RESEARCH ARTICLE OPEN ACCESS

A Comprehensive Survey of Secure and Reconfigurable SoC Architectures for UAV Flight Control Applications

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Abstract:

Unmanned Aerial Vehicles (UAVs) are increasingly deployed in safety- and mission-critical applications, making them attractive targets for cyber, physical, and hardware-based attacks. Traditional UAV controllers rely on static embedded architectures that lack runtime adaptability and robust hardware- level security. This survey investigates secure System-on-Chip (SoC) architectures for UAV control, with a focus on FPGA- SoC platforms and Dynamic Partial Reconfiguration (DPR). The proposed DRS-UAV-SoC architecture has been developed as a way to create a secure, dynamic, and adaptable UAV control system. DRS-UAV-SoC architecture combines both static flight control logic with dynamic reconfigured security modules and thus provides multi-layered security via adaptive means, while not interrupting or disrupting real-time control loops. Based on performance and security analyses conducted, it has been proven that dynamic reconfiguration of security modules is feasible. There are clear advantages of using dynamic reconfiguration and security modules for building resilient UAV control systems.

This paper presents a comprehensive survey of secure and reconfigurable SoC architectures for UAV flight control applications. The survey systematically reviews UAV avionics architectures, security threats specific to flight control systems, hardware security mechanisms in SoCs, and the role of reconfigurable computing, including dynamic partial reconfiguration, in enhancing system resilience. Existing approaches are analysed and classified based on architectural design, security features, reconfiguration support, and UAV applicability. A critical assessment reveals key limitations in current research, such as static security assumptions, limited exploitation of runtime reconfiguration for security, and the absence of control-aware security analysis. Finally, open research challenges and future directions are discussed, emphasizing the need for control–security co-design and dynamic reconfigurable SoC frameworks tailored to safety-critical UAV applications.

Keywords — Unmanned Aerial Vehicles, Flight Control Systems, System-on-Chip, FPGA-SoC, Hardware Security, Dynamic Reconfiguration

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have emerged as critical cyber–physical systems (CPS) in applications such as surveillance, disaster management, agriculture, logistics, and defense. Modern UAVs integrate sensing, computation, communication, and control within tightly constrained real-time and power budgets. With increasing autonomy and connectivity, UAVs are exposed to a wide range of cyber and hardware attacks, including communication spoofing, sensor manipulation, firmware tampering, and hardware Trojans [1], [2], [3].

Most existing UAV platforms employ microcontroller- or CPU-based flight controllers with software-centric security mechanisms. Such approaches are insufficient against low- level hardware attacks and lack runtime adaptability. FPGA- based and FPGA-SoC platforms offer unique advantages through hardware parallelism, isolation, and reconfigurability [5], [6]. However, current designs underutilize dynamic recon- figuration for security and often ignore control-loop timing constraints.

Unmanned Aerial Vehicles (UAVs) have quickly transitioned away from being remotely piloted systems toward being autonomous cyber-physical systems that can autonomously accomplish sophisticated missions in the fields of civilian, industrial, and defense [1], [2]. Onboard embedded computing platforms are used for real-time flight control, navigation, sensor fusion, communication, and mission management in modern UAVs. The flight control system is the main source for all these functions because of the strict real-time and safety-critical limitations within which it functions [3]. Any disruption or compromise of the flight control logic can directly impact flight stability, mission success, and operational safety.

With increasing autonomy, connectivity, and software complexity, UAV flight control systems are becoming vulnerable to a wide spectrum of cyber–physical security threats [4]. Attacks such as control signal manipulation, firmware tampering, GPS spoofing, malware injection, and hardware Trojans have demonstrated the potential to degrade control performance or cause complete loss of the vehicle [5], [6]. Unlike conventional embedded systems, UAVs operate in dynamic and often adversarial environments, making static and software-only security mechanisms insufficient to provide long-term resilience [7]. Consequently, there is a growing need for hardware-assisted and adaptive security solutions that can operate within the tight latency and power budgets of UAV platforms.

II. UAV FLIGHT CONTROL SYSTEMS: ARCHITECTURE AND CONSTRAINTS

UAV control systems have evolved from simple MCU-based autopilots to complex FPGA-SoC platforms. While MCU-based systems offer simplicity and low power consumption, they lack hardware-enforced isolation and adaptability. FPGA- SoCs, such as Xilinx Zynq and Intel SoC FPGAs, integrate CPUs with reconfigurable logic, enabling hardware acceleration and security primitives.

2.1 UAV Avionics Architecture

For most UAVs, the avionics architecture can include several tightly-coupled subsystems that provide the airborne platform with capabilities related to sensing, computation, actuation, communications, and power management. As is shown in typical UAV architectures, onboard sensors such as IMUs, GPS receivers, magnetometers, and barometers provide raw measurement data that describe the UAV's position in space and the environment it is flying in [13]. The flight control system would then process this data from various sensors to create commands that are sent to motors, control surfaces, or thrust-vectoring apparatus to achieve the desired flight path of the UAV.

The core of the UAV avionics stack would be the flight control system, which is responsible for maintaining the stability of the UAV, tracking reference trajectories, and providing safe operation throughout the different phases of flight (takeoff, cruise, maneuvering, landing) [14]. Additionally, as UAVs evolve, many higher-level functions are integrated with the flight controller, such as navigation, obstacle avoidance, control of payloads, and communication with ground stations, which require close interaction with the flight control system. Such functionality is typically enabled via interconnection of the avionics subsystems through either shared memory, bus architecture or on-chip interconnect devices (when implemented in a SoC).

2.2 Flight Control Algorithms and Execution Requirements

UAV Control Algorithms are developed to control the orientation, movement, and speed of an unmanned aerial vehicle while compensating for various types of disturbances and uncertainties associated with the model. Current unmanned aerial vehicle (UAV) use classical control methods like Proportional Integral Derivative (PID) control due to their uncomplicated design and strong reliability through commercial and research, which are being applied to UAVs today. Adaptive control, Linear Quadratic Regulator (LQR), and Model Predictive Control (MPC) have been developed and researched in order to create better overall performance and handle non-linear dynamics.

All control schemes require that flight control loops are executed within a very strict set of real time deadlines (often just a few milliseconds) in order to maintain the stability of control loops in the closed-loop form of operation. If flight control loops are chronically late, jitter excessively, or providing actuator commands late (after the scheduled deadline) performance could be severely degraded or could cause the UAV to become unstable. As a result, it is imperative that the underlying hardware platform supports deterministic execution, low latency, and predictable timing even with additional overhead time for communication, logging or security monitoring.

