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## Satellite Heat Transfer Control Using a Nonlinear PI Method

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Abstract


Thermal control in satellites is a critical discipline that maintains allowable temperature conditions across all subsystems. Satellite thermal regulation can be achieved through various approaches, which are broadly classified into passive and active methods. In passive control, thermal conditions are managed using passive elements such as coatings, insulation, radiators, and similar components. In contrast, active control typically employs closed-loop systems with temperature feedback. In this paper, the design of an active thermal control system for an Earth-orbiting satellite is carried out using a Nonlinear Proportional–Integral (NPI) control strategy. In this approach, the temperature of each subsystem is considered as a state variable, while heaters are modeled as actuators. Through comparative analyses, it is demonstrated that, due to actuator saturation effects, the nonlinear PI controller exhibits superior performance compared to the classical Proportional–Integral (PI) method, particularly in reducing overshoot and settling time.

**Keywords:** Thermal control, Nonlinear proportional–integral control, Earth-orbiting satellite.

## 1 | Introduction

Over the last four decades, many spacecraft have been designed for scientific, military, and business applications. Based on their characteristics, these spacecraft may be classified into three major categories: three-axis stabilized, spin-stabilized, and platform-based. Among all systems on the spacecraft, the thermal control system is considered essential, as it ensures that all mechanical and electrical components maintain proper temperatures throughout the mission. Several comprehensive textbooks have laid out the basic concepts of thermal control in spacecraft [1], while modern studies focus on new problems, including miniaturization and high-power components [2].

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The satellite in orbit will be exposed to thermal loads from external sources, such as the Sun's radiation, Earth's albedo, and Earth's infrared radiation, as well as from internal sources, such as onboard equipment operation. These thermal loads cause a rise in temperatures, and low temperatures will be experienced during the Earth's eclipse. Precise models are needed for thermal control of satellites, and robust statistical techniques can be employed for this process [3]. Passive techniques, such as coatings, insulations, and radiators, are usually implemented, but active techniques are needed where tight tolerance and fast response are required.

Review papers have comprehensively reviewed progress in the design and development of thermal control techniques for satellites, especially the transition from traditional passive control techniques to advanced active control approaches [4]. More recently, nonlinear control techniques have attracted increasing interest due to the nonlinear nature of satellite thermal dynamics, driven by radiation heat transfer and actuator saturation. Traditional linear control approaches, such as Proportional–Integral (PI) control, often fail to achieve optimal performance under these conditions due to excessive overshoot and slow response time. The nonlinear nature of satellite thermal dynamics has also been demonstrated through the analysis of lumped-parameter models [5]. On the other hand, a new small-perturbation analytical model has recently been developed to analyze the frequency response of spacecraft thermal control [6].

To overcome these limitations, Nonlinear Proportional–Integral (NPI) controllers have been proposed and theoretically analyzed. Zhao et al. [4] provided a rigorous design framework for robust nonlinear PID control that goes beyond linear assumptions. The effectiveness of nonlinear temperature regulation has been demonstrated in various applications; for example, Song et al. applied adaptive bandwidth tuning to a nonlinear thermal system and compared its performance against standard PID [7]. In the specific context of CubeSats, Al-Hemery et al. [8] developed a model-predictive control with anti-windup PID for temperature tracking, demonstrating the need for advanced control methods. Further improvements in nonlinear PI controllers have been achieved through output transformations to enhance performance for nonlinear dynamical processes [9].

One of the most basic research studies on robust PI passivity-based control for nonlinear systems, applied to temperature control, was conducted by Aranovskiy et al. [10]. Recent research has successfully demonstrated the application of nonlinear PID and sliding-mode controllers in the design of a micro pump for small satellites [11]. Moreover, a straightforward intelligent nonlinear PI controller with ambient temperature control has achieved better results than classic PI control in nonlinear systems [12]. Finally, a general approach to nonlinear control has been developed from the standpoint of adaptive control of unknown strict-feedback nonlinear systems with nonsmooth actuator nonlinearity [13], [14]. Actuator saturation poses a serious challenge for satellite thermal control, as the heating capacity of heaters is physically limited. Various researchers have addressed the problem of designing controllers for thermal systems subject to actuator saturation constraints [15].

