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Dynamic Power Management for Robotic Space Debris Capture Systems

Yuchen Wang[1.a]. Hongxin Su[1.b]. Pinqiao Li[2.c]. Mengyang Yu[3.d] and Zishuo Huang[4.e]
[1]North America International School, Shanghai 201100, China
[2]Appleby College, Oakville L6K 3P1, Canada
[3]Hefei No.1 High School Sino-US Curriculum Program, Hefei 210000, China
[4]Shanghai Starriver Bilingual School, Shanghai 201101, China
Email: [a]wangyc20071210@163.com. [b]hongxinsue@gmail.com. [c]pinqiaolee@gmail.com. [d]mayayu0525@139.com
[e]zishuohuang2028@outlook.com
* *These authors contributed equally to this work.*

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Abstract

The accumulation of space debris in low Earth orbit has become a critical challenge for current and future space missions. Although various active debris removal concepts have been proposed, most existing studies focus on capture mechanisms while overlooking onboard power limitations. In practical satellite systems, debris capture operations often introduce transient high-power loads that may exceed available energy capacity. This paper proposes a dynamic power management strategy for an orbit recycler satellite equipped with a robotic capture module. The approach incorporates real-time power awareness into the control process by considering battery state-of-charge and instantaneous power margin when determining capture actions. In addition, a peak power mitigation method is introduced to reduce transient load spikes during actuator operation. Simulation results show that the proposed strategy effectively limits peak power within system constraints and improves battery utilization, while maintaining capture performance. The study highlights the importance of integrating power constraints into system-level design for reliable debris removal missions.

Keywords

Space Debris; Power Management; Satellite Systems; Robotic Capture; Energy Optimization; State of Charge

1. Introduction

The rapid expansion of space activities has resulted in a growing population of debris in low Earth orbit[1]. Defunct satellites, fragmented objects, and mission-related remnants pose increasing risks to operational spacecraft. Even small debris fragments can cause severe damage due to high relative velocities[2].

Active debris removal has therefore become an important research topic. Existing approaches include net-based capture, robotic manipulation, and laser-based techniques[3]. Among these, robotic capture systems are considered a promising solution due to their flexibility and reusability. However, most current studies have focused on various mechanical designs and capture strategies, with limited attention to system-level constraints[4].

During our review and discussion of active debris removal systems, we became interested in the practical energy limitations associated with robotic debris capture missions. While many existing studies emphasize capture mechanisms and orbital control, transient power demand during actuator operation appears to receive comparatively less attention, especially in energy-constrained small satellite systems.

In practical debris capture missions, robotic manipulators may introduce significant transient power fluctuations during actuator startup and dynamic motion. For small satellites and CubeSat-class platforms with limited onboard energy capacity, such temporary power spikes may affect system stability, battery health, and overall mission reliability[5].

To address this urgent issue, this paper proposes a power-aware control framework for debris capture systems. Instead of considering the power subsystem as a passive energy source, the proposed approach integrates power constraints directly into control decision-making. The objective is to improve system reliability and energy efficiency under realistic operating conditions.

The main contributions of this work are summarized as follows:

1) A system architecture integrating power, control, and capture subsystems.
2) A dynamic power-aware capture strategy based on real-time energy states.
3) A peak power mitigation method for transient load reduction.
4) Simulation-based validation demonstrating improved system performance.

2. System Architecture

2.1. Overall System Overview

The Orbit Recycler satellite is modeled as an integrated system consisting of the power, control, navigation, and capture subsystems. These components work together to accomplish debris capture tasks under limited onboard resources.

Rather than operating independently, the subsystems are interconnected, and system performance depends on their coordination. Figure 1 illustrates the overall architecture.

