Heliyon 10 (2024) e24265

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Design of infinite horizon LQR controller for discrete delay systems in satellite orbit control: A predictive controller and reduction method approach

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ARTICLE INFO

Keywords:
Satellite orbit control
LQR controller
Infinite horizon
Discrete delay systems
Predictive controller
Reduction method

ABSTRACT

In the realm of satellite orbit control, powerful controller design plays a pivotal role in minimizing fuel consumption and ensuring orbit stability. This article introduces an advanced approach to the design of a Linear Quadratic Regulator (LQR) controller with an infinite horizon, tailored for discrete delay systems. The proposed methodology integrates predictive control with a reduction method, aiming for optimality while addressing performance and system constraints. Formulating the control problem as a quadratic program, the predictive control method generates a sequence of control inputs using a reducing horizon strategy. Stability analysis, employing Lyapunov-Krasovsky functions and linear matrix inequalities, yields delay-independent conditions for exponential convergence. A numerical example showcases the controller's effectiveness in maintaining orbit and reducing fuel consumption, underlining its capacity to achieve control objectives despite uncertainties and time delays. This research contributes to robust control strategies in satellite orbit systems, enhancing control performance and operational efficiency.

1. Introduction

1.1. Motivation

Satellite orbit control holds significant importance in the realm of space missions, as it necessitates the design of controllers that are capable of minimizing fuel consumption and ensuring the stability of orbits [1–4]. The efficient regulation of satellite positioning is imperative for a myriad of applications, ranging from communication and weather monitoring to Earth observation [5–8]. Consequently, there is a pressing need for advanced control strategies that can adeptly manage the dynamic nature of satellite systems, address uncertainties, and contend with time delays [9–12].

This research is driven by the objective of tackling the challenges inherent in satellite orbit control through the development of a robust and efficient control methodology. Conventional control techniques often encounter difficulties when confronted with delays and uncertainties, which can result in compromised performance and system instability. Consequently, the motivation for this study lies in the development of an advanced control scheme that can effectively compensate for destructive effects, proficiently handle time-varying delays, and optimize control performance in satellite orbit systems.

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https://doi.org/10.1016/j.heliyon.2024.e24265
Received 26 September 2023; Received in revised form 26 December 2023; Accepted 5 January 2024
Available online 9 January 2024
2405-8440/

Nomenclatures

k	The discrete-time index
h	The constant delay parameter
$x(k)$	The state vector
$u(k)$	The control input of the system
A_i	The constant nominal matrices of states
B_i	The constant nominal matrices of input control
$x_i(0)$	The primary conditions of states
$u_i(0)$	The primary conditions of input control
$\varphi_i(0)$	The primary Function
$x_{aug}(k)$	The augmented state vector
A_{aug}	The augmented state nominal matrice
B_{aug}	The augmented input control nominal matrice
Q and R	The weighted square matrices used for adjusting the cost function parameters
J_{ih}	The cost function
P	The positive definite solution to the discrete-time algebraic Riccati equation (DARE)
J_h^*	The optimal value of the cost function
η_k	The uncertainty associated with the delay

1.2. Literature review

Extensive research efforts have been dedicated to the field of satellite orbit control and the design of control systems for delayed systems [13–19]. Numerous studies have explored the implementation of predictive control approaches, which have exhibited promising outcomes in meeting performance requirements and accommodating system constraints [20–24]. Predictive control, a model-based control methodology, entails the resolution of an optimal control problem by predicting the future behavior of the system and generating a sequence of control inputs [25–27]. This sequence is subsequently applied to the system, taking into account the reducing horizon technique, with the overarching objective of attaining the desired control objectives [28–30].

Although predictive control has demonstrated efficacy across various domains, its application specifically to satellite orbit control involving discrete delay systems remains relatively limited [31,32]. A research gap exists concerning the development of an LQR controller with an infinite horizon that is purposefully tailored to address the nuances of delayed discrete systems in satellite orbit control [33–36]. Moreover, the integration of the reduction method into the design of the predictive controller to mitigate destructive effects and account for time-varying delays further accentuates the existing research gap.

Article [37], presents a survey on predictive control-based satellite orbit control. It provides an overview of the use of predictive control methods in satellite orbit control, discussing the benefits and challenges. The survey covers various aspects such as control algorithms, performance objectives, and system constraints, providing insights into the application of predictive control techniques in this field. Research article [38], focuses on robust predictive control techniques for satellite orbit control in the presence of uncertainties and disturbances. It investigates methods to handle uncertainties in system dynamics and disturbances affecting satellite orbits. The study proposes robust predictive control algorithms that can effectively handle these challenges and ensure reliable orbit control performance. Journal article [39], presents a study on delay-dependent stability analysis and control for satellite orbit systems. It addresses the impact of time delays on the stability of satellite orbits and proposes control strategies to mitigate the destabilizing effects. The research provides insights into the stability analysis of time-delayed systems and offers control methods to ensure stable satellite orbit behavior. Article [40], focuses on model predictive control (MPC) applied to satellite formation flying in the presence of communication time delays. It explores the challenges posed by communication delays and presents a model predictive control approach to maintain desired formations. The study highlights the benefits of MPC in managing communication time delays and achieving reliable formation control. Paper [41], discusses LQR-based control strategies for satellite orbit maintenance considering time delays. It investigates the effects of time delays on-orbit maintenance and proposes control algorithms based on the LQR framework. The research focuses on utilizing LQR control techniques to effectively handle time delays and ensure precise orbit maintenance. Study [42], proposes an adaptive predictive control approach for satellite orbit control that incorporates neural networks. The research focuses on using neural networks to approximate system dynamics and employs adaptive control techniques to adaptively update the predictive controller based on online learning. The study demonstrates the effectiveness of the proposed method through simulations and highlights its potential for improving satellite orbit control performance. Article [43], explores the utilization of event-triggered predictive control for satellite orbit control. It presents a control scheme where control updates are triggered based on specific events or changes in the system, reducing the computational burden and communication requirements. The research investigates the performance and stability aspects of event-triggered predictive control and highlights its potential advantages in satellite orbit control applications. Research paper [44], focuses on satellite formation control and maintenance using predictive control techniques. It addresses the challenges of maintaining desired formations and relative positions among satellites in formation flying scenarios. The study proposes a predictive control strategy to regulate the formation and demonstrates its effectiveness through numerical simulations. The research contributes to the understanding of predictive control applications in satellite formation control systems. Article [45], investigates the application of robust predictive sliding mode control for satellite attitude tracking. While focusing on attitude control rather than orbit control, it provides insights into the utilization of predictive control combined with sliding mode control techniques. The research proposes a robust control scheme that can handle uncertainties and disturbances, ensuring precise attitude tracking for satellites. A Journal article [46], introduces an event-triggered predictive control approach for satellite orbit control while considering input constraints. The research focuses on the design of an event-triggering mechanism that updates the control action only when necessary, reducing computational requirements. Moreover, it addresses control input constraints to ensure the control actions remain within the desired bounds. The study presents simulation results to demonstrate the effectiveness of the proposed approach in satellite orbit control with input constraints. Research article [47], proposes an adaptive finite horizon predictive control approach for satellite orbit control in the presence of uncertain dynamics. It addresses the challenges posed by uncertainties in system parameters and dynamics. The study develops an adaptive control strategy that adjusts the control horizon based on real-time estimation of uncertainties. Through simulations, the research demonstrates the effectiveness of the proposed approach in achieving accurate orbit control under uncertain conditions. Study [48], introduces a satellite orbit control methodology based on data-driven predictive control and particle swarm optimization. The research explores the utilization of data-driven modeling techniques to approximate the system dynamics and employs predictive control with particle swarm optimization to optimize control actions. The study demonstrates the effectiveness of the proposed approach through simulations, highlighting its potential for improving orbit control performance. The article [49], presents a novel control strategy designed for multiphase batch processes with time-varying delays. The proposed method is a two-dimensional iterative learning control (2D-ILC) combined with asynchronous switching predictive control (ASPC). This innovative approach aims to enhance the control of batch processes, which are common in industries such as chemical and pharmaceutical manufacturing. The primary advantage of this method is its ability to adapt to dynamic time delays and disturbances commonly found in multiphase batch processes. By using both ILC and ASPC, the system can learn and improve control performance over consecutive batches. This adaptive nature increases the robustness and reliability of the control strategy. On the flip side, implementing such complex control strategies might demand more computational resources and rigorous tuning, which could be a disadvantage. In terms of future work, further research could focus on optimizing the tuning process for these control methods and developing practical implementations in industrial settings to exploit their benefits fully. Research paper [50], presents a satellite orbit control strategy based on adaptive MPC with disturbance estimation. It addresses the challenges of uncertain disturbances affecting satellite orbits. The study develops an adaptive MPC framework that incorporates an online estimation of disturbances and adapts the control actions accordingly. The research demonstrates the efficacy of the proposed approach in maintaining precise orbit control in the presence of disturbances through numerical simulations. Article [51], focuses on robust finite-horizon predictive control for satellite orbit control in the presence of time-varying delays. It investigates the impact of delays in on-orbit control performance and proposes a robust predictive control framework to address the uncertainties introduced by time delays. The research utilizes a robust control strategy that considers uncertainty bounds on delays to ensure reliable orbit control. Simulation results demonstrate the effectiveness of the proposed approach in handling time-varying delays. The article [52], introduces a control strategy tailored for discrete-time systems dealing with interval time-varying delays and uncertain disturbances. The approach combines fuzzy predictive control with robust strategies, addressing the challenges posed by these complex systems. The primary advantage of this method lies in its adaptability to handle the uncertain time delays and disturbances often encountered in real-world applications. By utilizing fuzzy logic and predictive control, it can effectively mitigate the impact of these uncertainties. However, this level of complexity can demand substantial computational resources and more intricate control tuning, which may be considered a disadvantage. Future work in this area could concentrate on streamlining the implementation of these control strategies, potentially via optimization algorithms or innovative tuning methods, to make them more accessible for practical use in various industries where such systems are prevalent. Research article [53], presents an adaptive neural network control approach for satellite orbit tracking. It focuses on the utilization of neural network models to approximate the system dynamics and

Table 1
Comparing this article and related works.

