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Implementation of Low Earth Orbit Satellite Constellation Design

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Abstrak - Peningkatan penggunaan satelit orbit bumi rendah (LEO) menuntut adanya alat desain yang mudah diakses dan akurat sebagai alternatif untuk perangkat lunak profesional yang mahal. Proyek ini menjawab kebutuhan tersebut dengan mengembangkan aplikasi web komprehensif untuk desain orbit satelit LEO. Aplikasi ini mengintegrasikan beberapa fungsi utama, termasuk propagasi orbit, desain konstelasi untuk konfigurasi Train dan Walker-Delta, analisis cakupan, dan perhitungan anggaran tautan, semuanya dilengkapi dengan visualisasi interaktif 2D dan 3D. Aplikasi tersebut telah melalui validasi yang ketat terhadap perhitungan teoretis dan Alat Analisis Misi Umum NASA (GMAT), yang mengonfirmasi akurasi tinggi di semua modul. Modul propagasi orbit menunjukkan kesalahan kurang dari 0,78 km dalam simulasi satu jam, dengan kesalahan rata-rata kuadrat (RMSE) sebesar 31,8 km dibandingkan dengan integrator numerik GMAT. Penempatan konstelasi untuk konfigurasi Train dan Walker-Delta menunjukkan kesalahan posisi nol. Perhitungan cakupan akurat hingga 0,05 km pada ketinggian 2.000 km. Selain itu, analisis anggaran tautan mencapai kesesuaian sempurna dengan perhitungan manual, dengan selisih 0,00 dB dan menghasilkan margin uplink 31,87 dB serta margin downlink 18,76 dB. Prediksi akses stasiun darat sesuai dengan jadwal teoretis, dengan 11 lintasan dalam 24 jam dan durasi rata-rata 8,55 menit. Uji antarmuka pengguna menghasilkan tingkat keberhasilan 100%. Aplikasi ini berhasil menjembatani kesenjangan antara perangkat lunak profesional yang kompleks dan kebutuhan pendidikan dengan menyediakan alat yang tervalidasi, andal, dan mudah diakses untuk desain awal misi satelit LEO. Aplikasi ini memenuhi semua tujuan proyek dengan menggabungkan akurasi komputasi tinggi, fitur yang komprehensif, dan aksesibilitas berbasis web yang gratis, sehingga membuat desain orbit satelit lebih mudah diakses untuk tujuan pendidikan dan penilaian teknis awal.

Kata kunci: LEO, Desain Orbit Satelit, Konstelasi, Simulasi Orbit, Link Budget, Aplikasi Web.

Abstract - The increasing utilization of Low Earth Orbit (LEO) satellites necessitates accessible and accurate design tools that can serve as alternatives to expensive professional software. This project addresses this need by developing a comprehensive web-based application for LEO satellite orbit design. The application integrates several key functionalities, including orbit propagation, constellation design for both Train and Walker-Delta configurations, coverage analysis, and link budget calculations, all enhanced with interactive 2D and 3D visualizations. The application underwent rigorous validation against theoretical calculations and NASA's General Mission Analysis Tool (GMAT), confirming high accuracy across all modules. The orbit propagation module demonstrated an error of less than 0.78 km over a one-hour simulation, with a root mean square error (RMSE) of 31.8 km when compared to GMAT's numerical integrator. Constellation placement for both Train and Walker-Delta configurations showed zero positional error. Coverage calculations were accurate to within 0.05 km at an altitude of 2,000 km. Furthermore, the link budget analysis achieved perfect correspondence with manual calculations, showing a 0.00 dB difference and yielding an uplink margin of 31.87 dB and a downlink margin of 18.76 dB. Predictions for ground station access precisely matched theoretical schedules, with 11 passes in 24 hours and an average duration of 8.55 minutes. User interface testing resulted in a 100% success rate. This application successfully bridges the gap between complex professional software and educational needs by providing a validated, reliable, and accessible tool for the preliminary design of LEO satellite missions. It meets all project objectives by combining high computational accuracy, comprehensive features, and cost-free web-based accessibility, thereby making satellite orbit design more approachable for educational purposes and initial technical assessments.

Keywords: LEO, Satellite Orbit Design, Constellation, Orbit Simulation, Link Budget, Web Application

I. INTRODUCTION

A significant challenge in the aerospace and telecomunications sectors in the effective design and management of satellite constellations, particularly in Low Earth Orbit (LEO) [4], [19]. LEO is an increasingly popular choice for satellite operations due to its advantages, such as minimal latency and greater bandwidth [7], [52], with most satellites positioned between 500 and 1,600 km above earth [24]. The deployment of satellites in LEO is also more energy-efficient and does not require powerful signal amplifiers for effective data transmission [1].

