenging terrain render conventional propellers inefficient for generating lift and ensuring safe landings.

Rotorcraft Limitations: NASA's Ingenuity helicopter, a pioneering solution, featured relatively large propellers that spun at 2400 rpm to achieve flight in the Martian environment [6]. For comparison, identical propellers would generate sufficient lift at approximately one-tenth of this rotational speed on Earth. Despite these design challenges, Ingenuity successfully demonstrated Martian atmospheric flight, exceeding its planned mission duration with 72 flights before a blade sustained damage during its final landing. While Ingenuity proved feasibility, its design as a proof-of-concept limited its maneuverability, operational range (up to 160 feet horizontally), and altitude (10-15 feet above ground).

Fixed-Wing Advantage and Operational Gaps: The Martian Exploratory Guidance Aircraft (MEGA) is designed to overcome these rotorcraft limitations by achieving higher altitudes, greater speeds, and extended operational ranges. Mars's thin atmosphere poses less of an issue for fixed-wing flight, as lift is generated through forward airspeed. While this necessitates higher flight speeds compared to Earth, it presents a less complex design challenge than developing rotor and motor systems capable of generating ten times the lift required in a terrestrial environment.

Beyond specialized drone systems, reliable high-fidelity aerial terrain mapping on Mars is currently unsupported. Existing orbital satellites provide visual data but lack the resolution necessary for detailed terrain mapping. Moreover, these satellites adhere to predefined orbits, offering limited control over their observation times. Given Mars's propensity for violent dust storms that can rapidly alter terrain, the ability to quickly reorient and map damaged areas after a storm is mission-critical for surface operations.

NASA is currently developing a next-generation Mars helicopter featuring a larger design with six blades. The MEGA rocket design offers a distinct advantage by remaining significantly smaller and lighter than such proposed rotorcraft. This reduction in mass translates to a lower operating cost and decreased payload requirements for orbital insertion, allowing NASA to allocate more valuable weight to other mission-critical equipment.

Project Objectives

The primary objective is the design and development of a rocket-launched surveillance drone capable of autonomous flight and data acquisition. The proposed design incorporates a standard solid rocket motor for ballistic ascent. Upon motor burnout, the Martian Exploratory Guidance Aircraft (MEGA) transitions to glider mode, wherein wings deploy from the rocket fuselage. Controlled flight is subsequently achieved through the manipulation of controllable tail fin surfaces.

The internal architecture includes a data hub equipped for collecting and transmitting sensor data to a ground station during flight. For initial validation and testing, a suite of standard onboard telemetry instrumentation and a digital camera will be utilized for data gathering. The modular payload bay is designed to accommodate various sensor packages. For instance, the digital camera can be augmented or replaced with advanced sensors, such as a LiDAR system for high-resolution three-dimensional terrain mapping. This contrasts with previous platforms like NASA's Ingenuity, which primarily utilized conventional imaging sensors. The integration of a LiDAR sensor significantly enhances the platform's capability to gather precise 3D terrain data, offering substantially higher resolution and detailed topographic information.

THEORETICAL BACKGROUND

Literature Review

The current paradigm of Martian exploration is defined by three distinct tiers of observation, each with inherent trade-offs in resolution, speed, and energy efficiency. The Martian Exploratory Guidance Aircraft (MEGA) is designed to bridge the "data gap" between these modalities.

Surface Rovers: Current rover missions, such as *Perseverance*, are limited by significant mobility constraints. Maimone et al. [2] detail how the reliance on onboard Visual Odometry (VO) and the necessity for hazard avoidance restricts rover speeds to approximately 0.1 mph. This creates a "tactical blindness" where geological features beyond the immediate ridge cannot be assessed in real-time. The MEGA platform directly addresses this by offering rapid aerial reconnaissance to scout terrain ahead of surface assets, overcoming line-of-sight limitations.

Orbital Satellites: Orbital platforms provide global coverage, but remain decoupled from the surface. The HiRISE instrument on the Mars Reconnaissance Orbiter (MRO) offers the highest available resolution at 0.25 m/pixel. However, McEwen et al. [3] emphasize that even at this resolution, satellites cannot provide the low-angle perspective or the high-frequency atmospheric data required for localized scouting. MEGA aims to complement orbital data by providing on-demand, low-altitude perspectives and localized, high-resolution imaging unavailable from orbit.