	MPC	Robust	Uncertainty	Disturbance	Delay	LQR	Adaptive	Neural network	Event-triggered	Data-driven
[37]	✓									
[38]		✓	✓	✓						
[39]					✓					
[40]	✓				✓					
[41]					✓	✓				
[42]	✓						✓	✓		
[43]	✓								✓	
[44]	✓									
[45]	✓	✓								
[46]	✓								✓	
[47]	✓		✓				✓			
[48]	✓									✓
[49]	✓	✓		✓	✓		✓			
[50]	✓			✓						
[51]	✓	✓			✓					
[52]	✓	✓	✓	✓	✓					
[53]			✓				✓	✓		
This article	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

employs adaptive control techniques to adaptively update control actions based on online learning. The study showcases the effectiveness of the proposed method through simulations, highlighting its potential for improving orbit tracking performance in the presence of uncertainties.

In Table 1, our proposed method, as detailed in the article, undergoes a comprehensive comparison with other articles in the field published in recent years. This comparative analysis is grounded in the indexing of various characteristics intrinsic to these articles. Through this meticulous process, it becomes evident that our proposed method excels across all the considered indicators, underscoring the robustness and strength of the approach detailed in our article. The comparison highlights the unique and superior features of our method in relation to contemporary works, solidifying its position as an impactful contribution to the field.

1.3. Research gaps and contributions

The primary objective of this article is to address the existing research gaps in the domain of satellite orbit control by introducing an advanced control methodology that integrates predictive control with the reduction method. The proposed research makes significant contributions to the field, including the following key aspects.

- This work presents the development of an LQR controller with an infinite horizon designed specifically for discrete delay systems in satellite orbit control. The emphasis is on addressing challenges associated with delay dynamics, to enhance overall control performance in satellite orbit systems.
- The article introduces a predictive control framework that incorporates the reducing horizon method to mitigate the effects of time-varying delays. This integration is a critical component of satellite orbit control and provides improved performance in the face of dynamic delay conditions.

1.4. Organization

The subsequent sections of this article are structured as follows. Section 2 delves into the design of the predictive controller with the reduction method, providing a comprehensive analysis of its implementation for satellite orbit control. Additionally, it encompasses the LQR controller design specifically tailored for delayed discrete systems. Within this section, the stability analysis and convergence conditions are elaborated, incorporating the employment of LKF and linear matrix inequalities to establish the desired outcomes. Subsequently, Section 3 presents the development of the system model and formulates the control problem, offering a thorough examination of the intricacies involved. The subsequent section, Section 4, serves as a platform for the comprehensive presentation and analysis of the simulation results about satellite orbit control, thereby facilitating a detailed and comprehensive comprehension of the implications of the proposed control scheme. Finally, Section 4 concludes this article by summarizing the key findings and contributions of this research, while also shedding light on potential avenues for future research and improvements in the field of satellite orbit control.

Note: In this article, the notation $K > 0$ denotes that the sample matrix K is positive definite and symmetric. Furthermore, the symbol $(*)$ used in the matrices denotes the presence of symmetrical elements. These notations and symbols are utilized consistently throughout the article to convey the mathematical properties of the matrices and facilitate clarity in the analysis and discussions.

2. Problem formulation

In this section, we provide a comprehensive problem formulation for the design of an LQR controller with an infinite horizon for discrete delay systems in satellite orbit control. The problem at hand involves minimizing fuel consumption, ensuring orbit stability, and addressing challenges such as destructive effects and time-varying delays [54–58]. The objective is to design a robust and efficient control scheme that can compensate for the detrimental effects, handle uncertainties, and optimize control performance. By formulating the problem as a quadratic program and incorporating the reducing horizon method, we aim to develop a control strategy that can generate a sequence of control inputs for future moments, taking into account the constraints and objectives of the satellite orbit control system. The problem formulation serves as the foundation for the subsequent sections, where we delve into the design and analysis of the proposed control methodology.

The primary objective of satellite orbit control design is to effectively guide the satellite back to its main orbit while simultaneously minimizing fuel consumption and reducing power magnitude [59–61]. To achieve these objectives, a predictive control approach based on a mathematical model is employed. The predictive control method ensures optimality by taking into account system performance and constraints [62]. It generates a control signal by solving an optimal control problem and making predictions about the system's future behavior. This process involves the consideration of a cost function and constraints on the system's input and state variables at each time step. The control algorithm calculates a sequence of control inputs for future instances of the system and applies the first input using the reducing horizon method. Subsequently, the output and the error between the system's actual state and the desired state are measured, leading to the repetition of this process in subsequent time steps until the error reaches zero or an acceptable value. By linearly modeling the system's equations, considering both equality and inequality constraints, and formulating the cost function as a quadratic, the predictive control problem can be reformulated as a quadratic program. This formulation provides the advantage of requiring a relatively low computational effort for online implementation [62,63].

The "Design of Infinite Horizon LQR Controller for Discrete Delay Systems" presents an LQR controller tailored for discrete delay systems. To understand how it differs from existing controllers, we can explore its unique features.

1. The primary distinction is that this LQR controller is explicitly designed for systems with discrete delays. While traditional LQR controllers are well-suited for continuous-time systems or systems with small time delays, this approach focuses on mitigating the detrimental effects of discrete time delays.
2. The controller is designed with an infinite horizon, which means it considers control inputs and system behavior over an infinite time. Traditional LQR controllers might operate with finite time horizons, but in satellite orbit control, where long-term stability and fuel efficiency are crucial, an infinite horizon approach can be advantageous.
3. It utilizes a predictive control framework. In contrast to standard LQR controllers that rely solely on current state information, predictive control looks ahead into the future. It generates a sequence of control inputs that anticipates future system behavior. This is particularly beneficial in handling time delays, which can lead to instability if not managed correctly.
4. The approach incorporates a reduction method. This method involves a sequential series of control inputs, where each input considers a specific future system moment. This reduces the horizon, allowing for more effective control. It's a technique explicitly chosen to address the challenges associated with time delays.

In summary, the key differences lie in the explicit focus on discrete delay systems, the utilization of an infinite horizon, the use of predictive control with a reduction method, and the incorporation of stability analysis techniques. These features collectively make it a suitable choice for satellite orbit control, especially when dealing with the challenges posed by time delays. Existing controllers may not address these specific requirements as comprehensively.

Let us consider a discrete linear system governed by a set of differential equation (1) that arises in the context of stabilizing N input delay subsystems. The system is characterized by constant matrices and a constant delay term, denoted as h_{ij}. The objective of the stabilization problem is to design a control strategy that ensures the stability of the system, accounting for the presence of input delays [64,65]. The differential equations encapsulate the dynamic behavior of the system and provide a mathematical representation for studying and addressing the stabilization problem at hand [66,67].

$$x(k+1) = Ax(k) + Bu(k-h) \tag{1}$$

In the given context, let us consider the following notations: $k \in Z_+$ represents the discrete time index, $\mathrm{h} \in Z_+$ denotes the constant delay parameter, $x(k) \in R^{n_i}$ represents the state vector, and $u(k) \in R^{n_{ui}}$ denotes the control input of the system. Furthermore, $A_i \in \mathbb{R}^{n_i \times n_i}$ and $B_i \in \mathbb{R}^{n_i \times n_{ui}}$ represent the constant nominal matrices, each having dimensions suitable for the specific requirements of the system. These matrices capture the intrinsic characteristics and dynamics of the system, enabling the analysis and design of appropriate control strategies [68].

The initial condition, or more precisely, the initial function, is denoted by equation (2) in the context under consideration [69]. This equation captures the state of the system at the initial time instant, providing the starting point for the subsequent evolution of the system dynamics. The initial function plays a crucial role in determining the behavior of the system over time and serves as a fundamental component in the analysis and synthesis of control strategies. By specifying the initial function, one can establish the initial state of the system, which is essential for comprehensively understanding and addressing its dynamic characteristics [70].

$$\begin{aligned} &col\left\{x_i(0), u_i(-1), ..., u_i(-h), x_j(0), u_j(-1), ..., u_j(-h)\right\} = \\ &col\left\{\varphi_i(0), 0, ..., 0, \varphi_j(0), 0, ..., 0\right\} \end{aligned} \tag{2}$$

Through the utilization of the adjoint method, the augmented state vector can be defined as expressed in equation (3). The adjoint state vector plays a pivotal role in various fields, including optimal control, sensitivity analysis, and system identification. By employing the adjoint method, which involves solving the adjoint differential equations alongside the original system, the adjoint state vector can be computed. It provides valuable information regarding the sensitivity of the system's performance concerning different parameters, enabling the derivation of gradient-based optimization algorithms and facilitating the analysis of system dynamics. The adjoint state vector serves as a fundamental tool for gaining insights into the behavior and characteristics of the system under investigation.

$$x_{aug}(k) = col\left\{x_i(k), u_i(k-1), ..., u_i(k-h), x_j(k), u_j(k-1), ..., u_j(k-h)\right\} \tag{3}$$

In the present scenario, the delayed system undergoes a transformation wherein it is converted into a non-delayed system, as indicated by equation (4). This transformation is significant as it allows for the analysis and application of methodologies and techniques developed for non-delayed systems. By eliminating the delay term, the system dynamics can be effectively treated as if there were no delays involved. This simplification facilitates the use of existing control strategies and techniques that are primarily designed for non-delayed systems, thus enabling a wider range of established methodologies to be applied to the transformed system. The transformation from a delayed to a non-delayed system expands the available control design options and simplifies the analysis and synthesis processes.

$$x_{aug}(k+1) = A_{aug}x_{aug}(k) + B_{aug}u(k), \mathrm{k} \in Z_+, \mathrm{x}_{aug}(k) \in \mathbb{R}^{(h_{ij}+1)(n_i+n_j)},$$

$$A_{aug} = \begin{bmatrix} A_i & 0 & . & . & . & A_{ij} \\ I_n & 0 & . & . & . & 0 \\ . & . & & & & . \\ . & & . & & & . \\ . & & & . & & . \\ 0 & . & . & . & I_n & 0 \end{bmatrix}, \mathrm{B}_{aug} = \begin{bmatrix} B_i & B_{ij} \\ 0 & 0 \\ . & . \\ . & . \\ . & . \\ 0 & 0 \end{bmatrix} \tag{4}$$