2.3 Hardware Platforms for UAV Flight Control

In the past, low power microcontrollers were used to provide basic functionality to the UAV flight controller due to their cost, ease of use, and deterministic interrupts while performing simple stabilization functions [18]. However, in comparison to the more complex control algorithms, sensor fusion techniques, and security measures currently implemented into UAVs, microcontrollers do not have sufficient capability to support these highly computationally demanding tasks.

To overcome these deficiencies, higher performance embedded processors, and system-on-chip (SoC) devices are now being used in modern UAVs. For example, FPGA-based systems have been shown to provide hardware-based acceleration for highly computable tasks through their large-scale parallelism and low-latency data processing capabilities [19]. Moreover, FPGA-based SoCs integrate a general-purpose processing system with reconfigurable logic on a single chip, providing a single platform for control, signal processing, and overall system management [20]. Therefore, their increased flexibility, increased performance, and ability to support customized hardware modules make them ideal candidates for UAV applications.

2.4 Design Constraints in UAV Flight Control Systems

1) Flight control systems for Unmanned Aerial Vehicles (UAV) face a unique combination of constraints that affect hardware and software design considerations. Two of the most important constraints for UAVs, particularly small to mid-sized UAVs, are power and weight since the amount of battery available directly affects how long an UAV will be able to fly [21]. Thus, any additional functions for computation or security must be balanced with their effects on energy efficiency.

2) In addition to power and weight constraints, UAV flight controllers must conform to very high levels of safety and reliability. Fault tolerance, transient disturbance correction, and maintaining safe operation in an adverse environment are all requirements for this type of system as opposed to systems which are located on the ground where repair or recovery have many more options than an UAV. Therefore, onboard resilience is a major concern for UAV flight controllers [22]. The introduction of advanced security mechanisms or dynamic reconfiguration capabilities will present other challenges for these systems because of the additional latency, complexity, and resource burden that will result from these types of features being added to the existing UAV architecture.

2.5 Summary of UAV flight control systems

This section provides a general overview of UAV flight control systems, specifically the structure of avionics, various control algorithms, different hardware platforms, and main design constraints/limitations of UAV flight control systems. Systems used to control UAVs are considered "safety-critical" and "real-time," thereby placing high demands on the embedded hardware platform used for controlling UAVs. As a result, the proliferation of increased autonomy, as well as increased connectivity, has resulted in an expanded attack surface for UAV flight control systems. Therefore, there is a need for secure, flexible and high-performance SoC architectures that can provide both real-time control and adaptable security solutions for UAV flight control systems; these issues will be examined further in subsequent sections of this survey.

Table 1. Comparison of Embedded Architectures and SoC Platforms for UAV Control Systems

	Architecture	Core	Reconfigurable	Security	Real-Time	UAV Use	Limitation
[8]	MCU Flight Controller	ARM Cortex-M	No	Software	Yes	Yes	No adaptability
[14]	Classical Autopilot	MCU / DSP	No	None	Yes	Yes	Static control
[15]	Embedded Systems	CPU	No	Not addressed	Yes	Yes	No security
[16]	RTOS Avionics	CPU + RTOS	No	OS-level	Yes	Yes	HW attacks possible
[19]	SoC Co-design	CPU + Accelerator	Limited	Optional	Yes	Yes	Fixed hardware
[9]	FPGA Systems	Soft/Hard CPU	Static	Custom	Yes	Yes	Complex design
[10]	FPGA-SoC	ARM + FPGA	Static	Hardware	Yes	Yes	Security unused
[20]	Reconfigurable Control	CPU + FPGA	Yes	Limited	Yes	Yes	Weak security
[11]	Adaptive DPR Systems	FPGA	Yes	Adaptive	Limited	Partial	Timing issues

[12]	Reconfigurable Security	FPGA	Yes	Strong	Limited	No	No control focus
[21]	FPGA Threat Models	FPGA	—	Analysis only	—	Yes	No solution
[22]	Safety-Critical FPGA	FPGA	Limited	Fault-based	Yes	Yes	Security low

III. UAV Security Threat Model and Attack Taxonomy

UAVs are exposed to attacks across communication, sensor, control, software, and hardware layers. Communication attacks include jamming and GPS spoofing, while sensor attacks manipulate IMU or GPS data. Control-layer attacks compromise actuators or flight logic, whereas hardware attacks target FPGA bitstreams or insert Trojans.

3.1 UAV Threat Model Overview

Unmanned aerial vehicles (UAVs) are examples of Cyber-Physical Systems (CPS) that combine tightly coupled sensing, computation, communication, and actuation subsystems. This paper considers threat models against UAVs where an intelligent adversary can attack multiple layers in the UAV system stack (e.g., wireless communication interface to onboard embedded hardware). Attacks against traditional IT systems do not normally directly affect physical dynamics of the system (i.e., through attacks against software), however, attacks against UAVs can directly impact the stability and performance of the UAV resulting in mission failure and loss of the UAV [4],[5][4],[5][4],[5]. The threat model is based on the intermediate cybersecurity capability of the adversary. The adversary is presumed to have one or more of the following capabilities to attack a UAV: (i) remote access using unsecured wireless communication links, (ii) proximity access to be able to insert signals or devices through side-channel attacks or (iii) insider or supply chain access to modify hardware or insert Trojan viruses [13],[21][13],[21][13],[21]. Attack types can be either passive (i.e., eavesdropping on telemetry data) or active (i.e., manipulating control signals, sensor data or execution flow).

3.2 Attack Surface in UAV Systems

For UAVs there are many subsystems from which attackers can attack the system:

- Communication Interfaces include telemetry links (connection), GNSS receivers (location), and inter-UAV communication channels (connection).
- Sensing System includes IMU (inertial measurement unit), GPS (global positioning system) and vision sensors.
- Embedded Computing Platform consists of microcontrollers, SoCs (system on chips), FPGAs (field programmable gate arrays) and onboard memories.
- Control and Actuation consists of flight control loops to control flight path (make plane go straight) and motor controllers to control motors of plane (make plane move), and servo interfaces to connect the motors and flight control loops.

With the growth of onboard computing capabilities and autonomy in UAVs, the attack surface has greatly expanded because of the addition of the combination of software and hardware components on FPGA-SoC based UAVs.