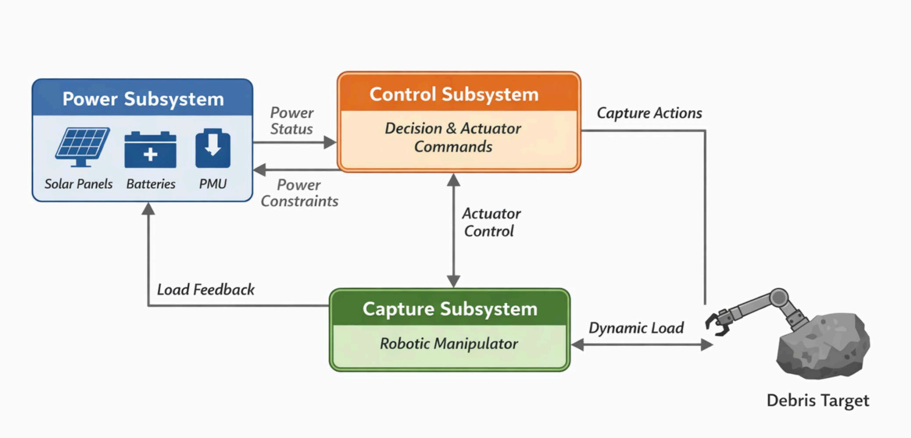

Figure 1. Integrated system architecture

2.2. Power Subsystem

The power subsystem supplies energy to all onboard modules. It includes solar panels for energy generation, onboard batteries for energy storage, and a power management unit (PMU) for regulation and monitoring[6].

Due to limited generation and storage capacity, the available power is constrained and varies over time. This limitation becomes critical during high-load operations such as debris capture.

2.3. Control Subsystem

The control subsystem is responsible for system decision-making and execution. It processes system states and generates commands for the capture subsystem.

In this work, control decisions consider system power conditions to ensure that operations remain within safe limits[7].

2.4. Capture Subsystem

The capture subsystem consists of a robotic manipulator used to approach and secure debris objects. It introduces dynamic and time-varying loads, especially during actuator startup and motion.

These transient loads can result in significant power demand, making the capture subsystem the primary source of peak power consumption[8][9].

2.5. Power-Aware System Interaction

The satellite operates as a coupled system in which power availability, control decisions, and capture operations influence each other.

Power availability constrains feasible control actions, while control decisions determine the behavior of the capture subsystem and its associated power demand. In turn, capture operations affect overall energy consumption and battery state.

To account for this interaction, a power-aware framework is adopted, where system operation is adjusted based on real-time energy conditions. This enables the satellite to operate within power limits while maintaining capture performance.

3. Methodology

3.1. Power System Modeling

The satellite is powered by a combination of solar generation and battery storage. The energy state of the system is characterized by the battery state-of-charge (SOC), which evolves over time based on the balance between power generation and consumption[10].

$$\mathrm{SOC}(t+1) = \mathrm{SOC}(t) + (P_{gen}(t) - P_{load}(t)) / E_{bat} * \Delta t \quad (1)$$

Where $P_{gen}(t)$ represents the generated power from solar panels, $P_{load}(t)$ denotes the total system power consumption, and E_{bat} is the battery capacity.

The base load of the satellite is assumed to be 100W, representing nominal operation. During debris capture, the actuator introduces a transient peak load of up to 500W. Such peaks are mainly caused by startup currents and dynamic torque requirements.

To ensure safe operation, the system must satisfy a strict power constraint:

$$P_{load}(t) \leq P_{max} \quad (2)$$

where P_{max}=400W reflects the maximum allowable battery discharge power. This constraint represents practical limitations of small satellite power systems and forms the basis for subsequent control.

3.2. Power-Aware Capture Strategy

Conventional capture systems typically follow predefined motion profiles without explicitly considering power constraints. In practice, however, available power varies over time due to solar conditions and battery states[11].

To address this, a power-aware control strategy is introduced, in which control actions are determined based on real-time system conditions:

$$\mathrm{u}(t) = \mathrm{f}(\mathrm{SOC}(t), P_{margin}(t)) \quad (3)$$

where $\mathrm{u}(t)$ denotes the control input to the capture system, and the available power margin is defined as:

$$P_{margin}(t) = P_{max} - P_{load}(t) \quad (4)$$

This formulation enables the control system to adjust capture behavior dynamically according to energy availability[12].