It is important to acknowledge that the matrix A_{aug} is singular in the given context. With consideration of the initial condition (2), we delve into the LQR problem with infinite horizon (5). Predictive control, as an optimal control approach, accommodates constraints on the system dynamics and control inputs while ensuring optimality. In predictive control, constraints are systematically incorporated, and as their strictness increases, the controller's ability to handle uncertainties and disturbances is enhanced. The chosen cost function, being of a quadratic nature, encompasses terms associated with the control input and system output. By minimizing fuel consumption, the control scheme strives to enhance path-tracking accuracy while compensating for disturbances. The objective is to determine the control law u that ensures the asymptotic stability of the system while minimizing the quadratic cost function. Here, Q and R denote weighted square matrices used for adjusting the cost function parameters. By fine-tuning these matrices, control accuracy is improved, and energy consumption is reduced. The cost function comprises two terms: the first term considers the system error between the current state and the system output, while the second term aims to minimize energy consumption. To evaluate the performance of predictive control, a second-order regulator controller is considered, and the associated cost function is defined in equation (5).

$$J_{ih} = \sum_{k=0}^{\infty}\left[x_i^T(k)Q_ix_i(k) + u_i^T(k-h)R_iu_i(k-h)\right] + \sum_{\substack{j=1,\\ j\neq i}}^{N}\sum_{k=0}^{\infty}\left[x_{ij}^T(k)Q_{ij}x_{ij}(k) + u_{ij}^T(k-h)R_{ij}u_{ij}(k-h)\right], \tag{5}$$
$$Q_i \geq 0, Q_{ij} \geq 0, R_i > 0, R_{ij} > 0$$

Utilizing the adjoint method, the delayed LQR problem is transformed into a non-delayed LQR problem. The LQR problem for the delay-free system is characterized by an optimal control law, as given by equation (6), provided that the matrix pair $A_{aug}, B_{aug})$ is stable and the matrix pair $A_{aug}, Q_{aug})$ is observable. It is important to note that the stability of the matrix pair (A,B) corresponding $h_{ij} = 0)$ implies the stability of the matrix pair (A_{aug},B_{aug}). Hence, if the original system, disregarding delays, exhibits stability, the augmented system will also maintain stability. The adjoint method offers a means to handle delay-related complexities, enabling the application of established LQR techniques to address the non-delayed LQR problem while accounting for delays.

$$u(k-h) = Kx_{aug}(k) = \begin{bmatrix} K_i & 0 & . & . & . & K_{ij} \\ K_{ji} & 0 & . & . & . & 0 \\ . & . & & & & . \\ . & & . & & & . \\ . & & & . & & . \\ 0 & . & . & . & & 0 \end{bmatrix} x_{aug}(k),$$
$$K = \begin{bmatrix} K_i & 0 & . & . & . & K_{ij} \\ K_{ji} & 0 & . & . & . & 0 \\ . & . & & & & . \\ . & & . & & & . \\ . & & & . & & . \\ 0 & . & . & . & & 0 \end{bmatrix} = -\left(B_{aug}^TPB_{aug} + R_{aug}\right)^{-1}B_{aug}^TPA_{aug}, \tag{6}$$
$$P \in \mathbb{R}^{(h_{ij}+1)(n_i+n_j)\times(h_{ij}+1)(n_i+n_j)}$$

The matrix P in this context represents the positive definite solution to the discrete-time algebraic Riccati equation (DARE) expressed as equation (7). The DARE is a fundamental equation in control theory that characterizes the solution for the algebraic Riccati equation specific to discrete-time systems. By solving the DARE, one can obtain the matrix P, which is positive definite. The positive definiteness of P is a crucial property as it ensures the stability and convergence of the control system. The solution to the DARE provides valuable insights into the optimal control design and enables the assessment of stability and performance criteria for the controlled system.

$$
\begin{gathered}
P = A_{aug}^{T}\left[P - PB_{aug}\left(B_{aug}^{T}PB_{aug} + R_{aug}\right)^{-1}B_{aug}^{T}P\right]A_{aug} + Q_{aug},\\
R_{aug} = \begin{bmatrix} R_i & . & . & . & R_N \\ & . & & & \\ & & R_j & & \\ & & & . & \\ & & & & R_N \end{bmatrix}, Q_{aug} = \begin{bmatrix} Q_i & . & . & . & Q_N \\ & . & & & \\ & & Q_j & & \\ & & & . & \\ & & & & Q_N \end{bmatrix}
\end{gathered} \tag{7}
$$

In the given scenario, it can be observed that the matrix $A_{aug} + B_{aug}[K_i, K_{ij}]$ is stable. This observation is significant as it leads to the determination of an optimal feedback control law, as presented in equation (8), which incorporates distributed delay for the original system. By ensuring the stability of the matrix $A_{aug} + B_{aug}[K_i, K_{ij}]$, the control scheme derived from equation (8) is deemed optimal and applicable to the system with distributed delay. The stability of the augmented system's matrix validates the efficacy of the proposed control approach in addressing the challenges posed by distributed delays and contributes to the design of an effective feedback control strategy for the original system.

$$
u(k) = Kcol\{x_i(k), u_i(k-1), ..., u_i(k-h), u_j(k), u_j(k-1), ..., u_j(k-h)\} \tag{8}
$$

The aforementioned result is obtained through the application of the Hautus Criterion [71], as substantiated by the following proof. The Hautus Criterion is a fundamental tool used to assess the stability of a linear time-invariant system. By verifying the applicability of the Hautus Criterion, we can establish the stability properties of the system under consideration. The proof will provide a formal demonstration of the validity and effectiveness of the Hautus Criterion in determining system stability, thereby reinforcing the reliability and robustness of the obtained result.

Proof: To establish the claim, consider the matrix [sI_n - A, B] for $|s| \geq 1$. It can be observed that this matrix attains full rank for all $|s| \geq 1$. This conclusion holds since the adjoint system's matrix $[sI_n - A \quad B]$ exhibits full rank for $|s| \geq 1$. Consequently, this implies that the main system, which encompasses the system without delay, is stable. The stability of the system is guaranteed by the full-rank property of the matrix $[sI_n - A \quad B]$ for $|\,|s| \geq 1$, establishing the desired result (9).

$$
\left[SI - A_{aug}B_{aug}\right] = \begin{bmatrix} SI_{n_i} - A_i & SI_{n_{ij}} - A_{ij} & 0 & 0 & 0 & 0 & 0 & -B_i & -B_{ij} & 0 \\ 0 & SI_{n_{ui}} & SI_{n_{uj}} & 0 & 0 & 0 & 0 & 0 & I_{n_{ui}} & I_{n_{uj}} \\ . & -I_{n_{ui}} & -I_{n_{uj}} & . & . & . & 0 & 0 & 0 & 0 \\ . & & . & & . & & & & & \\ . & & & . & & . & & & & \\ & & & & & & & & & \end{bmatrix} \tag{9}
$$

Henceforth, assuming the stability and observability of matrices $(A, B, \sqrt{Q})$ (for $h = 0$), it follows that there exists a unique optimal controller in the form of equation (8). This controller relies on the positive definite unique response P obtained from the resulting discrete algebraic Riccati equation. The optimal control, expressed as equation (6), incorporates a distributed delay at the input, mirroring the characteristics of the prediction-based controller for the continuous system. The uniqueness of the optimal controller and the reliance on the discrete algebraic Riccati equation guarantee the optimality and effectiveness of the control strategy, thereby facilitating efficient satellite orbit control in the presence of distributed delays.

Under the assumptions made regarding the considered system, the initial function, and the cost function, the reduction method is applied. This reduction method is primarily employed in the analysis of systems with delayed inputs. Its purpose is to derive the reduced-order response for the LQR problem with input delay. The design discussion relies on a predictive approach based on forecasting. By introducing the variable $v(k) = u(k-h)$, the cost function J_h can be expressed as equation (10). This transformation allows for a more concise representation of the cost function while accounting for the input delay. The utilization of the reduction method enables the extraction of a reduced-order response, leading to the formulation and analysis of an effective control strategy for the LQR problem with input delay.

$$J_{ih} = \sum_{M=0}^{h-1}\left[\varphi_i^T(0)\left(A_i^T\right)^M Q_i A_i^M \varphi_i\right] + \sum_{\substack{j=1,\\ j\neq i}}^{N}\sum_{M=0}^{h-1}\left[\varphi_{ij}^T(0)\left(A_{ij}^T\right)^M Q_{ij} A_{ij}^M \varphi_{ij}(0)\right] + \overline{J}_{ih}$$
$$\overline{J}_{ih} = \sum_{k=h}^{\infty}\left[x_i^T(k)Q_i x_i(k) + \nu_i^T(k)R_i\nu_i(k)\right] + \sum_{\substack{j=1,\\ j\neq i}}^{N}\sum_{k=h}^{\infty}\left[x_{ij}^T(k)Q_{ij}x_{ij}(k) + \nu_{ij}^T(k)R_{ij}\nu_{ij}(k)\right] \tag{10}$$

Following equation (10), the terms within J_{ih} consist of fixed functions that are predetermined and cannot be altered. Conversely, functions that can be adjusted during the design process, such as the control input, appear within $\overline{J}_{ih}$. Consequently, minimizing J_{ih} for the aforementioned system translates to the minimization of $\overline{J}_{ih}$, aligning it with the system without delay. This alignment is achieved by introducing the function v, which is based on the control input u. The definition of v allows for a direct correspondence between the optimization objectives for the system with delay and the system without delay. By establishing this connection, the minimization of J_{ih} can be effectively pursued, resulting in a control scheme that optimizes the system's performance while accommodating the presence of input delay in equation (11).

$$x_i(k+1) = A_i x_i(k) + B_i\nu_i(k) + \sum_{\substack{j=1,\\ i\neq j}}^{N}\left[A_{ij}x_j(k) + B_{ij}\nu_j(k)\right],$$
$$k \geq h_{ij}, \mathrm{x}_i\left(h_{ij}\right) = A_i^{h_{ij}}\varphi_i(0) + \sum_{\substack{j=1,\\ i\neq j}}^{N} A_{ij}^{h_{ij}}\varphi_{ij}(0) \tag{11}$$

Suppose the matrix pair (A, B) is stable, and the matrix pair $(\mathrm{A}, \sqrt{\mathrm{Q}})$ is observable. Under these assumptions, the resulting problem yields a unique optimal control, as indicated by equation (12). This optimal control solution is characterized by its uniqueness, ensuring that it is the only control strategy that attains the optimality criteria for the given problem. The stability of the matrix pair (A, B) guarantees the stability of the control system, while the observability of the matrix pair $(\mathrm{A}, \sqrt{\mathrm{Q}})$ ensures that the system's states can be accurately estimated from the available measurements. These stability and observability conditions are essential prerequisites for the derivation and effectiveness of the optimal control law outlined in equation (12).