Aerial Rotorcraft: The *Ingenuity* helicopter demonstrated the feasibility of Martian flight but highlighted the extreme energy cost of lift. Balaram et al. [1] explain that because the Martian atmosphere is $\approx 1\%$ of Earth's density, rotors must spin at 2400 rpm to sustain lift, severely limiting flight duration and payload capacity. MEGA's fixed-wing glider design offers a more energy-efficient solution for extended flight durations and greater payload potential in thin atmospheres by leveraging forward airspeed for lift.

Tube-Launched UAV Mechanics and Transition: The transition from a compact, stowed configuration within a cylindrical launch vehicle to a fully deployed aerodynamic state is a primary engineering challenge for the MEGA platform. Finigian et al. [5] provide a foundational case study and technical guidance in the design and flight testing tube-launched UAVs. This research directly informs MEGA's critical mechanical systems for robust, repeatable mid-air wing deployment from a rocket fairing.

Governing Physics

The MEGA mission involves three distinct physical regimes: ballistic ascent, mechanical geometry transition, and fixed-wing glide.

Aerodynamic Stability: The stability of the vehicle is defined by the Static Margin (SM), the distance between the Center of Gravity (X_{CG}) and the Center of Pressure (X_{CP}), normalized by the mean aerodynamic chord ($\bar{c}$):

$$SM = \frac{X_{CP} - X_{CG}}{\bar{c}} \tag{1}$$

The "wine-opener" rack-and-pinion mechanism must move the X_{CG} forward during wing deployment to transition from a rocket's high-stability margin to a glider's maneuverable margin.

Mars Scaling and Reynolds Number: To justify an Earth-based demonstration for a Martian application, we utilize the Reynolds Number (Re), which characterizes the flow regime:

$$Re = \frac{\rho v c}{\mu} \tag{2}$$

Where ρ is density, v is velocity, and c is the chord length. Because $\rho_{Mars} \approx 0.01\rho_{Earth}$, the Martian version of MEGA requires significantly larger wing surface area (S) to generate equivalent lift (L) as defined by:

$$L = \frac{1}{2}\rho v^2 S C_L \tag{3}$$

Assumptions

To focus the scope of this technology demonstration, the following assumptions are made:

GPS-to-VO Proxy: We assume that successful autonomous navigation via GPS on Earth is a direct functional proxy for Visual Odometry (VO) navigation on Mars.

METHODOLOGY AND ARCHITECTURE

System Overview

A flow chart showing the process of rocket deployment is shown in figure 1. This shows the process of the mechanical operations of the rocket, starting from placing the rocket on a launch station, to the rocket deploying its wings and flying back to base.

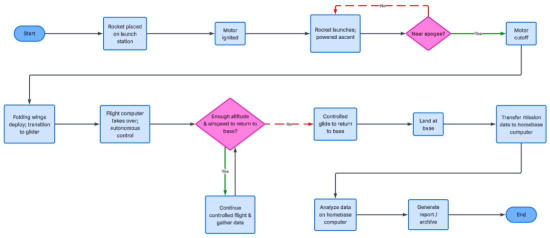

Figure 1: Flow chart showing rocket deployment process

Apparatus / Design

The rocket has been designed in whole using Autodesk Fusion. This includes the folding wing mechanism, working controlled tail fins, rocket structural supports, and visual representation of electronic packaging. Fusion screenshots showcasing the folding wings and tail section are shown in figures 2 and 3.

Folding Wings: The wing mechanism functions by having both wings engaged with a ribbed rod that can move linearly inside the rocket body. This rod is spring loaded and retained with a pin to keep the wings folded inside the rocket during launch. Once the rocket has reached apogee, the retaining pin is pulled out via a servo motor, and the rod is pulled towards the front of the rocket by the spring. As the rod moves forward, the wings are rotated backwards by their engagement with the ribs. This creates an efficient and reliable way for the wings to deploy quickly and evenly to their proper sweep angle. In addition this moves mass front to back (which we will tune to achieve proper balance) moving the center of gravity to be correct for stable fixed wing flight.

