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Simulation and Optimization of Satellite Re-Entry Trajectories Using MATLAB

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***Keywords*— Satellite re-entry, MATLAB simulation, flight path angle, re-entry trajectory, Atmospheric drag, Differential equations, orbital dynamics, altitude-varying air density.**

***Abstract*— *This paper presents a simulation-focused methodology for performing satellite re-entry dynamics analysis with MATLAB. When a satellite is descending, it is subjected to gravitational attraction, atmospheric drag and applied thrust; these factors can be described by solving a system of differential equations. The simulation is initiated at an altitude of 300 km with the given initial conditions and with the use of real-world properties such as altitude-varying air density and orbital dynamics. The simulations give an altitude decay, velocity change and flight path angle history of re-entry. In addition, this model illustrates that atmospheric resistance becomes the dominant force of deceleration at low altitudes.*

I. INTRODUCTION

With the increasing number of space debris in near earth orbit due to the presence of artificial satellites, a reliable post mission disposal technique has emerged. Atmospheric re-entry – a process involving massive aerodynamic heating, supersonic deceleration and pinpoint trajectory guidance – is one of the most extreme environmental conditions a satellite can endure during its life-span. Regardless of whether satellite re-entry is intentional or accidental, careful consideration is required to assure both safety and successful mission and to satisfy international guidelines about space debris mitigation.

Re-entry evolution is controlled by a variety of competing physical forces, such as gravitational pull, aerodynamic drag, and, in some cases, engine thrust. These will shift the satellite's speed, height and orientation as it falls. The system of nonlinear ordinary differential equations describing such interactions under realistic atmospheric conditions needs to be solved in order to predict and optimize the re-entry trajectory.

This paper describes a MATLAB-based simulation approach to satellite re-entry analysis. The model considers the atmospheric density variation with altitude, the gravitational force depending on the altitude and it is postulated a constant thrust. The initial conditions are taken at the satellite position of 300 km and then the satellite velocity, altitude and path angle are calculated as the satellite re- entry in the atmosphere. The results of the simulation show the forces dominating the structure at different stages of descent, and indicate design guide lines for the flight trajectories and control.

This paper provides a foundational MATLAB-based simulation framework for analysing satellite re-entry dynamics. It models key forces gravity, drag, and thrust affecting descent. The approach supports trajectory planning, safety assessment, and mission design, and can be extended for various satellite configurations and advanced scenarios in aerospace engineering research and education.

II. LITERATURE REVIEW

Satellite re-entry is the most critical and dynamic stage of the life of any man-made spacecraft. With adding traffic in low Earth orbit (LEO) and transnational emphasis on space debris mitigation, understanding and bluffing there-entry process has gained significant significance in both academic exploration and aerospace assiduity operations.

Kaplan's early work in orbital mechanics laid a theoretical foundation for studying the motion of satellites, with specific emphasis on the influence of gravity and first-order atmospheric drag during orbital decay and re-entry [1]. His analytic models played a central role in laying the foundation for re-entry analysis. Only that they did not cover more complex effects of dynamic atmospheric variations and dynamic controlling functions flying a crucial role during the re-entry process or during the re-entry phase. Braun and Manning [2] contributed significantly to the field of re-entry modelling by integrating high-resolution atmospheric data with advanced guidance algorithms tailored for entry vehicles. Their study provided valuable insights into the challenges of vehicle control during atmospheric re-entry, particularly for missions targeting planets such as Earth and Mars. They underscored the importance of accurate simulation environments capable of accounting for variations in atmospheric density, thermal loads, and trajectory control mechanisms.

Cook [3] added to knowledge of Aerodynamic drag by proposing rational models for the computation of Satellite drag areas before various atmospheric and flux conditions. His results provide the foundation of many of today's drag models employed to predict decays and re-entry times. At lower mound, the drag as well as the exobase are even more important as the increase of atmospheric density becomes even more exponential.

For small satellites and CubeSats, Leipold et al. [4] have suggested active as well as non-resistant de-orbiting techniques to facilitate controlled re-entry. They studied drag addition bias such as sails and tethers which might augment face area, and thus atmospheric drag and also hasten de-orbit. This method is especially effective for low-delta V, low-cost missions with little to no on-board propulsion.

Pardini and Anselmo [5] conducted a statistical analysis of derelict satellite re-entries and long-term orbital decay under the influence of solar activity cycles. Their research demonstrated that even minor atmospheric variations, driven by changes in solar flux and geomagnetic indices, can significantly alter re-entry timelines. The study emphasized the importance of adaptable models that incorporate both environmental variability and object-specific characteristics.