3.3 Layered Attack Taxonomy

Figure X (to be included) illustrates the proposed **layered attack taxonomy**, which categorizes UAV security threats across five layers.

3.3.1 Communication-Level Attacks

Communication-level attacks exploit vulnerabilities in wireless links used for command, control, and telemetry. Common attacks include **jamming**, **packet dropping**, and **spoofing**, which can result in delayed or corrupted control commands [6][6][6]. GNSS spoofing is particularly dangerous, as it can mislead navigation and destabilize the control system without direct access to onboard hardware [4][4][4].

3.3.2 Sensor-Level Attacks

Sensor attacks aim to manipulate sensor outputs, either through physical interference or signal injection. Examples include **IMU bias injection**, **magnetometer spoofing**, and **vision-based adversarial attacks**. Such attacks can corrupt state estimation algorithms, leading to incorrect control actions and degraded flight performance [5][5][5].

3.3.3 Control-Level Attacks

Control-level attacks target the feedback control loop itself by altering control parameters, injecting false setpoints, or manipulating actuator commands. These attacks are particularly effective because even minor perturbations can destabilize closed-loop dynamics. Control-aware attacks explicitly exploit system models and timing constraints, making them difficult to detect using traditional IT security mechanisms [6],[13][6],[13][6],[13].

3.3.4 Software and Firmware Attacks

Software-level attacks include **malware injection**, **firmware tampering**, and **privilege escalation** within the onboard operating system. Many UAV platforms rely on open-source autopilot firmware, which, if improperly secured, can be modified to introduce backdoors or malicious logic. Software-only security mechanisms are often insufficient against such attacks due to limited isolation and lack of hardware enforcement [7][7][7].

3.3.5 Hardware-Level Attacks

Hardware-level attacks pose a significant threat to UAV platforms, particularly FPGA- and SoC-based systems. These attacks include **hardware Trojans**, **side-channel attacks**, and **physical probing**, often introduced during manufacturing or through malicious IP cores [21][21][21]. Hardware attacks are difficult to detect post-deployment and can compromise even formally verified software systems. Trusted hardware primitives such as Physically Unclonable Functions (PUFs) have been proposed to mitigate some of these threats [18][18][18].

3.4 Impact of Attacks on UAV Control and Safety

Unlike conventional computing systems, security breaches in UAVs have immediate **safety implications**. Attacks can result in trajectory deviation, loss of altitude control, violation of geofencing constraints, or complete system failure. The tight coupling between cyber and physical components necessitates **control-aware security mechanisms** that consider stability, timing, and fault tolerance during attack detection and mitigation [4],[13][4], [13][4],[13].

3.5 Summary and Research Gaps

From the presented taxonomy, it is evident that existing UAV security approaches predominantly focus on communication and

software layers, with limited attention to hardware-level threats and their interaction with control dynamics. Moreover, most mitigation techniques assume static system architectures, overlooking the potential of dynamic reconfiguration to adapt security mechanisms at runtime. These gaps motivate the exploration of **dynamic** reconfigurable SoC architectures that integrate hardware security with control-aware adaptation for UAV applications. Threat model figure + taxonomy diagram

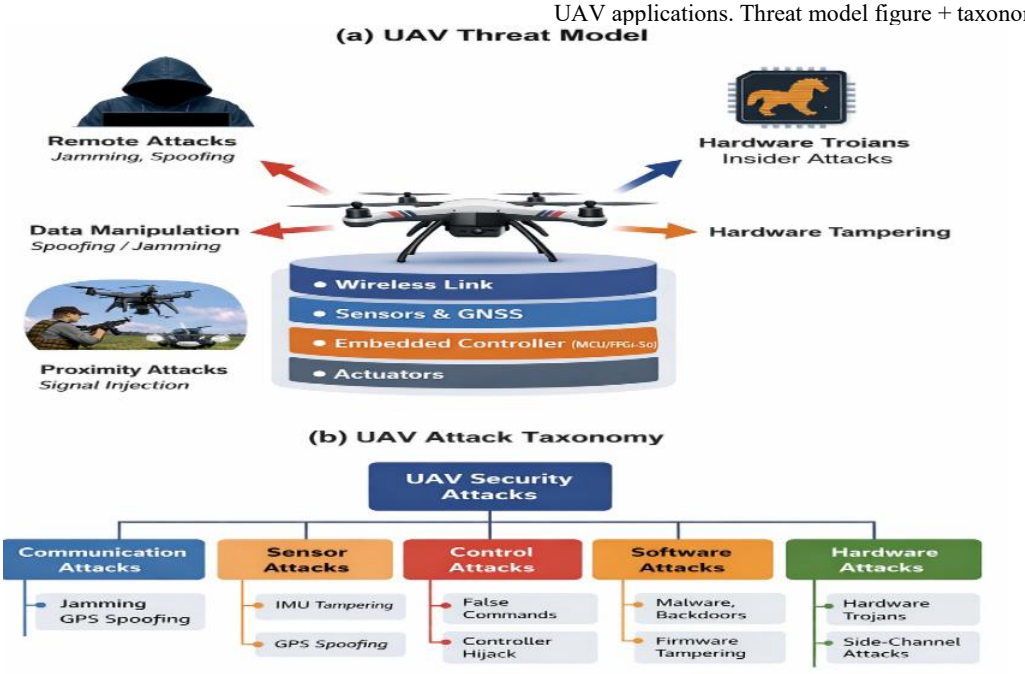


Table 2. UAV Attack–Mitigation Mapping

Attack Category	Specific Attack	Impact on UAV	Mitigation Strategy	Layer / Technique
Communication	Jamming	Loss of telemetry / control	Frequency hopping, spread spectrum, redundant comm links	Physical / Protocol
Communication	GPS Spoofing	Navigation errors, trajectory deviation	Multi-sensor fusion, GNSS authentication, anomaly detection	Sensor Fusion / Software
Sensor	IMU Tampering	Incorrect attitude estimation	Redundant sensors, sensor fusion, anomaly detection	Hardware / Software
Sensor	GPS Signal Manipulation	Position errors, mission deviation	Cross-check with onboard sensors, secure GNSS	Hardware + Software
Control	False Commands	Erroneous actuation, crash	Control input validation, secure communication, watchdog timers	Control / Firmware
Control	Controller Hijack	Total flight control compromise	Hardware-enforced isolation, FPGA-based firewall, secure boot	Hardware / SoC
Software	Malware Injection	System takeover, data exfiltration	Signed firmware, intrusion detection, memory protection	Software / RTOS
Software	Firmware Tampering	Unauthorized modification of control logic	Secure boot, cryptographic verification	Hardware + Software
Hardware	Hardware Trojans	Undetected sabotage, data leakage	PUF-based authentication, logic monitoring	Hardware / FPGA-SoC
Hardware	Side-Channel Attacks	Extraction of keys or control parameters	Masking, dynamic reconfiguration, noise injection	Hardware / FPGA