Achieving global coverage with LEO satellites necessitates the deployment of large constellations, often consisting of hundreds or even thousands of interconnected nodes, sometimes through Inter-Satellite Optical Links (ISLs) [4]. This complexity demands advanced software tools for designing and simulating orbits, optimizing trajectories, and ensuring consistent global coverage [5]. While professional software solutions like AGI's System Tool Kit (STK) and NASA's General Mission Analysis Tool (GMAT) exist, their complexity and high licensing costs can be prohibitive [21].

This project was initiated to develop a web-based application that offers a comprehensive and user-friendly platform for designing LEO satellite orbits, making this technology more accessible for educational and preliminary design purposes [15]. The application is designed to integrate key functionalities such as orbit propagation, constellation design, coverage analysis, and link budget calculations within an intuitive interface featuring interactive 2D and 3D visualizations [12]. By providing a reliable and accessible tool, this work aims to bridge the gap between complex professional software and the needs of a broader audience interested in satellite technology [1].

II. THEORY REVIEW

A. Simplified General Perturbations 4 (SGP4)

The SGP4 algorithm is a widely used method for simulating the orbits of near-Earth satellites by forecasting their future position and velocity from known orbital elements. Developed in the 1970s, it is recognized for its relative simplicity, efficiency, and accuracy, and is specifically designed to work with orbital data in the Two-Line Element (TLE) format. The satellite position coordinates generated by SGP4 are typically presented in the True Equator Mean Equinox (TEME) system, an Earth-Centered Inertial (ECI) system. However, a key limitation is its reliance on TLE data, which can be imprecise or outdated, leading to potential prediction errors [18]. Additionally, SGP4 simplifies perturbative effects, which may result in inaccuracies for satellites influenced by factors like atmospheric drag or gravitational interactions [19].

B. System Tool Kit (STK) by AGI/Ansys

STK is a software suite designed for modeling and analyzing the performance of complex systems in space, air, land, and sea. It provides high-fidelity simulations of satellite orbits, mission planning, and scenario analysis, incorporating various propagation algorithms, including SGP4 and more sophisticated numerical integration techniques. STK also offers advanced 3D visualization capabilities for modeling satellite trajectories and ground station coverage [20]. Despite its strengths, STK can be complex to use and may require significant computational resources for large-scale simulations, with licensing costs posing a barrier for some users [21].

C. NASA's General Mission Analysis Tool (GMAT)

GMAT is an open-source software application from NASA designed for trajectory optimization and mission analysis. It supports various numerical integration techniques for simulating and predicting satellite orbits with high accuracy. GMAT provides a flexible framework for modeling complex missions, including interplanetary trajectories and satellite constellations, and its user-friendly interface makes it accessible to a wide range of users [21]. However, its accuracy is highly dependent on the precision of the input data and models [22].

D. General Perturbation Methods

General Perturbation methods are techniques used to simulate satellite orbits by accounting for perturbative forces such as gravitational influences from other celestial bodies, atmospheric drag, and solar radiation pressure. While these methods can yield high accuracy in predicting satellite positions over extended periods, they often require significant computational power and can be complex to implement [23]. The accuracy of these methods also depends heavily on the precision of the input orbital elements and environmental models, making them more suitable for scenarios where high fidelity is critical [18].

III. RESEARCH METHODS

The development of the LEO satellite orbit design application followed a structured methodology, beginning with the definition of system specifications and limitations. The core of the application was designed to be modular and user-friendly, supporting the simulation and visualization of LEO satellite movements. The interface design was influenced by professional tools like STK and GMAT to ensure usability and functionality. The development utilized Visual Studio Code, with JavaScript and the Three.js library for dynamic 3D visualizations, and HTML for the web page structure. The backend was managed using PHP with the Laravel framework, which follows the Model-View-Controller (MVC) architectural pattern.

A crucial part of the development process was the implementation of a robust testing and validation plan to ensure the application's accuracy and reliability. The validation was structured into three main layers: integration testing, reliability testing, and interaction testing.

A. Integration Testing

Focused on the individual modules for orbit propagation, coordinate transformations, and link budget calculations. Each function was tested with numerical scenarios and compared against theoretical values to ensure accuracy within a 1% deviation in position error.

B. Reliability Testing

Involved comparing the overall simulation results with NASA GMAT as a reference. This included scenario and visual validation to ensure the application's outputs were consistent with industry-standard software.

C. Interaction Testing

Was conducted to ensure that all User Interface (UI) features functioned as expected. This involved systematic testing of all interface components across multiple browser environments to verify operational reliability and consistency.

The testing process followed a standardized sequence, including environment initialization, simulation creation with a standard epoch time, input of specific orbital parameters for each test scenario, and repeated test runs to ensure consistency. This comprehensive approach to design, implementation, and testing ensured the final application was both functional and accurate.

IV. RESULT AND ANALYSIS

The LEO Satellite Orbit Design Application demonstrated high precision and reliability across all tested modules. The validation process, which included comparisons with manual calculations and NASA GMAT, confirmed the accuracy of the application's core functionalities.