In addition, the application of nonlinear model identification adaptive control has been proven superior to conventional PID control in heater temperature control applications [16]. There have been recent developments in high-accuracy temperature control systems under low-frequency perturbations [17], and an approach to simulation-based temperature control in spacecraft thermal test experiments using Simulink has been illustrated [18]. Moreover, spatiotemporal event-triggered observer-based fuzzy resilient control has been applied to the temperature profile of fast-moving spacecraft, achieving excellent performance despite the spacecraft's dynamic nature [19].

In this study, we propose a novel design for an active thermal control system for an earth-orbiting satellite using a nonlinear PI controller. Each subsystem temperature is assumed to be a state variable, while the heaters serve as actuators, which are subject to saturation. By comparing the results of various simulations, we demonstrate that the nonlinear PI controller effectively reduces overshoot and settling time compared to classical PI control methods.

## 2 | Satellite Thermal Modeling

The goal of satellite thermal modeling is to create a simulated environment in which the satellite's thermal status can be examined and thermal control strategies tested. Through thermal-state analysis, we estimate parameters such as temperature levels, temperature gradients, temperature change rates, and sensitivity to thermal impacts. In other words, we need to develop a dynamic model that allows us to estimate those characteristics under specific operating conditions. Also, it has to give some insight into their changes over time.

In addition, the thermal control system should be able to use the satellite model and perform actions that modify the output values and, consequently, affect its performance. Therefore, if we treat our thermal control system as a closed-loop configuration (see *Fig. 1*), our thermal modeling should be viewed as a single block that predicts the temperature histories of each subsystem in the satellite. At the same time, we have to consider inputs, which are control actions generated by the controller based on comparisons between the real and model output parameters and their references.

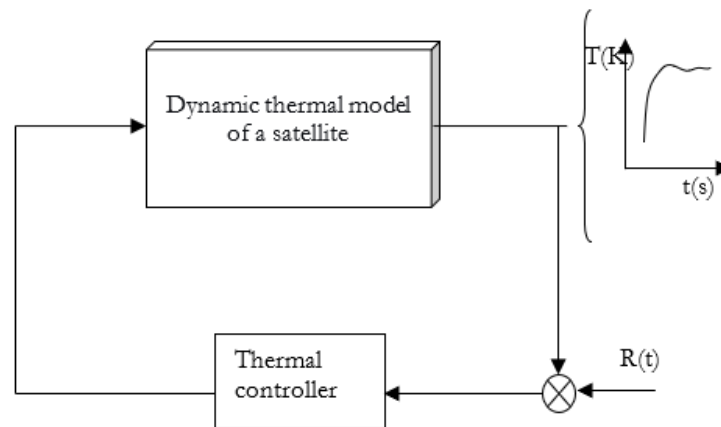


Fig. 1. Closed-loop control system model.

## 3 | Approach for Modeling Satellites

A satellite is made up of several components, including an antenna, batteries, etc. Feedback obtained by the thermal controller while in operation involves temperature information about these components. Hence, when developing the simulation model, the time series should consist of the temperatures of the different satellite components. Thermal modeling of satellites may be carried out using any of the following three approaches:

- I. Classical approach
- II. Lumped parameter approach
- III. Methods of numerical integration

In this research work, the approach used in thermal modeling is a combination of the lumped parameter approach and numerical integration methods.

### 3.1 | Classical Approach

The dynamic thermal behavior of a satellite can be formulated using the governing heat-transfer equations of the system. In this regard, the heat transfer equations may be derived by considering the definition of the system or the control volumes. Then, the application of the first law of thermodynamics to the systems or the control masses may be done. The first law of thermodynamics indicates that the net rate of energy transfer from and to the system should be equal to the rate of change of internal energy of the system [20].

$$\dot{U} = (\dot{Q}_{in} - \dot{Q}_{out}). \quad (1)$$

In Eq. (1), the rate of change of internal energy may be represented as [21]:

$$\dot{U} = (Q_{in} - Q_{out}), \quad (2)$$

where  $M_c$  denotes the thermal capacitance of the considered mass. Since  $T$  has been incorporated into the equation, the system dynamics have been captured, as  $\dot{T}$  is the rate of change of system temperature, which has been the goal of this discussion. By applying the first law of thermodynamics to each element, the satellite's dynamic thermal behavior can be quantified.