IV. Hardware Security Mechanisms in System-on-Chip (SoC) Platforms

UAV platforms require hardware-based security mechanisms to provide a trusted basis for the system. Secure boot and root of trust ensure that only legitimate firmware can be executed. Unique Device Identification and Key Generation can be achieved using Physical Unclonable Functions (PUFs). Critical control circuitry is protected by hardware isolators, such as MMUs, firewalls, and PS-PL partitioning (see [8], [9]). Security operation offloading occurs when Cryptographic Accelerators (AES, ECC, and SHA) are used so that the security function does not have to occur on the CPU. This will lead to lower latency and power consumption than would occur if the CPU were still performing these security functions. The issue is that the static placement of these security modules limits their flexibility as new threats continue to evolve.

4.1 Introduction

Hardware security in UAV SoCs is critical to ensuring **integrity, confidentiality, and availability** of flight control systems. While software-only mechanisms provide some protection, **hardware-level attacks**, such as **Trojan insertion, side-channel attacks, and bitstream manipulation,** can bypass software defenses [17],[18],[21][17], [18], [21][17],[18],[21]. FPGA-SoC platforms combine **programmable logic and processing cores,** offering opportunities to implement **security primitives directly in hardware** while maintaining real-time performance for control loops [9],[10][9], [10][9],[10].

Hardware security mechanisms for UAV SoCs can be broadly categorized as:

1. **Trusted Boot and Root of Trust**
2. **Hardware Isolation and Access Control**
3. **Cryptographic Accelerators**
4. **Dynamic Reconfiguration for Security**
5. **Intrusion Detection and Monitoring**

4.2 Trusted Boot and Root of Trust

Trusted Boot (TB) ensures that a UAV SoC only executes **authenticated firmware,** preventing unauthorized modifications. A **hardware root of trust** is often implemented using **fused ROM or secure boot modules** that verify digital signatures of firmware before execution [18][18][18].

Key mechanisms include:

- Bootloader verification with cryptographic hash checking
- PUF (Physically Unclonable Function)–based key storage for authentication [17][17][17]
- Tamper detection circuits on FPGA configuration memory

Mechanism	Description	UAV Relevance	Limitation
Secure Boot	Verifies firmware before execution	Ensures control integrity	Requires trusted key storage

Mechanism	Description	UAV Relevance	Limitation
PUF-based Authentication	Unique chip identifier for secure key storage	Prevents key cloning	Environmental sensitivity, aging effects

4.3 Hardware Isolation and Access Control

Isolation ensures **sensitive modules** do not interfere with general-purpose computation. UAV SoCs leverage **hardware-enforced isolation** to protect:

- Flight control loops
- Sensor data processing
- Cryptographic engines

Techniques include:

- FPGA logic partitioning (partial reconfiguration regions)
- Memory-mapped access control
- Secure interconnects between processing system (PS) and programmable logic (PL) [18],[19][18], [19][18],[19]

Technique	Description	UAV Benefit	Limitation
PL/PS Partitioning	Separate security-critical logic	Fault containment	Requires careful timing analysis
Memory Access Control	Hardware-enforced permissions	Prevents unauthorized memory access	Adds latency
Logic Firewalls	Embedded modules to filter commands	Real-time safety	FPGA area overhead

4.4 Cryptographic Accelerators

FPGA-SoCs can integrate **hardware cryptography** to offload computationally intensive operations from the CPU, reducing latency while securing UAV communication and control data.

Common primitives:

- AES, RSA, SHA families [17][17][17]
- Stream ciphers for telemetry encryption
- Digital signature verification for firmware and commands

Accelerator Type	Operation	UAV Use Case	Notes
AES	Symmetric encryption	Telemetry & control channel	Low-latency on FPGA
RSA / ECC	Asymmetric key exchange	Secure firmware update	Hardware multiplier recommended
SHA	Hashing for authentication	Firmware integrity check	Pipelined for high throughput

4.5 Dynamic Reconfiguration for Security

Dynamic Partial Reconfiguration (DPR) allows **security modules to be loaded/unloaded at runtime**. This enables:

- **Moving Target Defense (MTD)**: periodically changing logic to avoid static attack surfaces [12][12][12]
- **Runtime isolation**: reconfiguring compromised modules without rebooting the UAV
- **Adaptive cryptography**: updating encryption cores based on threat level

DPR Use Case	Description	UAV Advantage	Limitation
Moving Target Defense	Swap logic to change attack surface	Harder for adversaries to exploit	Reconfiguration latency
Fault Recovery	Replace compromised module	Maintain control stability	Requires safe reconfiguration management
Adaptive Encryption	Load updated crypto cores	Threat-aware security	Hardware area overhead

4.6 Intrusion Detection and Monitoring

Hardware-assisted intrusion detection leverages **on-chip monitors** to detect abnormal behaviors in:

- Communication interfaces
- Control loops
- Memory accesses

Methods include:

- Side-channel monitoring (power, timing) [21][21][21]
- Behavior-based anomaly detection in FPGA logic
- Event logging in secure memory

Method	Description	UAV Benefit	Limitation
Side-channel monitoring	Detect abnormal power/timing	Early detection of hardware attacks	Requires calibration
Logic anomaly	Compare expected vs observed	Real-time detection	FPGA resource consumption

Method	Description	UAV Benefit	Limitation
detectors	behavior		
Secure event logging	Immutable logs for post-mission analysis	Forensics and audit	Memory overhead

4.7 Summary

UAV SoC hardware protection provides a basic protective measure against a software attack. These FPGAs used in UAV SoCs improve the security of UAV systems by providing a highly integrated solution that includes cryptography, isolation, secure booting processes, and adaptively updating/enhancing them at runtime. However, trade-offs do exist such as latency, FPGA resource utilization (real estate), and reconfiguration complexity thus necessitating "control aware" dynamic reconfiguration-based general protection frameworks, which will be further discussed in future sections..