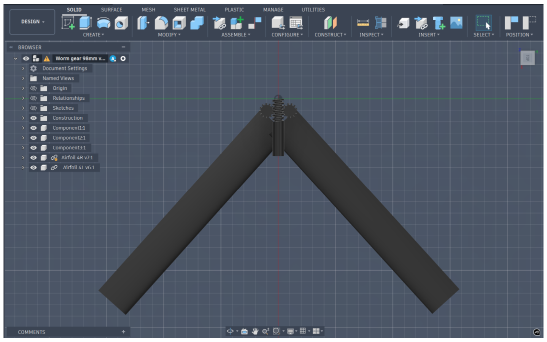

Figure 2: Folding wing mechanism

<u>Tail Section:</u> The tail of the rocket features 4 movable aerodynamic fins. These fins are each attached to a servo motor via a dog-bone style linkage connecting the fin to the servo. The tail fins are held within a carrier that locks them in place to the dog-bone linkages without allowing for any slack in the system. All of these components are mounted to a 3D printed housing. A design challenge we had to consider here is that the rocket motor is mounted directly next to all of these components. Heat shielding is used to protect the components from the hot gasses of the rocket motor.

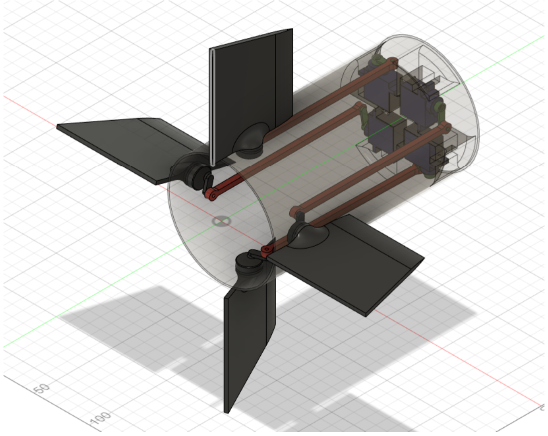

Figure 3: controllable tail fin mechanism

<u>Circuitry:</u> MEGA's circuitry can be broken into 3 main components. The onboard control, the onboard power, and the ground station transmission and receiving. The full diagram is shown in 4.

<u>Onboard Control:</u> Firstly, the onboard control is primarily housed inside the MicroAir405 flight controller which is the primary flight data gathering device, including an accelerometer, magnetometer, gyroscope, barometer and an onboard processor. Plugging in to the MicroAir M10 GPS, this setup provides up to date and accurate telemetry data for the rocket. This circuit is powered by a 6S lipo battery which runs through the electronic speed control (ESC) voltage regulator. There are motor output PWM cables that send signals to the 5 servos (4 contorl for control surfaces, 1 for wing deployment). Finally, there are 2 radio transmitters, one for telemetry data and one for video that communicate the real time flight status. The telemetry receiver also serves to accept the transmission of new mission directives based on the video data processed by the ground station.

<u>Onboard Power:</u> Secondly, the onboard power circuit is supplied by a second 6S Lipo battery that is regulated by a 10A 6V voltage regulator that provides power to the 5 servos. The ground is also tied to the flight controller ensuring a common reference.

<u>Ground station:</u> Finally, the ground station transmission and receiving circuit is the video receiver and the telemetry receiver/transmitter connected and powered by an M1 Mac. This circuit will receive all rocket data in real time and using a CV model updates the proposed flight path to investigate an object of interest. Then sending these decisions back to the onboard flight controller will make the realtime adjustments needed to accomplish this task. Finally new data will be transmitted back to the ground station completing this loop.

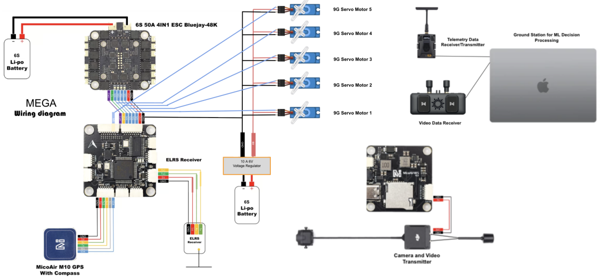

Figure 4: Full MEGA Circuitry

PRELIMINARY VALIDATION

Command-and-Control Loop Success

Bench-top testing has successfully validated the communication loop. Using the custom Python interface, WASDQE inputs successfully mapped to the tail fin servos with minimal latency.

Telemetry and Video Stream

Data acquisition was confirmed by successfully streaming telemetry data and live video. All sensors pass pre-flight calibrations and report data accurately in real time. The video is received cleanly and accurately in real time/

Thermal Reliability

The integrated cooling fans successfully prevented thermal throttling during extended diagnostic sessions, confirming the electronics can remain powered during and through launch maximizing reliability.