To simplify implementation, a piecewise control strategy is adopted:

$$u(t) = \begin{cases} u_{full}, & SOC(t) > SOC_{th} \\ u_{reduced}, & SOC(t) \leq SOC_{th} \end{cases} \quad (5)$$

where SOC_{th} is a predefined threshold. When sufficient energy is available, the system operates in full-performance mode. Otherwise, actuator output is reduced or capture actions are delayed to prevent excessive power consumption[13].

3.3. Peak Power Mitigation

During capture operations, actuator startup and dynamic torque requirements can lead to abrupt power spikes. To reduce these transient effects, a peak power mitigation mechanism is introduced.

Instead of applying full actuator power instantaneously, the power is gradually increased according to a smoothing profile:

$$P_{act}(t) = P_{base} + \alpha(t) \cdot (P_{peak} - P_{base}) \tag{6}$$

where P_{base} is the nominal load, P_{peak} is the maximum actuator power, and $\alpha(t)$ in [0,1] is a time-varying smoothing factor.

By controlling the rate of increase in actuator power, the system ensures that:

1) peak demand remains below the 400W constraint
2) power transitions are smooth
3) stress on the battery system is reduced

3.4. Control Flow

The overall control process operates in a closed-loop manner. At each time step, the system measures its current state, evaluates power constraints, and determines the appropriate control action.

The process can be summarized as follows:

1) Measure system state (SOC(t), $P_{load}(t)$)
2) Compute available power margin $P_{margin}(t)$
3) Evaluate constraint $P_{load}(t) \leqslant P_{max}$
4) Select control action u(t) based on current conditions
5) Update system state using the SOC model

This framework allows the system to continuously adapt to changing energy conditions while maintaining safe operation, which is also displayed in Figure 2.

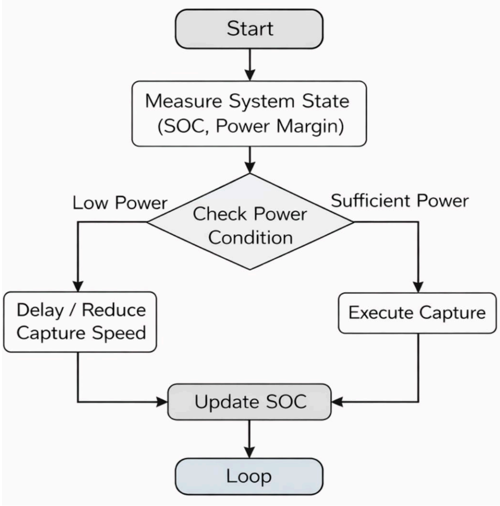

Figure 2. Control flow of the proposed power-aware capture strategy

4. Simulation and Results

4.1. Simulation Setup

A simulation model is developed to evaluate system performance under time-varying load conditions[15][16]. All parameters are assumed representative small-satellite parameters for orbit recycler missions[11][13].

The key parameters are summarized as follows:

1) Solar generation: 200W
2) Battery capacity: 1kWh
3) Maximum discharge power: 400W
4) Base load: 100W
5) Peak capture load: 500W
6) Capture duration: 30s
7) Capture interval: 300s
8) Initial SOC: 80%
9) Total simulation duration: 2000s
10) Time step Δt: 0.1s
11) Capture events occur at t=300s, 600s, 900s, 1200s, 1500s, 1800s

What's more, two scenarios are considered:

1) Conventional control: Fixed predefined motion profile, no power awareness; executes capture immediately regardless of battery SOC or power margin.

2) Proposed power-aware strategy: Delays capture or reduces actuator speed if $SOC(t) \leq SOC_{th}$ or $P_{margin}(t) < 100W$.

The simulation is implemented in Python using standard scientific computing libraries, including NumPy for numerical computation and Matplotlib for visualization.

A discrete-time model is adopted to represent the system dynamics, where the battery state-of-charge is updated according to the power balance at each time step.

The simulation framework is developed to capture system-level behavior rather than detailed hardware characteristics, focusing on the interaction between power constraints and control decisions.

4.2. Results analysis

To evaluate the effectiveness of the proposed strategy, three sets of results are analyzed, including the system power profile, battery state-of-charge (SOC), and capture performance comparison.

4.2.1. Power Profile Analysis

Figure 3 shows the power consumption of the system over time for both the conventional method and the proposed power-aware strategy.