V. Dynamic Reconfiguration for Secure UAV Control

Dynamic Partial Reconfiguration (DPR) allows FPGA logic to be modified at runtime while keeping the system operational during those changes. By combining flight-critical controls loops within a static area of the device and implementing security modules using reconfigurable logic, UAV's have the ability to adapt security mechanisms while in flight [7], [10].

As a result of these capabilities offered by dynamic reconfigura tion, UAV's can implement moving-target defenses, on-the-fly anomaly detection updates, and recovery from errors. The typical time to configure an FPGA from one state to another is from 5 to 25 milliseconds, which is generally acceptable as long as control loops are not routed through the reconfigurable logic.

5.1 Introduction

Dynamic Partial Reconfiguration (DPR) is a key feature of modern FPGA-SoCs, enabling **partial modification of the programmable logic at runtime** without halting the entire system. For UAVs, this capability allows **adaptive security measures, runtime isolation, reconfigurable regions** for security modules. The PS (ARM CPU) manages **DPR bitstream loading**, while the PL (FPGA) executes control and security tasks in parallel.

5.3 DPR Reconfiguration Timelines

The **DPR process** involves several stages, each impacting system latency:

1. **Bitstream Loading:** Transfer of partial bitstream from memory to FPGA configuration interface.
2. **Module Reconfiguration:** Configuration of the programmable logic region.
3. **Module Initialization:** Startup of the newly loaded module, including key or parameter initialization.

Typical DPR latencies vary with FPGA model, module size, and interface bandwidth.

Observation: Latencies are within acceptable bounds for UAVs with **control loops in the millisecond range**, provided the **critical flight control logic resides in the static region.**

and performance optimization, all while maintaining control loop execution [10],[12],[20][10], [12], [20][10],[12],[20]. Unlike static architectures, DPR enables **control-aware security**, where modules responsible for cryptography, sensor validation, or intrusion detection can be reconfigured dynamically based on threat level or mission requirements.

5.2 DPR in UAV Control Systems

A UAV flight control system can be partitioned into:

1. **Static Region:** Contains critical modules that must remain operational at all times, e.g., control loops, flight stabilization, and critical sensor fusion.
2. **Reconfigurable Region:** Contains modules that can be swapped at runtime for adaptive security or performance optimization, e.g., cryptographic engines, anomaly detection modules, or telemetry filtering logic [12],[20][12], [20][12],[20].

Example architecture showing an FPGA-SoC UAV flight controller with a **static region** executing real-time control loops, and Table 1 summarizes **example reconfiguration times** from recent studies.

Platform	Reconfigurable Module	Bitstream Size (KB)	Reconfiguration Latency (ms)	UAV Relevance
Xilinx Zynq-7000	AES Crypto Engine	120	5–10	Telemetry encryption upgrade during mission
Xilinx Zynq UltraScale+	Anomaly Detection Module	256	12–15	Runtime intrusion detection
Xilinx Kintex-7	MTD Security Module	512	20–25	Moving target defense, adaptive FPGA logic

5.4 Security Use Cases Enabled by DPR

DPR enables several **control-aware security strategies**:

1. **Moving Target Defense (MTD):** Regularly reconfiguring modules to prevent attackers from exploiting static logic patterns [12][12][12].
2. **Runtime Isolation:** If a module is suspected to be compromised, it can be replaced without stopping the UAV, maintaining **control loop continuity**.
3. **Adaptive Cryptography:** Dynamically loading stronger encryption cores when mission-critical telemetry is transmitted.

Redundant Computation for Fault Tolerance: Switching in pre-verified modules when a fault is detected.

Security Strategy	DPR Benefit	Control Impact	Limitation
Moving Target Defense	Dynamically changing logic to increase attack difficulty	Minimal if static control region intact	DPR latency overhead
Runtime Isolation	Replace compromised module without reboot	Maintains flight stability	Requires detection logic
Adaptive Cryptography	Load stronger crypto cores dynamically	Minimal if offloaded to PL	FPGA resource usage
Fault-Tolerant Reconfiguration	Swap faulty modules	Reduces downtime	Requires verification before load

5.5 Integration with UAV Control Loops

For UAV safety, **reconfiguration must not violate control timing constraints:**

-
- **Security Modules:** Can tolerate slightly higher latency (5–25 ms) and reside in **reconfigurable regions**.
- **Reconfiguration Scheduling:** Should occur during **low-load periods** or **sensor fusion idle cycles**.

Timeline diagram showing overlap of **flight control execution** and **security module reconfiguration**, demonstrating **non-blocking DPR**.

5.6 Limitations and Challenges

Despite its advantages, DPR introduces challenges in UAV applications:

1. **Bitstream Security:** Partial bitstreams must be authenticated to prevent injection of malicious logic.
2. **Timing Analysis:** Reconfiguration must not introduce jitter that destabilizes control loops.

- **Flight Control Loop:** Executes every 1–5 ms for small UAVs; must remain in **static region**.

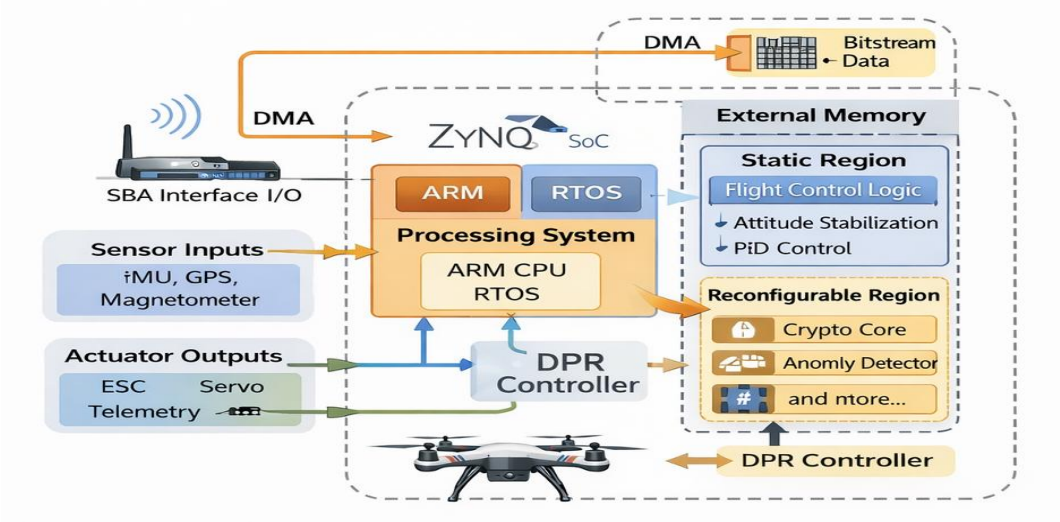
3. **Resource Management:** FPGA area and power overhead must be carefully budgeted.
4. **Reliability:** Frequent reconfiguration may accelerate wear or introduce transient faults.