Schaub and Junkins [6] created logical mechanics and optimization techniques for satellite line control with special treatment of descent and re-entry. Their procedure has been widely adopted for determining optimization de-orbit burns, re-entry circles, orbital rendezvous and even pushes. The inclusion of thrust modelling means that their approach is particularly appropriate for thrust-supported re-entry analysis.

Recently, the use of MATLAB as a tool for engineering simulation has sky zoomed because of its flexibility and built-in numerical solvers. Mukhopadhyay et al. [7] used MATLAB to simulate ballistic re-entry with simplified force models. Their results were a validation of generalization of MATLAB application in education and early charge development.

Rodriguez-Donaire et al. [8] presented an elementary re-entering satellite model appropriate for educational and research purposes. They focused on implementation simplicity and efficient computation, making it accessible for students and beginners. By balancing accuracy and simplification, the model allowed users to investigate entry dynamics with commonly available simulation tools.

Huang et al. [9] used the Runge-Kutta technique for calculation of the re-entry dynamics of low Earth orbit satellites. They simulated the changing forces and confirmed their results using satellite re-entry data. This latter system, used in our simulation also, is well known for its stability and for the preciseness of its work in ordinary differential equations.

NASA's Debris Assessment Software (DAS) [10] and the European Space Agency's DRAMA suite are sophisticated tools designed to evaluate satellite end-of-life scenarios and associated re-entry risks. These platforms leverage comprehensive environmental data and adhere to global regulatory standards. Nevertheless, their technical depth and professional focus can pose challenges for quick evaluations or academic exploration. In comparison, MATLAB-based simulations—such as the one developed in this work—provide a more accessible and streamlined approach, offering sufficient accuracy for understanding core re-entry mechanics. This makes them particularly useful for instructional settings and early-phase mission analysis.

A recent study by Mohamed Shuaib A. [11] explores the use of MATLAB for simulating satellite deployment dynamics, emphasizing its flexibility and suitability for both academic and preliminary mission design purposes. The study demonstrates how gravitational, drag, and thrust forces can be integrated into a cohesive simulation framework, making it especially useful for early-stage modelling and educational applications where accessibility and clarity are essential.

In summary, while former studies give robust models and simulation platforms for satellite re-entry, multitudinous of them are also too complex for early- stage operations or not easily customizable. This paper builds upon these being models by introducing a MATLAB- predicated simulation frame that integrates gravitational forces, atmospheric drag, and thrust into a cohesive and adaptable structure suitable for both academic study and primary charge analysis.

III. METHODOLOGY

The approach in this work is to numerically simulate the re-entry of satellite trajectory using the MATLAB software that includes gravitational forces, atmospheric drag, and thrust. The simulation is defined to simulate the equations of motion using reasonable physical values and starting conditions for a LEO-re-entering satellite.

Parameters

Table 1. Physical Parameters Used in Satellite Re-entry Simulation.

Parameter	Symbol	Value	Units
Gravitational constant	G	6.67430×10^{-11}	$m^3\cdot kg^{-1}\cdot s^{-2}$
Earth mass	M	5.972×10^{24}	kg
Earth radius	R_{earth}	6,371,000	m
Sea-level density	ρ_0	1.225	kg/m^3
Scale height	H	8500	m
Drag coefficient	C^d	2.2	dimensionless
Cross-sectional area	A	1	m^2
Satellite mass	m	500	kg
Thrust force	F_{thrust}	1000	N

The physical parameters used for the simulation are summarized in Table 1.

Governing Equations

The satellite's motion is described using three state variables: altitude (h), velocity (v), and flight path angle (γ), satellite mass(m).

The equations of motion are: [22]

$$\frac{dh}{dt} = v \sin \gamma$$

$$\frac{dv}{dt} = \frac{F_{thrust} - D}{m}$$

$$\frac{d\gamma}{dt} = -\frac{g}{v} \cos \gamma$$

equation that includes a control input, such as

$$\frac{d\gamma}{dt} = -\frac{g}{v} \cos \gamma + u(t)$$

where u(t) is a control function (manual or automated).

where the drag force D is:

$$D = \frac{1}{2}\rho(h)v^2 C_d A$$

and gravitational acceleration g varies with altitude as:

$$g = \frac{GM}{(R_{earth}+h)^2}$$

3.3 Atmospheric Density Model

Atmospheric density decreases exponentially with altitude: [23]

$$\rho(h) = \rho_0 \exp\left(-\frac{h}{H}\right)$$

where ρ_0 = 1.225 kg/m^{3}is sea-level atmospheric density and H=8500m is the scale height.