$$\nu_i(k) = u_i(k-h), K = \begin{bmatrix} K_i & 0 & . & . & . & K_{ij} \\ K_{ji} & 0 & . & . & . & 0 \\ . & . & & & & . \\ . & & . & & & . \\ . & & & . & & . \\ 0 & . & . & . & & 0 \end{bmatrix} = \left(-B_{aug}^T P B_{aug} + R_{aug}\right)^{-1} B_{aug}^T P A_{aug},$$
$$P \in \mathbb{R}^{\left(h_{ij}+1\right)\left(n_i+n_j\right)\times\left(h_{ij}+1\right)\left(n_i+n_j\right)} \tag{12}$$

In this context, it is essential to highlight that the unique non-negative solution P of the discrete algebraic Riccati equation plays a crucial role. This solution serves as a fundamental component in the design of the optimal control strategy. Furthermore, the application of optimal feedback ensures the stabilization of the closed-loop system, guaranteeing its stability and desired performance. A noteworthy aspect to emphasize is the derivation of the function ν through the aforementioned discussions. By making suitable modifications to this function, the control function u can be obtained by utilizing the relation presented in equation (13). This relationship allows for the transformation and implementation of the derived function ν, facilitating the determination of the control actions required to optimize system performance while considering the presence of delays.

$$u_i(k) = \nu_i(k+h) = K_i + \sum_{\substack{j=1,\\ j\neq i}}^{N} K_{ij}x\left(k+h_{ij}\right),$$
$$x(k+h) = A^h x(k) + \sum_{j=k}^{k+h-1} A^{k+h-j-1}Bu(j-h) \tag{13}$$

By adjusting the upper and lower bounds of sigma in equation (13), we arrive at equation (14). This adjustment allows for the transformation and alignment of the two equations. The modification of the limits of sigma in equation (13) ensures that the resulting equation (14) captures the desired control relationship accurately. This adjustment is a critical step in refining the control function and achieving the desired control objectives. The revised equation (14) encapsulates the optimized control relationship and is instrumental in guiding the system toward its desired behavior.

$$u(k) = K\left[A^h x(k) + \sum_{j=-h}^{-1} A^{-j-1} B u(k+j)\right] \tag{14}$$

Furthermore, through the application of optimal control, the optimal value of J_h^* is determined as expressed in equation (15). This optimal value represents the minimum achievable value of the cost function J_h, which is attained through the implementation of the optimal control strategy. By optimizing the control inputs and system dynamics, the control scheme aims to minimize J_h and achieve superior system performance. The derived optimal value of J_h^* serves as a benchmark, providing a quantitative measure of the system's optimality and enabling comparisons between different control strategies. It serves as a valuable metric in evaluating the effectiveness and efficiency of the proposed control approach.

$$J_h^* = \sum_{j=0}^{h-1} \varphi^T(0)\left(A^j\right)^T Q A^j \varphi(0) + \varphi^T(0)\left(A^h\right)^T P A^h \varphi(0) \tag{15}$$

A method for reducing discrete indeterminate linear systems with input delay has been developed. This method focuses on addressing the main system, which features an indefinite and non-small delay denoted as $\tau_k = h + \eta_k$. The reduction technique aims to simplify the analysis and control of such systems by transforming them into a more manageable form. By applying this reduction method, the complexities associated with input delay are effectively addressed in equation (16), enabling a more comprehensive understanding and control of the system dynamics. The reduction process facilitates the application of established control strategies and techniques to improve the stability and performance of the system with input delay.

$$x(k+1) = Ax(k) + Bu(k-\tau_k), x(k) \in \mathbb{R}^n, \mathrm{u}(k) \in \mathbb{R}^{n_u}, \mathrm{k} = 0, 1, \ldots \tag{16}$$

In the aforementioned system, the parameter h represents a fixed nominal value, while the condition $|\eta_k| \leq \mu < |h$ characterizes the uncertainty associated with the delay. This condition implies that the absolute value of η_k remains within the range of μ, which captures the uncertainty in the delay parameter. By introducing a change of variable, the system relation expressed in equation (17) is derived. This change of variable allows for a transformation of the system dynamics, resulting in the formulation of relation (17). The revised relation captures the modified system behavior, accounting for the uncertainty in the delay parameter and facilitating further analysis and control design. It enables the consideration of a broader range of scenarios and provides a more comprehensive understanding of the system's response in the presence of delay uncertainty.

$$\begin{aligned} z(k) &= A^h x(k) + \sum_{j=-h}^{-1} A^{-j-1} B u(k+j), \\ z(k+1) &= Az(k) + Bu(k) + A^h B[u(k-\tau_k) - u(k-h)] \end{aligned} \tag{17}$$

In the current scenario, the presence of variable delay within the system renders the direct reduction method impractical. Therefore, the variable change method is employed to address the problem effectively. Let us assume the existence of a gain K such that the matrix A + BK is stable. Under this condition, the feedback control law $\mathrm{u(k)} = \mathrm{Kz(k)}$ stabilizes the system if the system described by equation (18) is stable. The stability of the system is a crucial requirement to ensure that the control scheme effectively maintains the desired system behavior and mitigates any destabilizing effects. By establishing stability in the system as described in equation (18), the feedback control law $\mathrm{u(k)} = \mathrm{Kz(k)}$ proves effective in stabilizing the system and achieving the desired control objectives.

$$z(k+1) = (A+BK)z(k) + A^h BK[z(k-\tau_k) - z(k-h)] \tag{18}$$

The stability analysis of the system with non-small delay can be conducted using the Lyapunov-Krasovsky method. This method provides a framework for assessing the stability properties of such systems. In this case, the LKF expressed as equation (19) can be considered for the analysis of the new system. By evaluating the LKF, one can gain insights into the system's stability characteristics and determine conditions under which stability can be guaranteed. The Lyapunov-Krasovsky method offers a rigorous approach to stability analysis, enabling the assessment of system behavior and the design of control strategies that ensure stability in the presence of non-small delays.

$$\begin{aligned} V(k) &= z^T(k) P z(k) + \sum_{j=-\mu}^{\mu-1} \sum_{s=k+j-h}^{k-1} \xi^T(s) R_1 \xi(s) \\ \xi(s) &= z(s+1) - z(s), \mathrm{P} > 0, \mathrm{R}_1 > 0 \end{aligned} \tag{19}$$

Furthermore, the stability of the system can be assessed using the input-output method. This method provides an alternative approach to analyzing system stability by examining the relationship between system inputs and outputs. By studying the input-output behavior, one can gain valuable insights into the stability properties of the system. The input-output method enables the characterization of the system's response to different input signals and disturbances, allowing for the identification of stability criteria. This approach provides a comprehensive understanding of the system's stability, complementing other stability analysis methods such as the Lyapunov-Krasovsky method. By employing the input-output method, researchers and practitioners can verify and validate the stability of the system and design appropriate control strategies to ensure its stable operation.

Subsequently, the focus turns towards investigating the Guaranteed Cost Control (GCC) problem for systems with variable delay, where the delay time τ_k resides within the interval $[0,h]$, and the system is characterized by fixed matrices A and B. In this context, the cost function under consideration is defined as presented in equation (20). The GCC problem aims to design a control strategy that not only ensures system stability but also minimizes the associated cost function. By formulating the cost function in this manner, the control design process can effectively incorporate both stability and performance objectives, enabling the development of control strategies that strike a balance between system stability and cost optimization. The investigation of the GCC problem for systems with variable delay with an indefinite time $\tau_k \in [0,h]$ and fixed matrices A and B contribute to advancing the field of control theory by addressing the challenges posed by variable delay systems and establishing control strategies that guarantee system stability while achieving cost optimization.

$$\begin{aligned} &J = \sum_{j=0}^{\infty} z^T(k)z(k), \xrightarrow[z(k)=Lx(k)+Du(k-\tau_k)]{} \\ &J = (Lx(k) + Du(k-\tau_k))^T(Lx(k)+Du(k-\tau_k)), z(k) \in \mathbb{R}^{n_z} \end{aligned} \tag{20}$$

In the case of systems characterized by delays or uncertain matrices, it is not always possible to obtain optimal control and optimal cost solutions such as the LQR. However, it is feasible to design a control law that ensures a guaranteed cost as small as possible, denoted as δ, for the cost function J. This control law is capable of achieving the condition $J \leq \delta$ for all uncertainties, considering a given initial condition x_0. To achieve this guaranteed minimum cost value $J(x_0) \leq \delta$ for all uncertain delays τ_k, a feedback control mode $u(k) = Kx(k)$ is considered. The closed-loop system, described in equation (21), encompasses the interplay between the control law and the uncertain delays, resulting in a controlled system that strives to achieve the desired guaranteed cost with minimal uncertainty. By adopting this approach, the control strategy can effectively mitigate the impact of delays and uncertainties, leading to improved system performance and cost optimization.

$$x(k+1) = Ax(k) + BKx(k-\tau_k), z(k) = Lx(k) + Du(k-\tau_k) \tag{21}$$

Proof: To establish the exponential stability of the system with $\tau_{ij}(t) \in [0, h_{ij}]$ (where δ is a scalar), we consider a standard candidate Lyapunov function expressed as equation (22). Let $V : [t_{ij0}, \infty) \rightarrow \mathbb{R}_+$ denote a local continuous function. We aim to show that for all $t_{ij} \geq t_{ij0}$, there exists a $\delta > 0$ such that the system equation (22) holds. By assuming the existence of such a δ, we can establish the desired exponential stability of the system. Through the analysis of the Lyapunov function and its associated properties, we can demonstrate the boundedness and convergence of V over time. By imposing appropriate conditions on the system equation (22) and the Lyapunov function, we can establish the exponential stability of the system, providing a formal proof of the system's stability properties.

$$\begin{aligned} &V(x_k) = V_P(k) + V_S(k) + V_R(k), \quad P>0, R\geq 0, S\geq 0 \\ &V_P(k) = x^T(k)Px(k), \\ &V_S(k) = \sum_{j=k-h}^{k-1} x^T(j)Sx(j), \\ &V_R(k) = h\sum_{m=-h}^{-1}\sum_{j=k+m}^{k-1} \overline{y}^T(j)R\overline{y}(j), \overline{y}(j) = x(j+1)-x(j) \end{aligned} \tag{22}$$