### 3.2 | Lumped Parameter Approach

In this method, the entire system is broken down into a discrete number of components with constant temperatures and consistent thermophysical properties. The interactions among these components, as well as their interactions with the surrounding environment and actuators, determine the dynamics of the entire system.

In such a scenario, all parts of the satellite, such as the batteries, solar panels, and other subsystems, are treated as elements, or simply nodes. A node here denotes a finite spatial volume that accounts for the thermal dynamics of that particular volume. To ensure an appropriate model, nodes must be placed so that each node represents a volume with nearly uniform thermal dynamics.

There are many factors to consider when assigning nodes. For instance, large surfaces, such as walls, require multiple nodes to achieve accurate results. Likewise, regions with a large temperature gradient require smaller nodes, since there is greater temperature variation over shorter intervals. In this study, 29 elements and 722 nodes are used.

### 3.3 | Numerical Integration Technique

To create a virtual environment for dynamically analyzing thermal models, MATLAB has been employed. In this technique, the output values of Thermal Desktop are first acquired and then applied to model the satellite's thermal behavior. Heat fluxes and the corresponding view factors are computed using Thermal Desktop.

Programming in the Simulink framework involves designing a program as a block diagram. Such an approach leads to a significant reduction in computing time, which is particularly important if timely simulation is the primary goal of the operation.

Once the system's differential equations have been derived, their solution yields the evolution of temperature. Given the problem formulation, the satellite's dynamics are described by a nonlinear set of differential equations that cannot be solved analytically.

$$\text{diag}(M) \times \dot{T} = - \left\{ \begin{array}{l} \sigma [R_s \times T^4 - T_s^4 R_s] + (O^{n \times n} - R) \times \\ T^4 + \{ \text{diag}(\text{sum}(C)) - C \} \times T \end{array} \right\} + Q_s. \quad (3)$$

These types of equations can be solved using the Simulink environment from MATLAB. There are mainly two reasons why such a program has been chosen. Firstly, Simulink provides highly efficient computation, which makes it very useful for real-time simulations. Secondly, it is known to provide high numerical precision in time-domain computations.

There are several numerical approaches for solving time-domain differential equations in the Simulink environment, depending on the problem under investigation. In this research, the ode45 approach has been selected to solve the equations; it is based on fourth-order Runge-Kutta methods. Fourth-order Runge-Kutta methods are among the most popular methods for numerically solving ordinary differential equations,

offering an optimal trade-off between numerical precision and computational complexity. In the formulation of such a type of algorithm, any set of first-order differential equations can be described in the form of:

$$\dot{\bar{y}} = \bar{f}(\bar{y}, t). \quad (4)$$

The relation above shows the most general representation of a first-order ordinary differential equation. As shown in the above relation,  $\bar{y}$  is a  $1 \times n$  vector containing all the dependent variables in the system. For example, in the satellite thermal dynamic model, this is the temperature vector for the various elements of the satellite. It is the time that is present in all the time-dependent equations. Also,  $\bar{f}$  is a  $1 \times n$  valued function for the right-hand sides of the equations. Therefore, in light of the previous derivation, the equation governing the differential equations of the system can take the following form.

$$\dot{T} = \text{diag}\left(\frac{1}{M}\right) \times [-\{\sigma[R_s \times T^4 - T_s^4 R_s] + (O^{n \times n} - R) \times T^4 + \{\text{diag}(\text{sum}(C)) - C\} \times T\} + Q_s], \quad (5)$$

where  $\text{diag}(1/M)$  is the diagonal matrix with the elements being the inverse thermal capacities of the system, as can be observed in the above relation, the right-hand side of the equation is equal to the  $\bar{f}$  in the general representation. Since integration must be solved numerically, the following time increment must be considered.

$$h = \frac{T^{i+1} - T^i}{\Delta t}. \quad (6)$$

$h$  will be automatically defined and will change as the differential equations vary.