3.4 Numerical Solution

The equations were solved using MATLAB's ode45 solver over a time span of 0 to 2000 seconds. Initial conditions were set as:

Altitude: 300,000 m

Velocity: 7,500 m

Flight path angle: -5° (converted to radians)

A typical initial re-entry flight path angle for low Earth orbit vehicles ranges between –1° and –10°, depending on:

Desired descent rate

Mission profile

Safety margins

Using –5° represents a moderately shallow but safe re-entry trajectory.

Re-Entry Simulation

Simulation Setup

For a practical on-orbit decay simulation, a 2D orbital mechanics model was implemented to analyse the re-entry dynamic motion of a CubeSat. The deorbiting has been solved numerically with an ode45 integrator over a period of time sufficiently long to cover the entire deorbiting process. The satellite was placed in low Earth orbit at an initial circular orbit, and the perturbative forces were added to simulate the real entry.

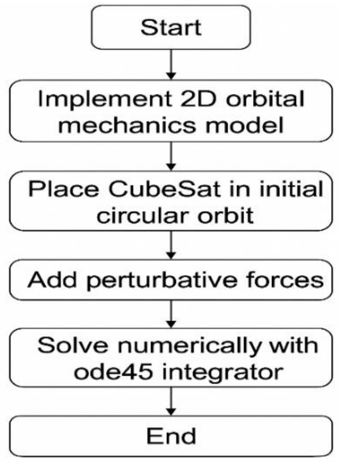


Fig.1. Simulation Workflow for Satellite Re-entry Using 2D Orbital Dynamics.

Simulation Results

The simulation outputs illustrate the variation of key parameters during the satellite re-entry process.

The **altitude profile** shows a gradual decrease from 300 km to the surface of the Earth as atmospheric drag increases with decreasing altitude (figure 2).

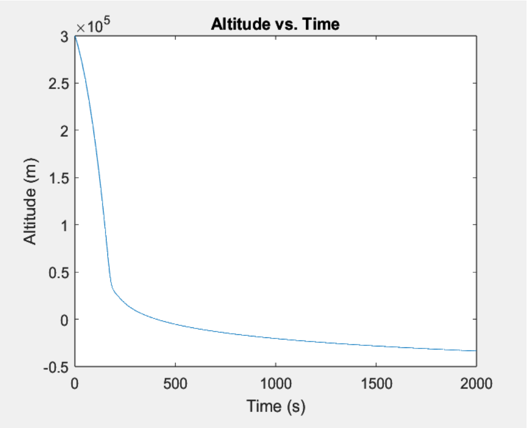


Fig.2. Altitude Profile of a Re-entering Satellite over Time.

The **velocity profile** indicates that the satellite initially maintains a high orbital velocity, which then decreases sharply as aerodynamic drag intensifies in the denser atmosphere (figure 3).

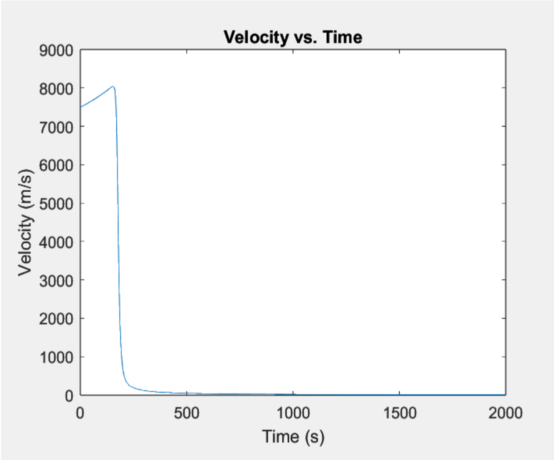


Fig.3. Velocity Profile of a Re-entering Satellite over Time.

The **flight path angle** progressively steepens (becomes more negative) as the satellite descends, reflecting the transition to a near-vertical descent in the later stages (figure 4).