A. Orbit Propagation Rate Testing

The orbit propagation simulation was conducted for a one-hour interval. The final satellite longitude predicted by the application was 79.317409°, which showed a minimal difference from the manually calculated longitude of 79.317666°. This close alignment highlights the precision of the orbital propagation simulator [24]. When compared with NASA GMAT, a noticeable difference in position was observed, which is attributable to the different propagation methods used. The web application employs an analytical propagator that averages the long-term drift from the J2 perturbation, while GMAT uses a high-fidelity numerical propagator (Runge-Kutta 4) that captures subtle, short-period oscillations [21], [24].

TABLE 1.
Detailed comparison of manual calculations vs. web application results.

Time (min)	Manual		Website		Position Error (km)	Error (%)
	Lat	Lon	Lat	Lon		
0	0°	−111.622°	0°	−111.622°	0.00	0.000
10	0°	−79.800°	0°	−79.799°	0.11	0.001
20	0°	−47.978°	0°	−47.976°	0.22	0.005
30	0°	−16.156°	0°	−16.152°	0.44	0.027
40	0°	15.666°	0°	15.671°	0.56	0.036
50	0°	47.488°	0°	47.494°	0.67	0.013
60	0°	79.310°	0°	79.317°	0.78	0.010

B. Constellation Satellite Placement Testing

The constellation placement tests validated four different methods using 1,000 km circular orbits. For the forward-train test, satellites were spaced by 10° in mean anomaly, resulting in equatorial longitudes that precisely matched analytical predictions. The backward-train formation and time-lagged train also produced coordinates that aligned with theoretical calculations. The Walker-Delta configuration correctly arranged 24 satellites into six polar planes with the expected spacing and phase shifts. In all cases, the simulated coordinates matched the analytical predictions with high numerical precision [4].

C. Coverage Area and Link Budget Testing

In coverage area testing, the system's calculated coverage radius of 1,228.00 km for a satellite at 2,000 km altitude with a 60° beamwidth was compared to the theoretical radius of 1,227.95 km. The negligible difference of approximately 0.05 km confirms the sub-kilometer accuracy of the coverage determination functionality [1], [24].

TABLE 2.
Comparison of theoretical calculations and web-application results.

Parameter	Theoretical	Web application	Absolute error	Relative error
Coverage angle	11.09°	11.05°	0.04°	0.36%
Coverage radius	1,227.95 km	1,228.00 km	0.05 km	0.004%
Coverage area	4.70 $\times 10^6\ km^2$	4.71 $\times 10^6\ km^2$	1.0 $\times 10^4\ km^2$	0.21%

The link budget analysis demonstrated exact agreement with manual calculations, with an uplink margin of 31.87 dB and a downlink margin of 18.76 dB, validating the correct implementation of all signal gain and attenuation factor calculations.

D. Ground Station and Satellite Link Testing

The application's predictions for satellite access schedules were also validated. The simulated results for a 24-hour period yielded 11 passes with an average duration of 8.55 minutes and a time to first access of 40.05 minutes, which perfectly matched the theoretical calculations. This confirms the system's capability to predict satellite access schedules with excellent precision [24], [47].

TABLE 3.
Comparison of theoretical calculations versus web application results.

Metric	Theoretical	Web Result	Difference	Error (%)
Number of passes	11	11	0	0.00
First pass time	40.05 min	40.05 min	0 s	0.00
Average duration	8.55 min	8.55 min	0 s	0.00
Total contact time	94.05 min	94.05 min	0 s	0.00
Duty cycle	6.53%	6.53%	0.00%	0.00

V. CONCLUSION

Based on the comprehensive design, implementation, and rigorous testing process, it can be concluded that the LEO satellite orbit design application has been successfully developed as a functional, integrated, and reliable web-based platform. The application has been validated through a series of quantitative tests, demonstrating that the simulation results for orbit propagation, constellation placement, coverage area, and communication link analysis are highly accurate and consistent with the fundamental principles of orbital mechanics [24].

The application effectively meets its primary objective of providing an intuitive and accessible tool for the design and analysis of LEO satellite missions [15]. It serves as a valuable resource for both educational purposes and initial technical analysis, successfully bridging the gap between complex professional software and the needs of a broader audience. The strengths of the application include its high accuracy, comprehensive feature set, interactive visualization [12], and web-based accessibility [1].

For future development, several enhancements are suggested. These include refining the dynamic models by integrating more complex perturbation effects, such as the gravitational pull of the Moon and Sun, solar radiation pressure, and atmospheric drag, to improve the accuracy of long-term simulations [22]. Integrating real-time TLE data from public sources would also be a valuable addition, allowing users to track active satellites [18]. Finally, developing advanced analysis modules for collision probability and communication link quality over time would further expand the application's capabilities [17].

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