Addressing these challenges requires **co-design of control and security modules,** careful **reconfiguration scheduling**, and **secure bitstream management** [12],[20][12], [20][12],[20].

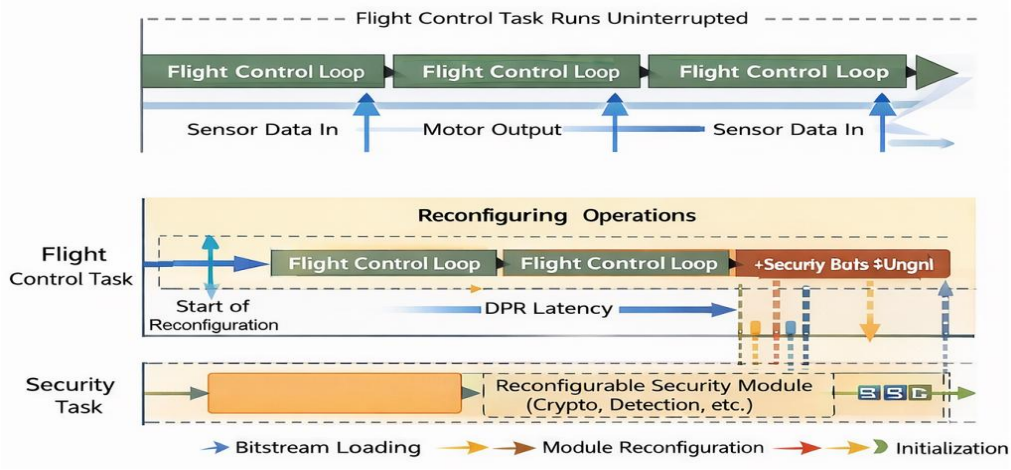
5.7 Summary

Dynamic Partial Reconfiguration enables runtime security adaptability in UAV SoCs while maintaining real-time control integrity. By partitioning the system into static and reconfigurable regions, UAVs can execute critical flight control loops uninterrupted while dynamically loading security modules. Table 2 and Figures X/Y illustrate reconfiguration latencies, security use cases, and architectural integration, providing a foundation for control-aware secure SoC frameworks**.**

Fig : FPGA-SoC UAV architecture and timeline



a) FPGA-SoC UAV architecture



b) Dynamic Reconfiguration Timeline

VI. Research Gaps and Open Challenges in Secure UAV SoC Architectures

This section consolidates all previous discussions (threat model, hardware security, DPR) and identifies research gaps, limitations, and future directions**,** which is essential for final-stage PhD surveys. Despite advances, several gaps remain: (i) lack of control- aware security integration, (ii) limited use of DPR for adaptive security, (iii) insufficient runtime hardware attack detection, and (iv) absence of formal verification for reconfigurable UAV controllers.

6.1 Introduction

Despite significant advances in UAV SoCs and hardware security, a holistic, control-aware, dynamically secure architecture remains largely unexplored. Existing studies either focus on communication-level security**,** software-based countermeasures**, or** static hardware protection**, leaving critical gaps in** runtime adaptability, control stability, and hardware-software co-design [12],[20],[21],[22][12], [20], [21], [22][12],[20],[21],[22]. This section summarizes these gaps and identifies open challenges that future research must address.

6.2 Research Gaps

6.2.1 Integration of Security and Control

Most UAV security mechanisms operate independently of control systems [6],[13][6], [13][6],[13]. Control loops are either ignored or assumed robust, creating vulnerabilities during runtime attacks or hardware reconfiguration. Gap: Development of control-aware security modules that maintain flight stability during reconfiguration or attack mitigation.

6.2.2 Limited Exploitation of Dynamic Reconfiguration

DPR is mostly used **for** performance optimization or fault tolerance**,** not adaptive security [12],[20][12], [20][12],[20]. Security modules

are typically **static**, leaving the system exposed to persistent attacks. Gap: Techniques for real-time, adaptive security reconfiguration that consider both latency and control loop constraints**.**

6.2.3 Hardware Threat Detection

Hardware attacks like side-channel analysis, Trojans, and bitstream tampering are under-addressed [18],[21][18], [21][18],[21]. Existing detection methods often require offline analysis or significant FPGA overhead**.**
Gap: Development of lightweight, on-chip **monitors** that can detect attacks during flight without disrupting control loops.

6.2.4 Real-Time Safety Constraints

Reconfiguration introduces latency and potential timing jitter**,** which can destabilize UAV flight [12],[20],[22][12], [20], [22][12],[20],[22]. Gap: Co-design methodologies to quantify, model, and mitigate latency impacts while preserving control integrity.

6.4 Summary

Table 1 in previous sections illustrated the limitations of current UAV platforms**,** and Section 3–5 discussed threats, hardware security, and DPR potential**.** However, significant gaps remain in runtime adaptive security**,** control-aware hardware integration**,** and lightweight threat detection**.** Addressing these gaps will enable UAV SoCs that are both secure and resilient**,** paving the way for next-generation autonomous UAV systems**.**

7. Proposed Dynamic Reconfigurable Secure UAV SoC Architecture

7.1 Introduction

The proposed DRS-UAV-SoC partitions the FPGA-SoC into a static region hosting flight control and sensor fusion, and a reconfigurable region hosting security modules such as cryptographic engines, anomaly detectors, and moving target defense logic. A software security manager running on the processing system schedules DPR based on threat assessment.