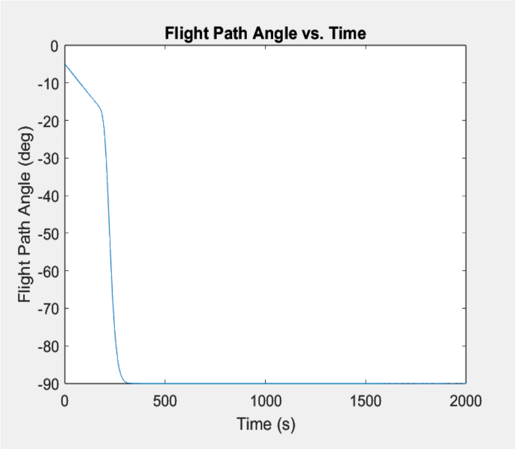


Fig.4. Flight Path Angle Profile of a Re-entering Satellite over Time.

The **drag force** rises significantly at lower altitudes where air density is higher, becoming the dominant decelerating factor (figure 5).

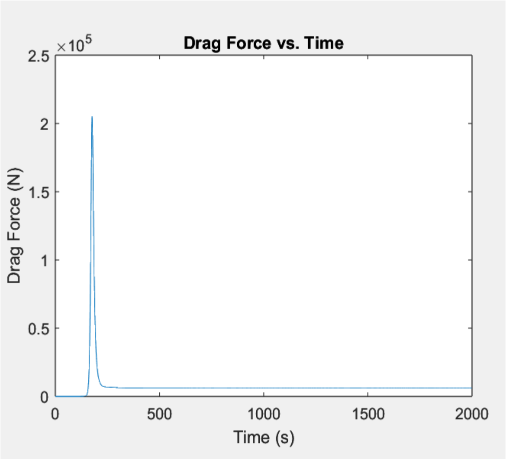


Fig.5. Drag Force Profile of a Re-entering Satellite over Time.

The **gravitational force** remains relatively constant but slightly increases due to the inverse-square law as altitude decreases (figure 6).

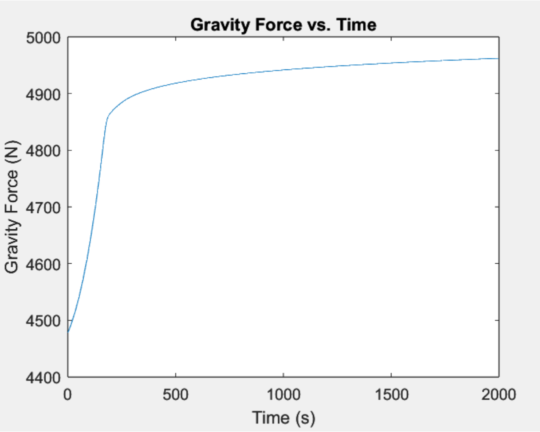


Fig.6. Gravity Force Profile of a Re-entering Satellite over Time.

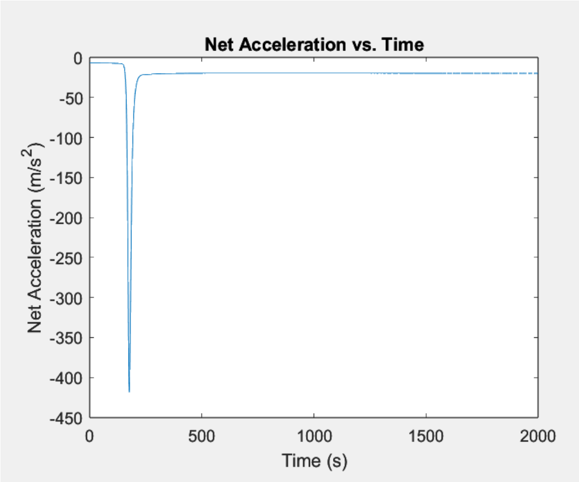


Fig.7. Net Acceleration Profile of a Re-entering Satellite over Time.

The **net acceleration** shows the combined effect of thrust, drag, and gravity, with drag dominating in the terminal phase and resulting in substantial deceleration (figure 7).

IV. RESULT AND DISCUSSION

The simulation was performed using the given initial conditions and physical parameters to the original problem for the satellite's re-entry line over a period of 2000-alternate steps. The key findings and their counter-accusations are batted below

Trajectory Profiles

Altitude: The spacecraft altitude decreases gradually from 300 km to the surface of the earth, representing the re-entry descent phase. The atmospheric viscosity grows exponentially in the direction of lower mound, causing larger aerodynamic drag and rapid altitude drop.