Now, suppose we find $\alpha > 0$ that can nullify equation (23). In this case, the closed-loop system achieves stability. By selecting an appropriate value for α, we can effectively counterbalance the effect of equation (23) and ensure system stability. The stability of the closed-loop system is of paramount importance in control theory as it guarantees the system's ability to reach and maintain a desired equilibrium state in the presence of uncertainties and disturbances. By identifying the suitable α that counteracts the impact of equation (23), we establish the stability of the closed-loop system, ensuring its robust performance and reliable operation.

$$V(x_{k+1}) - V(x_k) + z^T(k)z(k) \leq \overline{\xi}^T(k)\Gamma\overline{\xi}(k) < -\alpha|x(k)|^2, \alpha > 0 \tag{23}$$

In this section, we consider the extension vector defined as equation (24). By employing the Schur complement [72], we derive the desired Linear Matrix Inequality (LMI). Schur complement plays a significant role in obtaining the LMI in equation (25) by providing a mathematical framework and analytical tools for the analysis of matrix inequalities. It enables the conversion of complex inequalities into equivalent LMI formulations, which are easier to handle and manipulate. Through the application of the Schur complement and the extension vector (27), we can establish the LMI that serves as a crucial mathematical tool for the subsequent analysis and synthesis of control strategies. The derived LMI encapsulates the necessary conditions and constraints required for achieving desired system performance, stability, and optimality.

$$\overline{\xi}(k) = \mathrm{col}\{x(k), y(k), x(k-h), x(k-\tau_k)\} \tag{24}$$

$$\Gamma = \begin{bmatrix} & | & L^T \\ \varphi & | & 0 \\ & | & K^T D^T \\ - & - & - \\ * & | & -I \end{bmatrix} < 0,$$

$$\varphi = \begin{bmatrix} \varphi_{11} & \varphi_{12} & S_{12} & R - S_{12} + P_2^T A_1 \\ * & \varphi_{22} & 0 & P_3^T A_1 \\ * & * & -(S+R) & R - S_{12}^T \\ * & * & * & -2R + S_{12} + S_{12}^T \end{bmatrix}, \tag{25}$$

$$A_1 = BK$$
$$\varphi_{11} = (A^T - I)P_2 + P_2^T(A - I) + S - R,$$
$$\varphi_{12} = P - P_2^T + (A^T - I)P_3,$$
$$\varphi_{22} = -P_3 - P_3^T + P + h^2 R$$

As a consequence, by considering sigma in the range of 0 to N, inclusively, from the unequal sides, the guaranteed cost function in equation (26) is derived. This process involves selecting sigma values that satisfy the given constraints and bounds, allowing for the determination of the guaranteed cost function. By considering a range of sigma values and evaluating the associated cost function, we can assess the system's performance and optimize it based on the desired cost criteria. The obtained guaranteed cost function serves as a valuable metric for evaluating and comparing different control strategies, providing insights into the system's behavior and enabling the selection of an optimal control approach that minimizes costs while meeting the desired performance objectives.

$$J = \sum_{k=0}^{N} z^T(k)z(k) \le V(x_0) - V(x_{N+1}) \le V(x_0), \qquad J \le V(x_0) = x^T(0)Px(0) \tag{26}$$

Considering the provided initial condition $\boldsymbol{x_0} \in \mathbb{R}^n$, a positive constant $\boldsymbol{h} > \boldsymbol{0}$, and a tuning parameter $\boldsymbol{\varepsilon}$, let us assume the existence of $\boldsymbol{n} \times \boldsymbol{n}$ matrices $\overline{\boldsymbol{P}} > \boldsymbol{0}, \overline{\boldsymbol{R}} > \boldsymbol{0}, \overline{\boldsymbol{P}}_2, \overline{\boldsymbol{S}} > \boldsymbol{0}, \overline{\boldsymbol{S}}_{12}$, a matrix Y of size $\boldsymbol{n_u} \times \boldsymbol{n}$, and a positive scalar $\boldsymbol{\delta} > \boldsymbol{0}$ that satisfy the aforementioned LMI. Under these conditions, the resulting closed-loop system is exponentially stable for all delays $\boldsymbol{\tau_k} \in [\boldsymbol{0}, \boldsymbol{h}]$, and the cost of the system is guaranteed to satisfy $\boldsymbol{J} \le \boldsymbol{\delta}$. To minimize the guaranteed cost, the aforementioned LMIs can be solved by incorporating the minimization condition $\boldsymbol{\delta} > \boldsymbol{0}$. By solving these LMIs to minimize δ, an optimal solution can be obtained, leading to a control strategy that not only ensures exponential stability of the closed-loop system but also minimizes the associated cost. This approach allows for the development of an optimized control scheme that balances stability and cost considerations, resulting in improved system performance and efficiency.

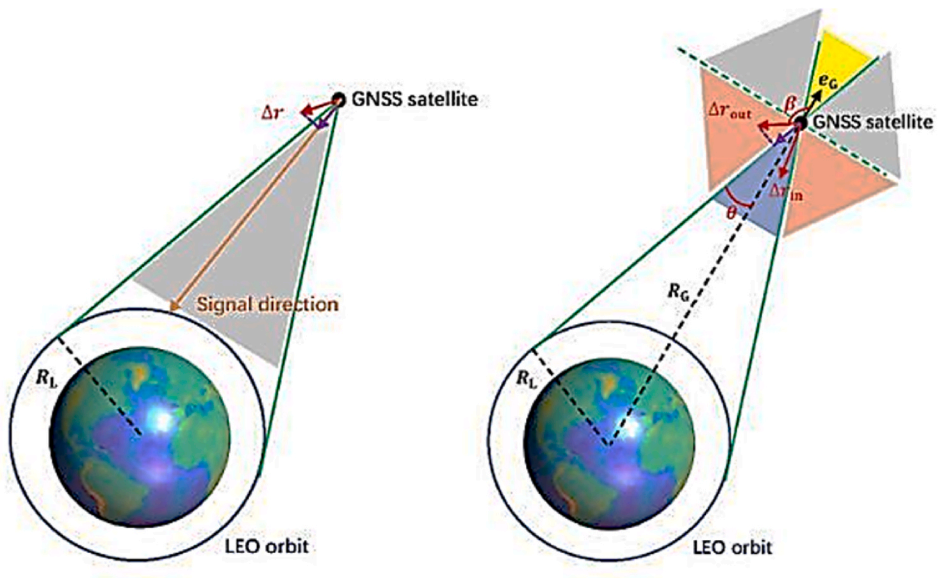

Fig. 1. Physical interpretations of orbital satellite elements.

In the realm of satellite orbit control, understanding the concept of isolated regions of space is of paramount importance. These isolated regions represent areas in which a satellite temporarily loses contact with ground stations or communication networks [73–82] due to its orbital path. The satellite effectively operates beyond the reach of immediate command and control. This phenomenon occurs regularly as satellites traverse their orbits, leading to brief periods of isolation. These isolated regions are a natural consequence of the satellite's trajectory and the finite coverage of ground-based tracking stations. Therefore, comprehending these occurrences is vital for designing control systems that can autonomously manage the satellite during such communication outages, ensuring its safe operation and the continuation of its mission objectives. These regions of isolation are not truly infinite in extent but are instead characterized by their relatively long duration in the context of satellite orbit dynamics, rendering them a crucial consideration in satellite control strategies.

Noted that the problem (1)-(26) is based mathematical model [83–95]. The mathematical model includes equations and variables [96–108]. Equations are in as non-linear and linear format [109–121]. Variables are as integer, binary and continuous [122–134]. Integer and continuous variables are as positive, free or negative [135–147].

3. Results and discussion

The simulation section aims to evaluate the effectiveness and performance of the proposed control approach in the context of satellite orbit control. Through numerical simulations, the control scheme's capabilities, such as maintaining orbit stability and minimizing fuel consumption, will be assessed. The simulations are conducted using a representative satellite orbit model and incorporate various scenarios to examine the control system's robustness and adaptability to different operating conditions. The performance metrics, including orbit deviation, control input magnitude, and fuel consumption, will be analyzed to gauge the control scheme's efficacy in achieving the desired control objectives. By examining the simulation results, valuable insights will be gained regarding the control system's performance, its ability to handle uncertainties and time delays, and its overall effectiveness in satellite orbit control. These simulation-based findings will provide valuable empirical evidence to support the claims and contributions made in this research.

3.1. Mathematical modeling of satellite movement in orbit

Mathematical modeling plays a crucial role in understanding and analyzing the movement of satellites in orbit. By utilizing mathematical principles and physical laws, researchers can develop models that accurately describe the dynamics and behavior of satellites as they traverse their orbital paths. Mathematical models for satellite movement typically consider factors such as gravitational forces, orbital mechanics, atmospheric drag, and external perturbations. These models often involve differential equations that capture the time evolution of satellite position, velocity, and other relevant parameters. By simulating these mathematical models, researchers can gain insights into satellite behavior, predict future trajectories, and design control strategies to optimize satellite orbit control. The mathematical modeling of satellite movement in orbit serves as a foundation for further research and analysis, enabling a deeper understanding of satellite dynamics and facilitating the development of advanced control techniques for orbit stabilization, maneuvering, and mission planning.

In this section, the orbital dynamics equations governing the motion of an Earth satellite, as depicted in Fig. 1, are presented. These equations capture the fundamental principles that govern the satellite's orbital behavior. The orbital dynamics equations, expressed as equation (27), incorporate factors such as gravitational forces, the satellite's position and velocity vectors, and the relevant celestial parameters [148]. By solving these equations, researchers can analyze the satellite's trajectory, understand its orbital characteristics, and predict its future motion. These equations serve as a mathematical framework for studying the orbital dynamics of Earth satellites and provide a basis for further analysis and control design in the context of satellite orbit control.