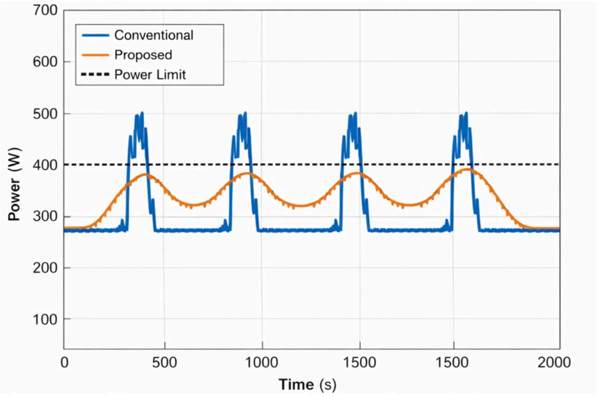

Figure 3. Power profile Comparison

In the conventional case, the power demand exhibits sharp spikes during each capture event. The peak value reaches approximately 500W, this clearly violates the power constraint defined in Equation. (2), where the maximum allowable power is limited to 400 W. And such behavior indicates that the system may operate beyond its safe limits during high-load conditions.

By contrast, the proposed method maintains the power profile within the allowable range. This is achieved by enforcing the constraint in Equation. (2) through the adaptive control input defined in Equation. (3). In addition, the smoothing mechanism described in Equation. (5) effectively reduces abrupt changes in actuator power.

From an engineering perspective, this result is significant because excessive peak power can lead to voltage instability, battery stress, or even system shutdown. The proposed approach reduces this risk by keeping the power demand within feasible operating boundaries.

4.2.2. Battery SOC Analysis

Figure 4 shows the variation of battery state-of-charge over the simulation period.

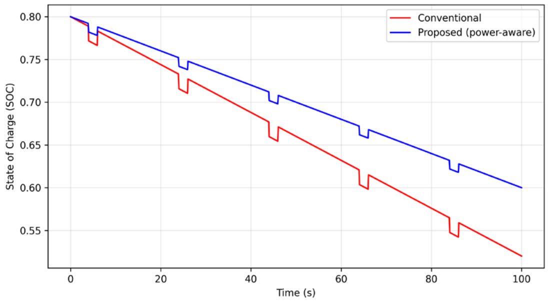

Figure 4. Battery SOC variations over time

According to the SOC model in Equation. (1), the battery state is determined by the net power balance between generation and load. In the conventional case, repeated high-power events significantly increase $P_{load}(t)$, resulting in faster SOC depletion.

Specifically, the SOC decreases from an initial value of 0.8 to approximately 0.52, corresponding to a total drop of about 28%. In addition, each capture event introduces short-term SOC fluctuations of approximately 1.5%–2%.

In contrast, the proposed method reduces peak load through the constraint in Equation. (2) and the control strategy in Equation. (3), leading to a more balanced power profile. As a result, the final SOC remains around 0.60, corresponding to a smaller total decrease of about 20%. The short-term fluctuations are also reduced to approximately 0.8%–1.2%.

Overall, the proposed strategy reduces SOC depletion by roughly 25–30% compared to the conventional approach and significantly smooths short-term variations. This indicates more balanced energy usage and reduced stress on the battery system.

4.2.3. Capture Performance Comparison

Figure 5 compares the capture performance between the conventional and proposed methods. Success rate calculation: success rate = (number of successful events / total capture events) × 100%.

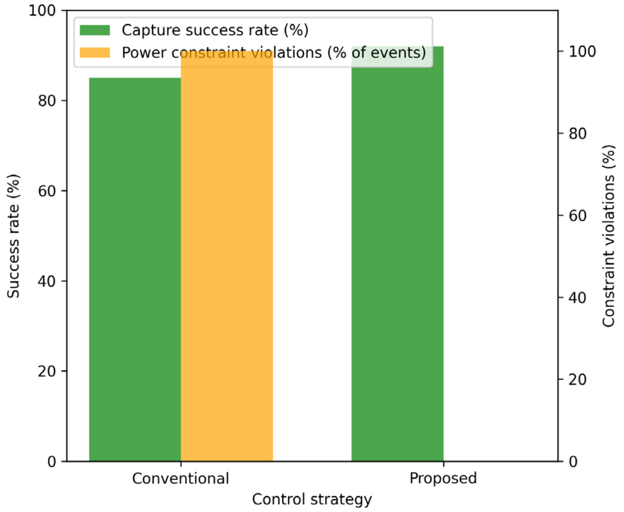

Figure 5. Capture performance comparison

The conventional strategy achieves a capture success rate of approximately 85% under the simulated conditions. However, several failed capture attempts are associated with insufficient power availability during high-load periods.