### 3.4 | Nonlinear PI Control

The controller used for thermal regulation of the satellite in this study is a Nonlinear PI controller. The classic PI controller provides better steady-state error reduction and ramp input tracking performance than the proportional P controller. However, due to the nature of the integral, it may exhibit overshoot, especially when disturbances are present.

Due to actuator saturation, the integral wind-up phenomenon affects the classic PI controller when the input magnitude changes. Performance deterioration occurs due to high overshoot and long settling time. This phenomenon occurs because the control action may take on large values under different environmental conditions. This issue causes the actuator to saturate, as it no longer responds to the process output.

However, with an integral controller, the error will continue to accumulate, leading to an integrator that becomes too large. Thus, once the system has returned to the desired operating region, it will take time for the controller to regain control, as the integral sum must either reduce or reverse its sign. Any integral controller can be affected negatively by saturation, leading to excessive transient response.

Khayyat [22] developed an anti-windup scheme for integral control to overcome some problems associated with integral wind-up. The method is described mathematically as follows and illustrated in *Fig. 2*. In this study, such controllers are implemented.

$$I(t) = [I(t - \Delta t) + k_t e_\theta(t) \Delta t - k_t e_s(t) \Delta t]. \quad (7)$$

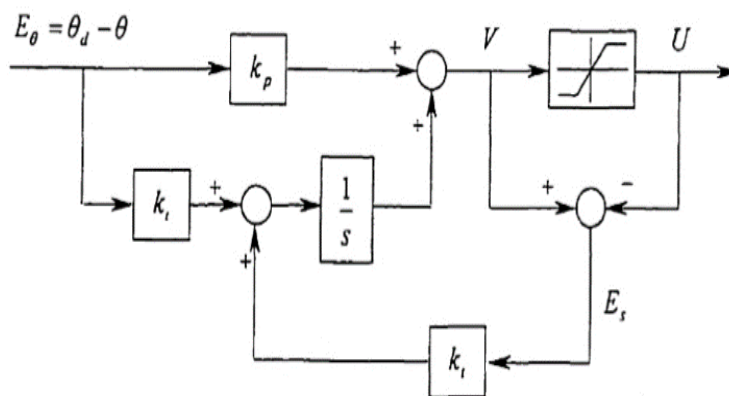


Fig. 2. Closed-loop model of the control circuit used [10].

There is another feedback link on the left side, designed to detect the actuator's output signal and calculate another error signal,  $e_s$ . Error signal  $e_s$  corresponds to the difference between the controller output signal and the output signal of the actuator. The error signal  $e_s$  is fed back to the integrator's input. Under the condition that there is no saturation in the control system, the error signal  $e_s$  equals zero; therefore, under regular conditions, the added feedback link has no impact on the control system. On the contrary, when the actuator saturates, the added feedback link helps drive the error signal to zero.

### 4 | Result and Discussion

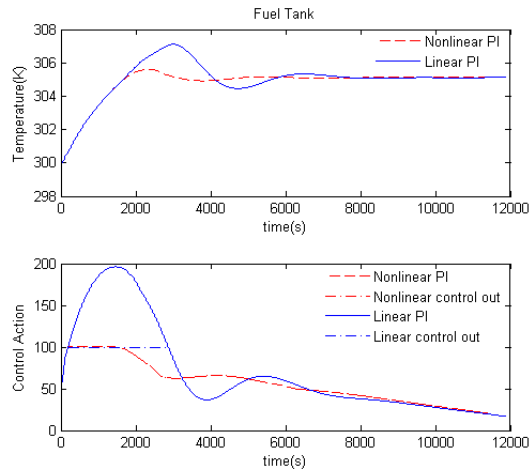
In the current investigation, two control methodologies are considered for application in the thermal management system of a satellite orbiting Earth: a classical PI controller and a nonlinear PI controller. The temperature behavior and actuator signals for three systems (fuel tank, helium fuel tank, and another system) are illustrated in *Figs. 3-5*.