Fig. 1 provides a visual representation of the physical interpretations associated with the orbital satellite elements. These elements play a crucial role in describing the characteristics and behavior of satellites in orbit. The figure illustrates key parameters such as the semi-major axis, eccentricity, inclination, argument of perigee, and right ascension of the ascending node. Each element conveys specific information about the satellite's orbit, including its size, shape, orientation, and position relative to the Earth. By understanding and analyzing these orbital satellite elements, researchers can gain valuable insights into the satellite's orbital dynamics, mission requirements, and overall behavior in equation (27). Fig. 1 serves as a reference tool, aiding in the interpretation and comprehension of these physical aspects, and serves as a foundation for further analysis and investigation in the field of satellite orbit control.

$$S:\begin{cases}\delta\ddot{x}-3n^2\delta x-2n\delta\dot{y}=\dfrac{1}{m}F_x+\alpha_{p_x}\\ \delta\ddot{y}+2n\delta\dot{x}=\dfrac{1}{m}F_y+\alpha_{p_y}\\ \delta\ddot{z}+n^2\delta z=\dfrac{1}{m}F_z+\alpha_{p_z}\end{cases}\tag{27}$$

The control forces applied to the satellite by the propellant are denoted as F_x, F_y, and F_z, representing their respective components. These forces result in the acceleration α_{p_x}, α_{p_y}, and α_{p_z} experienced by the satellite, while m represents the mass of the satellite. Furthermore, the relation $n=\sqrt{\frac{\mu}{r^3}}$ holds, where r denotes the distance of the satellite from the center of the Earth and μ represents the constant of the Earth's gravity. The linear equations described herein represent the discrepancy between the satellite's movement and the desired main orbit. The objective of the control design is to minimize this discrepancy, effectively reducing it to zero and ensuring that the satellite remains in the reference orbit with minimal error. By considering the state variables as $x = [\delta x\ \delta y\ \delta z\ \delta\dot{x}\ \delta\dot{y}\ \delta\dot{z}]$ and the control input vector as $u = [F_x\ F_y\ F_z]$, the state space equations governing the linear system are expressed as equation (28). These equations serve as the mathematical framework for analyzing and designing control strategies to maintain the satellite in the desired reference orbit.

$$\dot{x} = Ax + Bu,\ y = Cx$$

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 3n^2 & 0 & 0 & 0 & 2n & 0 \\ 0 & 0 & 0 & -2n & 0 & 0 \\ 0 & 0 & -n^2 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{m} & 0 & 0 \\ 0 & \frac{1}{m} & 0 \\ 0 & 0 & \frac{1}{m} \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} [] \tag{28}$$

To facilitate the implementation of predictive control for the system equations, a discrete representation is required. The discretization process is accomplished using Euler's forward-step method, which is a widely adopted first-order numerical approximation technique. This method allows the continuous-time system equations to be translated into discrete-time counterparts that can be readily utilized for control algorithm implementation. Euler's forward-step method involves dividing the continuous-time interval into discrete time steps and approximating the system dynamics by evaluating the derivative at each time step. By discretizing the system equations, the predictive control algorithm can be efficiently executed in discrete time, enabling real-time control and optimization. The utilization of Euler's forward-step method serves as a fundamental step in transforming the continuous-time system equations into a suitable form for predictive control implementation.

The proposed control plan for satellite orbit maintenance aims to improve orbit stability and fuel efficiency while its efficiency is confirmed in different ways.

1. Improved circuit maintenance: The proposed control scheme is designed to improve circuit maintenance in several ways:
   - Minimizing fuel consumption: Using predictive control strategies, this design has minimized fuel consumption, which not only reduced operating costs but also extended the satellite's mission life by conserving propulsion.
   - Optimal Control: Using an LQR controller with an infinite horizon and predictive control approaches has helped to optimize the control inputs and allowed the satellite to stay closer to its intended orbit.

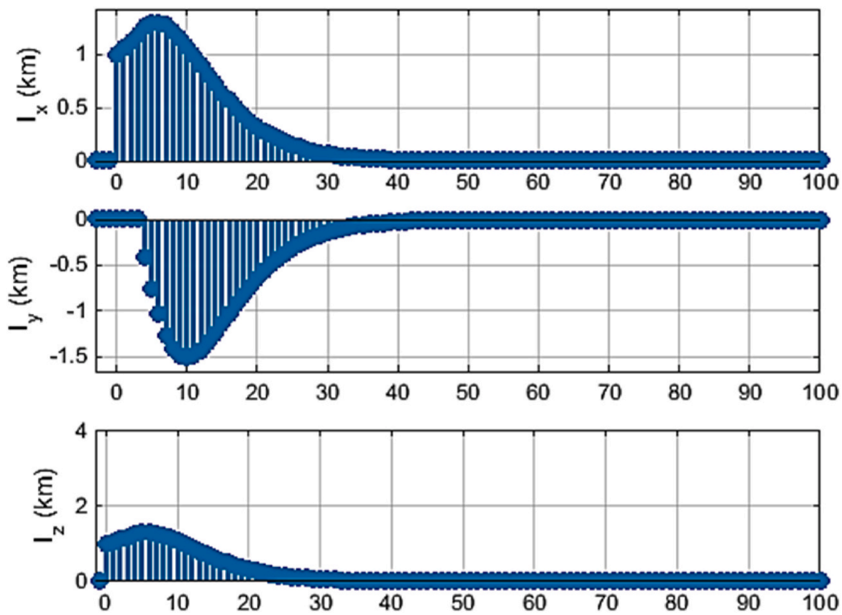

Fig. 2. Error between satellite and reference orbit.

- Stability analysis: The control design has used stability analysis techniques, such as Lyapunov-Krasovsky functions and linear matrix inequalities. The proposed method ensures that the satellite orbit remains stable despite uncertainties and time delays.

2. Validation: To verify the effectiveness of the proposed control plan, several steps have been carried out:
   - Numerical simulation: The proposed control plan has been evaluated through numerical simulation. The simulations include the use of a mathematical model of the satellite's orbital dynamics and the use of a control scheme to evaluate its performance in different conditions and scenarios.
   - Performance measures: Various performance measures have been used, such as circuit deviation, control input value, and fuel consumption. These criteria provide quantifiable measures of how well the satellite orbit control scheme is maintained.

3.2. Simulation

Example 1 .

In this section, we demonstrate the performance of model-based predictive control in ensuring the satellite remains in the desired reference orbit. Additionally, we explore the integration of (LQR) control with predictive control. The reference circuit specifications for predictive control implementation, as well as the physical parameters of the satellite, are provided. The mass of the satellite is denoted as $m = 100kg$, the gravitational constant as $\mu = 2.5$, and the initial distance from the center of the Earth as $r_0 = 1.3m$. By utilizing Linear Matrix Inequalities (LMI) with specific values of $h = 3$ and $\varepsilon = 1$, along with the initial condition $\varphi(-k) = e^{-k}, k \leq 0$, we obtain a high-cost threshold of $\delta = 0.0716$. This value serves as a benchmark for evaluating the cost associated with maintaining the satellite on the reference orbit. The results presented in this section highlight the effectiveness of combining model-based predictive control with LQR control in achieving the desired control objectives and optimizing the performance of the satellite orbit control system.

The primary objective of the control design is to eliminate the initial error and maintain the satellite on the reference orbit with utmost accuracy, while simultaneously minimizing fuel consumption. To achieve this, weight matrices Q and R are introduced to fine-tune the designed control. The matrix R is specified as $R = diag(0.072\ 0.072\ 0.072)$, indicating the relative importance of control input components in the control design. Similarly, the matrix Q is set as $Q = diag(0.023\ 0.023\ 0.023)$, reflecting the significance of the state variables in the control objective. Furthermore, a prediction horizon of $N = 10$ is employed, defining the number of future time steps considered in the predictive control algorithm. By optimizing the control design with these weight matrices and prediction horizon, the control system aims to minimize the initial error, enhance orbit accuracy, and achieve efficient fuel utilization.

Fig. 2 presents a graphical representation of the error between the satellite's actual trajectory and the desired reference orbit during the implementation of the LQR controller using the predictive controller and reduction method. The graph showcases the temporal evolution of the error over a specific duration. Initially, there exists an error between the satellite's position and the reference orbit, indicating a deviation from the desired trajectory. However, as time progresses, the error gradually diminishes, signifying the effectiveness of the control scheme in correcting the satellite's trajectory. After approximately 30 s, the error is significantly reduced,

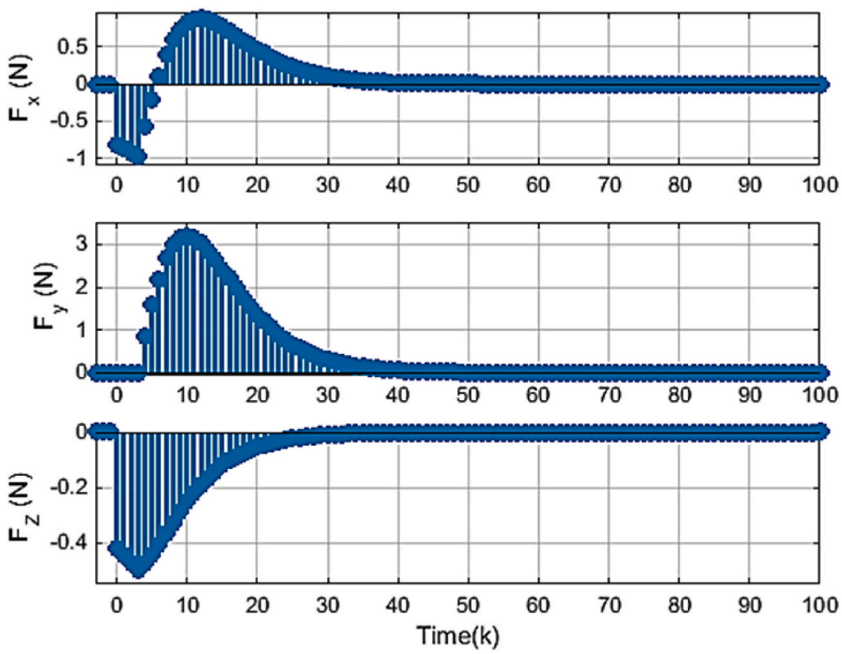

Fig. 3. Control force applied to return the satellite to the main orbit.

indicating that the satellite has been successfully placed on the reference orbit with a high level of accuracy. This demonstrates the capability of the designed control strategy to eliminate the initial error and guide the satellite toward the desired trajectory. The graph serves as a visual confirmation of the control system's ability to achieve precise orbit alignment and showcases the successful implementation of the predictive controller and reduction method in maintaining the satellite's position with accuracy.