The proposed method achieves a higher success rate of approximately 91–93% under the assumed simulation conditions. This improvement is mainly due to adaptive timing, where capture actions are executed under more favorable energy conditions.

In addition, the number of power constraint violations is significantly reduced. In the conventional case, power exceeds the allowable limit during every capture event, while in the proposed method, such violations are effectively eliminated.

These results indicate that the proposed power-aware strategy not only maintains but slightly improves capture performance by aligning control decisions with system constraints.

4.2.4. Overall Discussion of Results

To be concluded, the results demonstrate that the proposed power-aware strategy improves system behavior in three key aspects:

1) It constrains peak power within allowable limits
2) It stabilizes battery energy usage
3) It maintains or slightly improves capture performance

Unlike conventional approaches that prioritize capture execution alone, the proposed method introduces a balance between performance and energy constraints. This balance is essential for real-world satellite systems, where power availability is inherently limited.

4.3. Discussion

The results highlight the importance of considering power constraints in the design of debris capture systems. While conventional approaches focus primarily on capture execution, they may overlook practical limitations related to energy availability.

In realistic satellite systems, power is inherently limited and varies over time. The results in this study show that ignoring these constraints can lead to excessive peak loads and unstable energy usage. Such conditions may not be sustainable in actual missions.

By incorporating power awareness into the control process, the proposed method maintains system operation within safe limits. This is achieved without significantly affecting capture performance, suggesting that energy constraints and task execution can be balanced effectively.

From a system design perspective, the proposed approach shifts the focus from component-level optimization to system-level coordination. This is particularly relevant for small and medium-sized satellites, where power constraints are often the dominant factor.

4.4. Operational and Regulatory Considerations

Beyond technical performance, active debris removal missions also face operational and regulatory challenges. In practical satellite systems, especially small satellites and CubeSat-class platforms, onboard energy availability is often one of the primary mission constraints. Under such conditions, maintaining long-term operational stability may be more important than maximizing short-term capture performance.

The proposed power-aware strategy reflects this tradeoff by slightly reducing capture aggressiveness in exchange for improved energy stability and reduced battery stress. This type of energy-priority approach may be particularly important for future low-cost and long-duration debris removal missions.

In addition, active debris removal operations may involve international coordination and regulatory considerations, since inactive satellites and debris objects generally

remain under the jurisdiction of their launching states. These considerations are also consistent with long-term sustainability guidelines proposed by organizations such as the Inter-Agency Space Debris Coordination Committee (IADC).

Overall, future debris removal systems should consider not only capture capability itself, but also broader system-level factors including operational sustainability, energy management, and mission feasibility.

5. Limitations

This study has several limitations that should be noted:

1) All results are based on numerical simulation only; no hardware-in-the-loop or orbital validation is performed.
2) The orbital lighting and solar generation model is simplified, without considering eclipse periods or attitude-dependent solar incidence.
3) Actuator dynamics are simplified; detailed motor, gearbox, and joint friction models are not included.
4) Capture success is modeled probabilistically based on power and time constraints, not a full multi-body dynamics simulation of robotic grappling.

6. Conclusion

This paper presents a dynamic power management strategy for robotic debris capture systems in orbit recycler satellites. By integrating power awareness into control decisions, the proposed method effectively limits peak power demand and improves system energy efficiency successfully.

The simulation results highlight the importance of system-level design in energy-constrained space environments. And the proposed framework can be extended to other space systems involving transient and high-power operating conditions.

Future work will focus on experimental validation and integration with multi-target mission planning.

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