Wing Deployment

The custom-engineered "wine-opener" wing deployment mechanism has successfully demonstrated its functional design during preliminary bench-top testing. This system translates linear spring force into synchronized rotational wing extension, achieving the necessary aerodynamic transition from a compact rocket profile to a high-lift glider configuration.

FUTURE WORK: ATMOSPHERIC FLIGHT TRIALS

The immediate next phase of the MEGA project involves full-scale atmospheric testing to validate the transition from ballistic ascent to stable glide. While bench-top results confirm component functionality, the aerodynamic transition remains the primary flight risk.

Flight Sequence and Transition Validation

The first flight objective is to verify the mechanical reliability of the "wine-opener" deployment system under real-world aerodynamic loads. The flight sequence begins with a high-G launch to an estimated apogee of 850 feet.

Apogee and Deployment Upon reaching the point of minimum vertical velocity, the ArduPilot flight controller will trigger the wing deployment servo. It is critical to validate that the wings lock into place before the craft reaches its stall speed during the pitch-over maneuver.

Guided Path Following Once the wings are deployed and the craft has leveled, the flight controller will transition from a passive descent into a "Guided" flight mode. Initial trials will focus on the aircraft's ability to follow a series of pre-programmed GPS waypoints, confirming the effectiveness of the controllable tail fins in maintaining a stable glide slope.

FUTURE WORK: AUTONOMOUS INVESTIGATION

The second phase of future development focuses on the integration of real-time computer vision (CV) for dynamic target acquisition. This subsystem is designed to enable immediate alterations to the flight trajectory when geological anomalies are detected.

Geodetic Framework and Coordinate Transformation

Autonomous investigation requires the mathematical translation of 2D visual data into a 3D geodetic framework. When the CV model detects a Point of Interest (POI) at pixel coordinate (u, v), it must be transformed into actionable global spatial coordinates by leveraging the aircraft's instantaneous telemetry.

Pinhole Projection and Angular Offset

The pixel offsets from the image center $(\Delta u_{px}, \Delta v_{px})$ are converted into physical angular deviations (θ_u, θ_v):

$$\Delta u_{px} = u - \frac{W}{2} \quad ; \quad \Delta v_{px} = v - \frac{H}{2} \tag{4}$$

$$\theta_u = \Delta u_{px} \cdot \frac{FOV_x}{W} \quad ; \quad \theta_v = \Delta v_{px} \cdot \frac{FOV_y}{H} \tag{5}$$

where W, H represent resolution and FOV represents the Fields of View.

IMU Integration and Rotation Matrix

To account for the aircraft's attitude (pitch ϕ, roll θ, yaw ψ), a 3D rotation matrix $R_{body \to nav}$ transforms the camera-frame vector $V_c = [\theta_u, \theta_v, 1]^T$ into the navigation frame $V_{nav} = R_{body \to nav} V_c$:

$$R_{b \to n} = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix} \tag{6}$$

The horizontal ground distances (d_x, d_y) are then derived using the barometer altitude (h):

$$d_{x,ground} = h \cdot \frac{x_{nav}}{z_{nav}} \quad ; \quad d_{y,ground} = h \cdot \frac{y_{nav}}{z_{nav}} \tag{7}$$

Global Coordinate Calculation

Finally, these relative displacements are added to the drone's current GPS coordinates (Lat_0, Lon_0) to determine the target's precise location:

$$Lat_{target} = Lat_0 + \frac{d_{y,ground}}{R_{earth}} \tag{8}$$

$$Lon_{target} = Lon_0 + \frac{d_{x,ground}}{R_{earth} \cos(Lat_0)} \tag{9}$$

Experimental Validation Methodology

To validate this targeting subsystem, controlled field experiments will be conducted using a static, high-contrast target at a surveyed GPS coordinate.

Data Acquisition and Metrics

Telemetry will be logged at 10 Hz via the flight controller. The ground station's screen activity will be recorded to correlate detection with aircraft attitude. Accuracy will be quantified by the Coordinate Projection Error (the distance between calculated and surveyed GPS coordinates) and Target Centering Error (how closely the aircraft flew over the POI).

ACKNOWLEDGEMENTS

The author acknowledges Alec Jaffe (William & Mary) for his critical and significant contributions to the mechanical CAD modeling and structural design of the MEGA platform.

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