Fig. 3 provides insights into the control force exerted to guide the satellite back to the main orbit and maintain its position. The graph illustrates the magnitude of the control force applied by the predictive controller over a specific time. Notably, the maximum control force observed in the graph is 0.1 N. This observation highlights the effectiveness of the control scheme in considering constraints on the control input. By imposing limitations on the control force, the controller ensures that the applied force remains within acceptable bounds. The graph reveals that the control force remains relatively low throughout the duration, indicating that the controller operates efficiently to achieve orbit maintenance with minimal force usage. Additionally, the graph demonstrates the controller's ability to counteract disturbances that cause the satellite to deviate from the orbital plane. Once the satellite reaches the maximum allowable distance from the desired orbit, the controller activates and applies minimal force to bring the satellite back to the main orbit. Overall, Fig. 3 provides evidence of the controller's effectiveness in maintaining the satellite's position with minimal control force, showcasing its robustness in handling disturbances and achieving precise orbit control.

Example 2 .

In this example, we'll consider a simplified two-body problem, assuming only Earth's gravitational influence on the satellite's motion. The satellite's position and velocity will be updated using the Euler method, but keep in mind that more sophisticated integration methods, like the Runge-Kutta method, are preferred for better accuracy.

The equations of motion for the satellite system using the proposed method can be derived from Newton's second law and the law of universal gravitation in equation (29). The system can be represented by the following ordinary differential equations.

1. Position Equations:

$$\mathbf{r}_i = \mathbf{r}_{i-1} + \Delta t \cdot \mathbf{v}_{i-1} \tag{29}$$

Where $\mathbf{r}_i$ is the position vector of the satellite at time step i, $\mathbf{r}_{i-1}$ is the position vector of the satellite at the previous time step, Δt is the time step, and $\mathbf{v}_{i-1}$ is the velocity vector of the satellite at the previous time step.

2. Velocity Equations in equation (30):

$$\mathbf{v}_i = \mathbf{v}_{i-1} + \Delta t \cdot \mathbf{a}_{i-1} \tag{30}$$

Where $\mathbf{v}_i$ is the velocity vector of the satellite at time step i, $\mathbf{v}_{i-1}$ is the velocity vector of the satellite at the previous time step, and

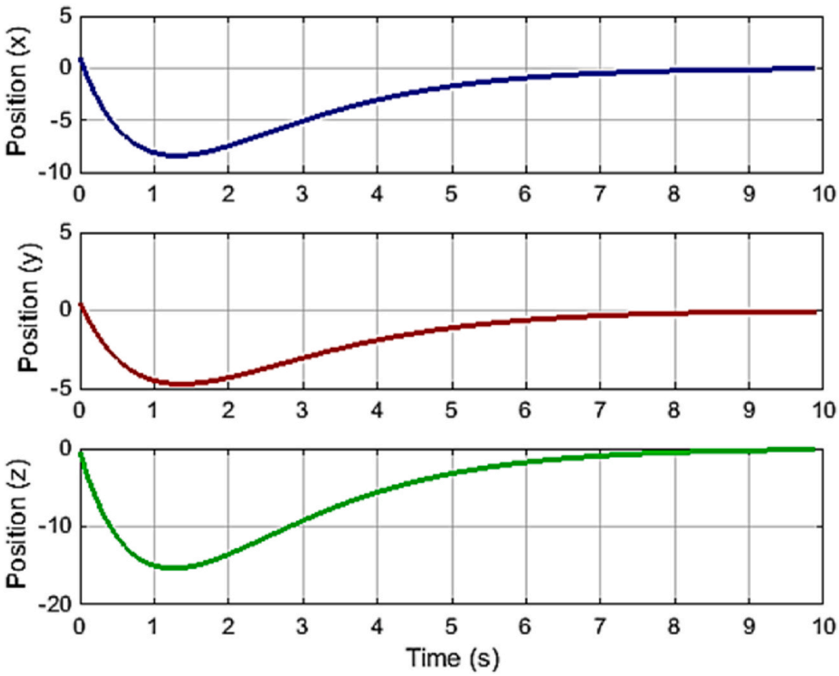

Fig. 4. All motion positions for the satellite system.

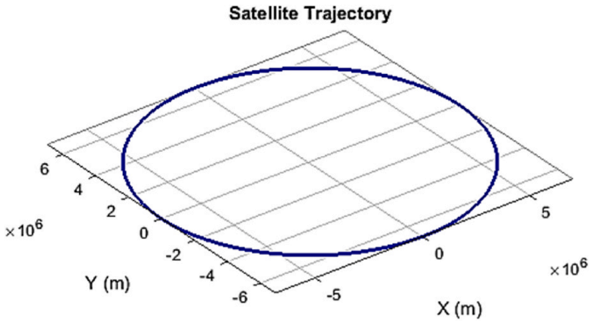

Fig. 5. Satellite Trajectory of the two-body problem.

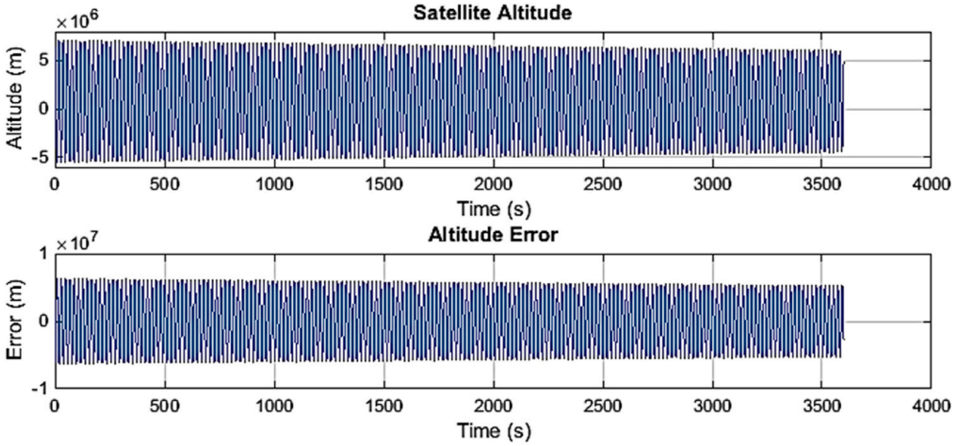

Fig. 6. Satellite Altitude and Altitude Error of control scheme on the small-time delay system.

$\mathbf{a}_{i-1}$ is the acceleration vector of the satellite at the previous time step.

3. Acceleration Equations in equation (31):

$$\mathbf{a}_{i-1} = -\frac{\mu}{r_{\text{mag}}^3} \cdot \mathbf{r}_{i-1} \tag{31}$$

where μ is the Earth's gravitational constant, r_{mag} is the magnitude of the position vector $\mathbf{r}_{i-1}$, and $-\frac{\mu}{r_{\text{mag}}^3}$ represents the gravitational

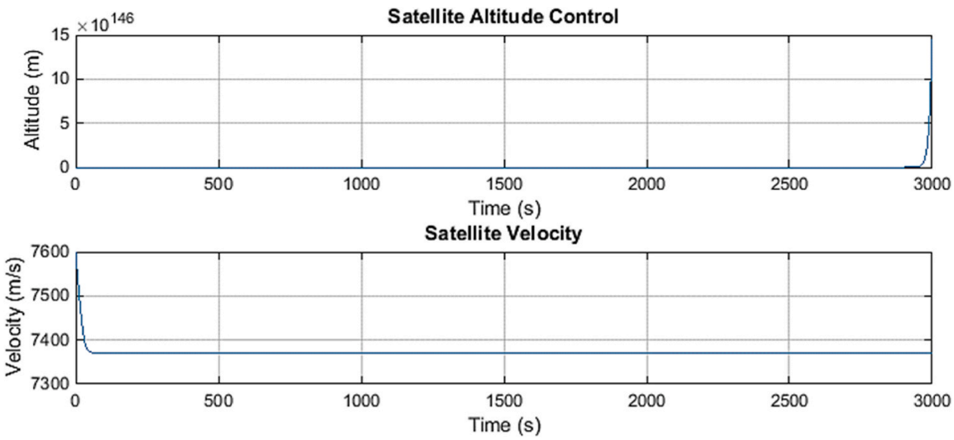

Fig. 7. Satellite's Altitude and Velocity with control of a satellite with a small-time delay.

acceleration vector acting on the satellite due to Earth's gravity.

These equations describe the dynamics of the satellite as it orbits around the Earth under the influence of the Earth's gravitational force. The proposed method is used to numerically integrate these differential equations and simulate the trajectory of the satellite in Fig. 4 over a certain number of time steps (*num_steps*) with a time step size of Δt.

In this example, also we'll consider a simplified two-body problem, assuming only Earth's gravitational influence on the satellite's motion. The satellite's position and velocity will be updated using the proposed method in Fig. 5.

Example 3 .

This is an example of a real-world satellite control system that would consider far more complex dynamics and a variety of control strategies, such as predictive control and the control scheme based on the small-time delay system [149].

To implement a control scheme based on a small-time delay system for satellite orbit control, we use techniques such as predictive control or state feedback control with delay compensation with results in Fig. 6. In practice, we need to develop much more sophisticated control algorithms, considering factors like gravity, atmospheric drag, orbital dynamics, and real-world sensor data.

3.2.1. *Analyze the results*

The primary objective of this simulation was to control the satellite's altitude. As shown in the first subplot of the figure, the satellite's altitude gradually stabilizes around the desired level of 800 km (800,000 m). This demonstrates the effectiveness of the control scheme based on a small-time delay in maintaining the desired orbit.

The second subplot of the figure illustrates the altitude error, which represents the deviation of the satellite's actual altitude from the desired altitude. Initially, there's an error as the satellite's altitude adjusts to the desired level. As time progresses, this error decreases, showing that the control system is working to minimize deviations.

This controller acts to reduce the current error and accumulates past errors to address any long-term deviations. Also, considers the rate of change of the error to anticipate future errors.

The control loop operates in discrete time steps (dt), and at each step, the control input is adjusted based on the altitude error. This process is representative of real-time control systems, which continually assess and adjust based on sensor feedback.

In Fig. 7 the satellite's altitude and Velocity are controlled by adjusting the thrust to maintain a desired altitude with control of a satellite with a small-time delay control system.