The graphs above show that a large temperature overshoot occurs when using the classical PI control scheme (represented by the dashed line) to control both fuel tanks. It is evident that the temperature overshoots the set point and undergoes multiple oscillations before reaching steady state.

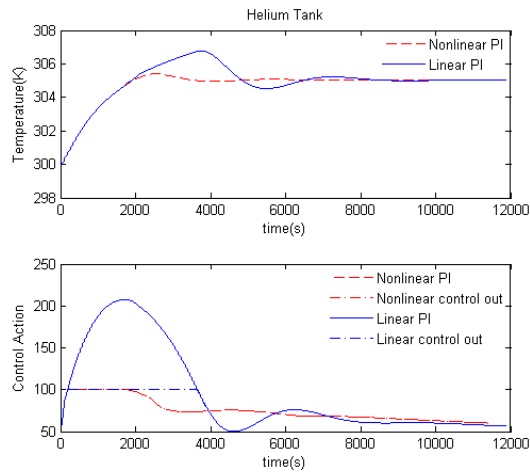
However, with the nonlinear PI controller, the temperature settles to the set point within a few seconds (solid line). Actuator signals (heater power) are shown in the lower subplots for each figure. In the classical PI control scheme, the actuator saturates due to integral wind-up, and the control action remains saturated for a long time, resulting in poor transient behavior.

In contrast, with the nonlinear PI controller, an anti-windup scheme is included, leading to quick release from the actuator saturation and dampening oscillations in the control action. Finally, the improved performance of the nonlinear PI control scheme is demonstrated using another subsystem (see *Fig. 5*).

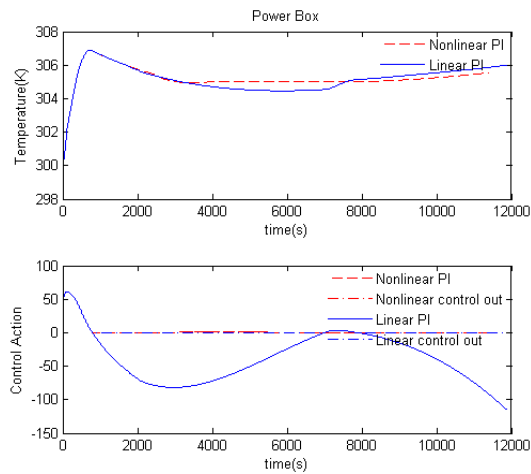
There is almost no overshoot, and the temperature reaches its desired steady state without any issues. The settling time is reduced by 40–50% compared to the classic PI controller. Overall, the simulation results prove the efficiency of the presented method in avoiding problems caused by actuator saturation.



**Fig. 3. Temperature and control actuator response for the fuel tank.**



**Fig. 4. Temperature and control actuator response for the helium fuel tank.**



**Fig. 5. Temperature and control actuator response for the third subsystem.**

## 5 | Conclusion

In this study, an active thermal control method for an Earth-orbiting satellite has been developed based on a nonlinear PI control approach. Temperatures in each satellite subsystem were chosen as state variables, whereas heaters were treated as saturating actuators. A comparative analysis of the proposed nonlinear PI control design and the classical PI control design was performed via simulation. According to the simulation results, integral wind-up leads to significant overshoot and long settling times in the classical PI control system due to actuator saturation. A nonlinear PI control system with a built-in anti-windup feedback scheme helps overcome problems associated with overshoot and increases the transient response speed.

As a result, a shorter time is required to reach steady-state mode for each of the studied satellite subsystems. Thus, it can be concluded that neglecting actuator dynamics is inappropriate when designing an active thermal control system. The nonlinear PI control technique offers a lower computational cost than other advanced control algorithms. Thus, it can be used for real-time control of thermal satellite systems. Future research may focus on developing methods for applying nonlinear PI control systems to MIMO thermal control tasks with disturbance rejection.

## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability

All data are included in the text.

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