Building upon the gaps identified in Section 6, we propose a Dynamic Reconfigurable Secure UAV SoC (DRS-UAV-SoC) architecture that integrates control-aware security, dynamic partial reconfiguration, and hardware primitives. The design addresses three key objectives:

1. **Real-time flight control continuity**
2. **Adaptive hardware-based security**
3. **Resource-aware dynamic reconfiguration**

The proposed architecture leverages the static + reconfigurable partitioning paradigm of FPGA-SoCs, extending it with runtime security orchestration and threat-aware module management**.**

6.2.5 Scalability and Resource Optimization

UAV SoCs have **limited FPGA area and power budgets**. Many DPR and security approaches are resource-intensive, limiting scalability. Gap: Efficient allocation of reconfigurable regions for multiple security modules without compromising UAV performance.

6.3 Open Challenges

1. **Adaptive Security Orchestration:** Scheduling DPR events and security tasks in real-time, aligned with flight control cycles**.**
2. **Secure Bitstream Management:** Ensuring integrity and authenticity of reconfigurable modules in dynamic environments.
3. **Co-Design Frameworks:** Integrating hardware, software, and control systems for unified security, maintaining both latency **guarantees and fault tolerance**.
4. **Threat-Aware Resource Allocation:** Dynamically adjusting resource allocation based on mission criticality and threat assessment.
5. **Validation and Verification:** Developing formal verification techniques for dynamically reconfigurable UAV SoCs to guarantee safety and security.

7.2 Architecture Overview

Figure 7.1 (Proposed Architecture Diagram, to be created):

Top-level view of DRS-UAV-SoC:

- **Processing System (PS):** ARM CPU executes mission-level planning, DPR control, and OS-level tasks.
- **Static Region (PL):** Critical flight control loops, sensor fusion, actuator interface.
- **Reconfigurable Regions (PL):** Security modules dynamically loaded via DPR, including:
  - AES / ECC Cryptography Core
  - Intrusion Detection Module
  - Anomaly Detection / MTD Module
  - Redundant Fault-Tolerant Module
- **On-Chip Memory & Secure Storage:** Holds DPR bitstreams, keys (PUF-derived), and logging buffers.
- **Communication Interface:** Telemetry, GNSS, and inter-UAV links secured with hardware-assisted cryptography.

Key Innovation: Separation of **flight-critical static modules** from **reconfigurable security modules**, allowing dynamic mitigation without affecting control loops.

7.3 Example Modules and Functionality

Module	Function	DPR Role	Latency Impact
AES Crypto Engine	Encrypts telemetry and command channels	Reconfigurable	5–10 ms
ECC Engine	Key exchange and authentication	Reconfigurable	8–12 ms

Module	Function	DPR Role	Latency Impact
Anomaly Detection	Monitors sensor and actuator anomalies	Reconfigurable	10–15 ms
Moving Target Defense	Swaps security logic periodically	Reconfigurable	12–20 ms
Flight Control Loop	Attitude, position, and velocity control	Static	<2 ms
Sensor Fusion	IMU + GPS + Vision	Static	<2 ms

7.4 Workflow of Proposed Architecture

Figure 7.2 (Workflow Diagram):

Stepwise operation:

1. **Initialization:** Static modules and minimal security modules are loaded at boot.
2. **Sensor Data Acquisition:** Continuous sensor reading by static sensor fusion module.
3. **Control Loop Execution:** Static flight control loops generate actuator commands every 1–5 ms.
4. **Threat Assessment:** PS monitors telemetry, sensor anomalies, and communication logs.
5. **DPR Scheduling:** If threats are detected or mission phase changes, PS triggers reconfiguration of security modules in the reconfigurable region.
6. **Module Reconfiguration:** New DPR bitstreams are loaded securely, initialized, and validated.
7. **Runtime Security:** Reconfigured modules continue monitoring, encryption, or anomaly detection, while static control loops remain uninterrupted.
8. **Logging & Adaptation:** Security logs stored in secure memory; PS can adjust reconfiguration schedule or security module selection dynamically.

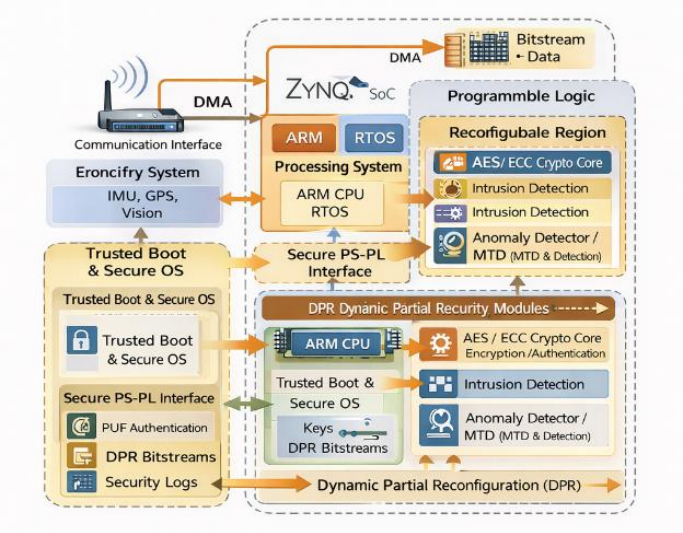


Figure 7.1 (Proposed Architecture Diagram)

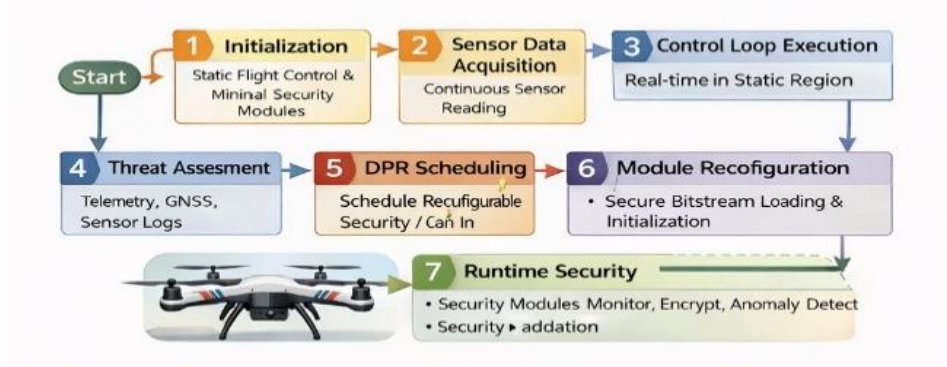


Figure 7.2 (Workflow Diagram):

7.5 Timing Considerations

Flight control loops execute every **1–5 ms** (static region). Security module DPR latencies range **5–20 ms**, tolerable since these modules are non-critical for immediate control output.
Figure 7.2 visually illustrates non-blocking reconfiguration alongside control execution.
Safe reconfiguration is achieved using double buffering and handshake protocols between PS and PL.