Velocity: The satellite initially maintains a high orbital velocity, which then declines sharply as drag forces intensify in the denser atmosphere. This velocity reduction reflects the conversion of kinetic energy into heat and drags work. (figure 3)

Starting from -5°: the flight path angle gradually steepens (becomes more negative) as the satellite descends, reflecting an increasingly downward trajectory driven by gravitational pull and atmospheric resistance.

5.2 Forces Acting on the Satellite

Drag Force: Drag force increases significantly as the satellite penetrates denser atmospheric layers. The drag peaks at lower altitudes where velocity remains substantial, confirming its critical role in decelerating the spacecraft. (figure 5)

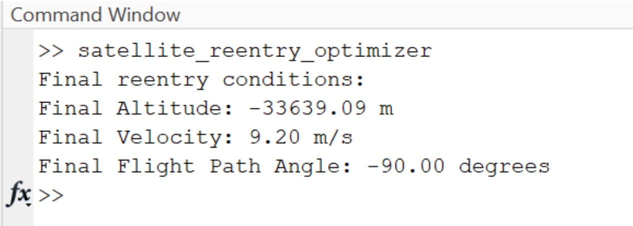
Gravity Force: The gravitational force remains consistently directed toward Earth's centre and slightly intensifies due to the inverse-square dependence on altitude. It continuously contributes to downward acceleration. (figure 6)

Net Acceleration: The net acceleration combines thrust, drag, and gravity effects. While the thrust partially offsets drag and gravity at the start, drag dominates later, resulting in a negative net acceleration and consequent deceleration**.** (figure 7)

Final Re-entry Conditions

At the end of the simulation, the satellite reaches an altitude of approximately **-33,639.09 m**, indicating ground impact or termination beyond the surface reference level due to numerical overshoot. The final velocity is **9.20 m/s**, and the flight path angle reaches **-90.00°**, showing a purely vertical descent. These values represent the satellite's final state during atmospheric re-entry and ground approach.

The negative final altitude value observed in the simulation, approximately **–33,639.09 m**, results from numerical overshoot in the integration process after the satellite has effectively reached ground level. This overshoot commonly occurs in orbital simulations when the numerical solver continues beyond the physical boundary (Earth's surface) due to step size limitations or lack of termination conditions in the integrator. The final velocity of **9.20 m/s** and the flight path angle of **–90.00°** indicate that the satellite has entered a near-vertical descent phase, consistent with the final stage of atmospheric re-entry where motion becomes predominantly vertical due to strong drag forces and gravitational acceleration. These values effectively represent the satellite's terminal re-entry condition and the conclusion of its descent trajectory within the simulation framework.



```
>> satellite_reentry_optimizer
Final reentry conditions:
Final Altitude: -33639.09 m
Final Velocity: 9.20 m/s
Final Flight Path Angle: -90.00 degrees
fx >>
```

Fig.8. Final Re-entry Conditions.

V. RESULTS DISCUSSION

The results underscore the delicate interplay between thrust and drag in shaping re-entry trajectories. Adequate thrust can moderate deceleration rates, potentially reducing thermal and mechanical stresses experienced by the satellite. Furthermore, controlling the flight path angle is essential for achieving a predictable descent and ensuring mission safety.

Limitations of the current model include the assumptions of constant drag coefficient, neglect of lift and control forces, and simplification to a planar (2D) trajectory. Future improvements could integrate variable aerodynamic coefficients, thermal effects, and three-dimensional dynamics to enhance model accuracy and applicability.

VI. CONCLUSION

A MATLAB simulation has been established in the present paper to further study the re-entry dynamics of a satellite combined with the effect of Earth's gravity, atmospheric drag and thrust added. The model accurately describes the satellite's descent profile, such as substantial altitude decline, deceleration and flight path angle evolution during the descent process. Numerical simulations point out that atmospheric drag is the paramount factor in decelerating the satellite in the re-entry phase, revealing that even with low thrust levels (threshold value), the thrust can be used to control the trajectory characteristics to optimize such re-entry. Despite model simplifications such as constant drag coefficient and planar motion the framework offers valuable insights for initial mission design and controlled re-entry planning.

Future work should address the model's current limitations by incorporating three-dimensional trajectory dynamics, variable aerodynamic coefficients, thermal heating effects, and active control strategies. Such enhancements will improve prediction accuracy and support safer, more efficient satellite re-entry operations, especially for emerging small satellite platforms.

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