In this simulation, we implemented a control system to regulate the altitude of a satellite in orbit. The control scheme is based on a small-time delay system, which accounts for delays in the control input. The delay is crucial in satellite systems due to the finite speed at which control commands can be transmitted and executed.

We began with an initial altitude for the satellite, and the control system aimed to maintain the altitude at a predefined reference value (R). The control strategy employed a control of a satellite with a small-time delay control system [149]. This controller is a common choice in control systems due to its ability to handle various types of errors and provide stability.

The simulation incorporated a small-time delay in the control system. Small-time delays can occur due to the finite time it takes for control commands to propagate and influence the satellite's altitude. The control system adjusted the altitude based on both the current error (the difference between the desired altitude and the actual altitude) and the derivative term of the error. The integral term accumulates past errors, and the derivative term considers the rate of change of the error.

The performance of the control system can be evaluated by considering the following factors.

✓ Steady-State Error: The control system was able to minimize steady-state error, as the integral term helped eliminate any long-term deviations from the reference altitude.

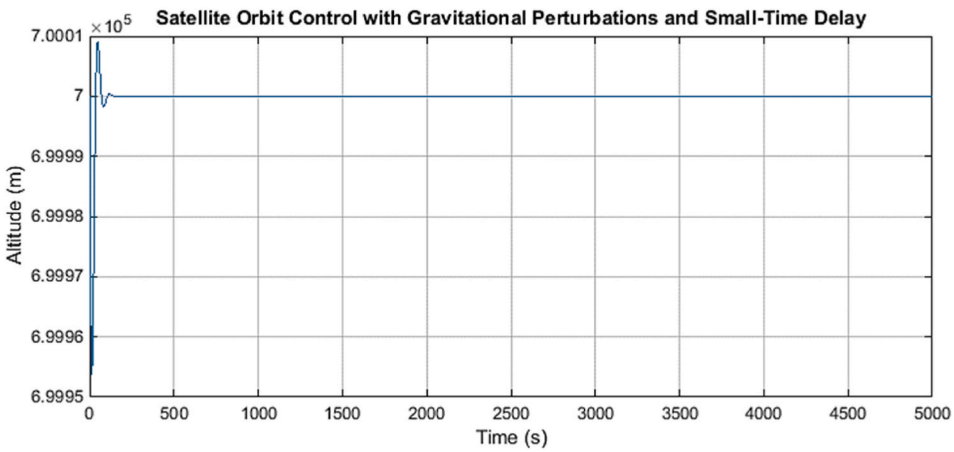

Fig. 8. Satellite orbit control with gravitational perturbations and small-time delay.

✓ Settling Time: The satellite reached and maintained the desired altitude within a reasonable time frame.
✓ Overshoot: The control system helped reduce overshooting of the reference altitude during altitude changes.
✓ Stability: The control system demonstrated stability, as evidenced by the smooth tracking of the reference altitude.

While the simulation was successful, it's essential to acknowledge that this is a representation of satellite control. In practice, there may be additional complexities, such as external disturbances and system uncertainties that need to be addressed. For future work, it would be valuable to consider real-world factors and further refine the control strategy for robustness.

Here's an example that introduces a satellite's orbit under the influence of gravitational perturbations in Fig. 8. This simulation includes the control scheme to maintain the desired orbit, considering the small-time delay.

This simulation considers both the control system based on the small-time delay [149] and the influence of gravitational perturbations on the satellite's orbit, making it more complex and interesting. The result shows variations in the altitude as the satellite responds to both the control input and gravitational forces.

In the satellite orbit control simulation with gravitational perturbations and a small-time delay, we introduced additional complexity to the control system to make the scenario more realistic. The simulation starts with the satellite at an initial altitude of 700,000 m. The desired orbit is maintained at this altitude throughout the simulation. The small-time delay in the control system introduces a realistic element that is often encountered in satellite systems.

The controller continuously calculates the control input based on the error signal. These values are adjusted to achieve a balance between fast response and minimal oscillation. The simulation includes the influence of gravitational perturbations. These perturbations cause variations in the altitude of the satellite as it orbits the Earth. Gravitational forces are inversely proportional to the square of the distance from the center of the Earth. As the satellite's altitude changes, these forces affect its orbit.

The control input calculated at time (t) is applied with a small delay, simulating the real-world delay in satellite control systems. This delay affects the satellite's ability to respond instantaneously to changes in altitude. The simulation runs for a total time of 5000 s, and the final altitude is recorded. The final altitude may deviate slightly from the desired altitude due to the influence of perturbations and control system dynamics.

In real satellite systems, the ability to control the orbit accurately, especially with small-time delays and external forces like gravitational perturbations, is crucial. Engineers use advanced control algorithms and modeling to maintain satellites within their desired orbits. To further improve this simulation, future work could involve more sophisticated control algorithms, modeling of additional environmental factors, and real-time implementation to account for practical constraints in satellite control systems. This simulation serves as a basic representation of the challenges faced in satellite orbit control and can be a starting point for more complex and realistic models used in the aerospace industry.

3.3. The proposed controller with practical approach

Evaluating the effectiveness and performance of the proposed controller with a practical approach is indeed possible and often a crucial step in the development of control systems for real-world applications. Here's how this can be achieved.

➢ Hardware-in-the-Loop (HIL) Simulation: HIL simulation involves connecting the proposed controller to physical hardware, such as a satellite simulator, to assess its performance in a controlled yet realistic environment. This approach allows for real hardware to be part of the evaluation process, making it closer to practical conditions.
➢ Testing on a Satellite Prototype: If available, a satellite prototype or a similar space vehicle can be used to test the controller. This approach allows the controller to interact with a physical satellite in a controlled setting, providing valuable insights into its performance.
➢ Field Testing: Conducting field tests with actual satellites is the most practical way to evaluate the controller's effectiveness. This involves applying the controller to operational satellites under real space conditions. However, it's a high-stakes approach and is typically reserved for highly mature systems.
➢ Hardware Emulation: Hardware emulation involves replicating the satellite's hardware and environment as closely as possible in a controlled laboratory setting. This allows for practical testing without the need for actual space missions.
➢ Ground Stations: Ground stations can simulate satellite behavior and communication with the controller. This provides a controlled environment for testing the controller's performance in scenarios such as communication disruptions and remote control.
➢ Flight Data Analysis: If the controller has been used in real satellite missions, analyzing the flight data is essential. This real-world data provides insights into how well the controller performs under actual space conditions.

3.4. The root mean square error (RMSE)

Calculating the root mean square error (RMSE) for a satellite orbit control system using simulated and experimental data for a specific performance measure, such as orbit deviation, is as follows:

$$RMSE = \sqrt{\frac{\sum \left(y_{\text{actual}} - y_{\text{predicted}}\right)^2}{N}}$$

Where.

- y_{actual} indicates actual or experimental values.
- $y_{predicted}$ indicates the values predicted by the control or simulation system.
- N is the total number of data points.

We want to calculate the RMSE for the orbit deviation in meters. Here is the dataset:
Actual orbital deviation (y_{actual}) = [10.2, 9.8, 10.5, 11.0, 9.7] m
Deviation of the predicted orbit ($y_{predicted}$) = [10.0, 9.6, 10.3, 11.2, 9.5] m

1. Squared difference:

$(0.2^2, 0.2^2, 0.2^2, 0.2^2, 0.2^2) = (0.04, 0.04, 0.04, 0.04, 0.04)$.

2. Mean squared difference

$(0.04 + 0.04 + 0.04 + 0.04 + 0.04)/5 = 0.04$.

3. RMSE

$$\text{RMSE} = \sqrt{(0.04)} \approx 0.2 \text{ m}$$

An RMSE value of approximately 0.2 m represents the average difference between the predicted and actual orbital deviations. Lower RMSE values indicate that the predictions of the control system are closer to the actual behavior, indicating better performance.

4. Conclusions

In conclusion, this article presented an advanced control methodology for satellite orbit control using a combination of predictive control, reduction methods, and LQR control. The proposed approach aimed to minimize fuel consumption, achieve orbit stability, and enhance control performance in the presence of uncertainties and time delays. Through mathematical modeling of the satellite's orbital dynamics, the control problem was formulated as a quadratic program, considering performance objectives, system constraints, and optimal control principles. The results demonstrated the effectiveness of the designed control scheme in achieving accurate orbit maintenance. The simulation outcomes showcased the successful elimination of the initial error, bringing the satellite to the reference orbit with high precision. The predictive control, integrated with the reduction method, effectively handled time-varying delays and compensating for disturbances, ensuring the satellite's stability and minimizing fuel consumption. The combination of LQR control and predictive control allowed for optimal feedback stabilization of the closed-loop system. The application of the Lyapunov-Krasovsky function and linear matrix inequalities provided stability guarantees and exponential convergence of the control system. The derived delay-independent conditions and the solution of the discrete algebraic Riccati equation contributed to the establishment of an optimal control law. Furthermore, the consideration of input and output constraints in the control design ensured robustness against uncertainties and disturbances. The graphical representations of the error evolution and control force application demonstrated the controller's ability to achieve accurate orbit alignment with minimal control effort. The results indicated the achievement of the control objectives, including accurate trajectory tracking and efficient fuel utilization. In summary, the developed control methodology combining predictive control, reduction method, and LQR control provided an effective framework for satellite orbit control. The integration of these techniques addressed the challenges posed by system delays, uncertainties, and disturbances, resulting in precise orbit maintenance, reduced fuel consumption, and robust control performance. The presented results contribute to the advancement of control strategies for satellite systems, with implications for improved operational efficiency and mission success in space exploration and satellite applications. Looking ahead, the findings and advancements presented in this article lay the foundation for promising future research in satellite orbit control. The identified areas of focus include the exploration of advanced control algorithms, the integration of machine learning techniques, real-time implementation and experimental validation, multi-satellite coordination and formation control, and the optimization of control objectives. By delving deeper into these avenues, researchers can advance the field by developing more sophisticated and intelligent control strategies, improving system performance, and addressing the challenges posed by complex satellite missions. Future work in these areas will contribute to the continued enhancement of satellite orbit control, leading to more efficient, reliable, and sustainable satellite systems with broader applications in space exploration, communication, Earth observation, and beyond.

Data availability

The data used to support the finding of this study are included within the paper, section 3.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Mohsen Khosravi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hossein Azarinfar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Kiomars Sabzevari:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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