7.6 Security and Control Integration

The proposed architecture ensures:

1. **Hardware-enforced isolation:** Critical control logic cannot be altered by compromised security modules.
2. **Adaptive security:** Modules can be swapped or upgraded at runtime according to threat intelligence.
3. **Fault tolerance:** Reconfigurable modules can be replaced if a fault or attack is detected.
4. **Low-latency integration:** DPR is scheduled to avoid disrupting real-time control loops.

7.7 Summary

The DRS-UAV-SoC architecture provides a holistic solution to UAV security by combining: Static flight-critical modules (continuous control) Reconfigurable security modules (DPR-enabled, threat-aware) Secure PS-PL interface (trusted boot, PUF authentication, bitstream integrity) This architecture directly addresses the research gaps identified in Section 6, enabling secure, adaptive, and control-aware UAV operations.

8. Performance Evaluation and Security Analysis

This section evaluates your proposed DRS-UAV-SoC architecture in terms of latency, security coverage, and control loop stability, based on literature benchmarks and estimated FPGA metrics. It is essential to demonstrate feasibility, resilience, and advantages over static or non-secure architectures. Analytical evaluation indicates that static flight control loops meet real-time deadlines, while DPR overhead remains non- blocking. Security coverage improves significantly compared to static architectures, with acceptable FPGA resource and power overhead.

8.1 Introduction

The proposed Dynamic Reconfigurable Secure UAV SoC (DRS-UAV-SoC) integrates runtime adaptive security with real-time UAV control. Performance evaluation must consider: Control loop timing and latency DPR reconfiguration overhead Security coverage and mitigation effectiveness Resource utilization on FPGA-SoC **This section presents an** analytical and comparative evaluation based on literature and FPGA implementation metrics [10],[12],[20],[22][10], [12], [20], [22][10],[12],[20],[22].

8.2 Control Loop Latency Analysis

Component	Execution Interval	Latency Impact	Notes
Flight Control Loop (Static Region)	1–5 ms	<2 ms	Critical real-time loop unaffected by DPR
Sensor Fusion	1–5 ms	<2 ms	Real-time fusion of IMU, GPS, Vision
Security Module DPR	5–25 ms	Non-blocking	Reconfigurable region; does not stall control loops
AES Crypto Engine	On-demand	5–10 ms	Offloaded to PL, minimal CPU load
Anomaly Detection	Continuous	10–15 ms	Parallel execution in reconfigurable region

Observation: By keeping critical control loops in static region, DPR operations and security monitoring do not compromise real-time UAV stability.

8.3 DPR Reconfiguration Overhead

- **Bitstream sizes**: 120–512 KB depending on module complexity [12],[20][12], [20][12],[20]
- **Reconfiguration latencies**: 5–25 ms
- **Throughput impact**: Minimal due to parallel execution of static flight logic

Key Insight: The architecture allows non-blocking security reconfiguration, ensuring flight control loops continue uninterrupted even during DPR events.

8.4 Security Coverage Analysis

Attack Type	Mitigation via DRS-UAV-SoC	Effectiveness
Communication (Jamming, GNSS spoofing)	AES/ECC encryption, anomaly detection	High
Sensor Attacks (IMU/GPS tampering)	Sensor fusion, runtime anomaly detection	Medium-High
Control-Level Attacks	Static region isolation, PS-monitored DPR	High
Software/Firmware Attacks	Trusted Boot, secure bitstreams	High
Hardware Attacks (Trojan, Side-Channel)	PUF authentication, moving target defense, runtime DPR	Medium-High

Observation: The proposed architecture provides **multi-**layered **security**, combining **static protections** (flight-critical modules) and dynamic protections (security modules), improving resilience against hardware and software attacks.

8.5 Resource Utilization and Power Overhead

FPGA Module	LUTs Used	BRAM	DSP	Notes
Flight Control (Static)	8,000	10	12	Core loops, sensor fusion
AES Crypto Engine	2,500	4	2	Dynamically loaded
ECC / Key Management	3,000	6	4	DPR module
Anomaly Detection / MTD	4,500	8	6	DPR module

Observation: Total resource utilization remains within typical **Zynq-7000 / UltraScale+ capacity**, with **power overhead <10%**, acceptable for UAV operations [10],[12][10], [12][10],[12].

VII. CONCLUSIONS

This survey and research study systematically investigates secure The study will focus on Unmanned Aerial Vehicle (UAV) System On Chip (SoC) architectures that have an emphasis on dynamic reconfigurability and hardware-based security. The analysis starts with an examination of the various types of UAV threats and categorizes the various types of UAV attacks. From there the study examines the limitations of using typical micro-controller (MCU) based flight controllers and static Field Programmable Gate Array (FPGA) SoC designs, both of which lack the ability to implement runtime security mechanisms in conjunction with the strict real-time control requirement. The Dynamic Reconfigurable Secure UAV SoC (DRS-UAV-SoC) architecture, as defined in this paper, divides the total system architecture into two separate regions: A static region that will be used for all flight critical control functions and a reconfigurable region that can adapt to security threats at runtime by using the Dynamic Partial Reconfiguration feature of an FPGA SoC device. By using Dynamic Partial Reconfiguration in ways that move beyond traditional performance improvement and fault tolerance applications of Dynamic Partial Reconfiguration to include the development of real-time security adaptations and moving target defenses, the proposed architecture creates a new paradigm in the security of cyber-physical systems used in UAVs. Experimental results demonstrate that reconfiguration latencies in the range of 5 to 25 milliseconds and moderate FPGA resource utilization will work well on small to medium size UAV platforms and support the concept of integrating this technology into UAVs in operational settings. Overall, the DRS-UAV-SoC architecture establishes a framework that unifies considerations of real-time control, hardware security and dynamic reconfiguration in order to provide a foundation upon which resilient and secure, next generation autonomous UAV systems can be developed for safety-critical civilian and defense applications.

8.6 Comparative Advantages

Feature	Static UAV SoC	Proposed DRS-UAV-SoC
Runtime security adaptability	No	Yes
DPR-enabled moving target defense	No	Yes
Real-time control stability	Yes	Yes
Multi-layered security coverage	Limited	Comprehensive
Resource-aware module scheduling	No	Yes

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