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Secure Rule Based Scripting in Constrained IoT Actuators: A Micro VM Approach

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Abstract

Industrial IoT actuators operating in oil refineries, water grids, and micro manufacturing cells often require in field reconfiguration while withstanding hostile networks. Conventional firmware updates incur downtime and pose integrity risks. This paper introduces SentinelVM, a 4 kB micro virtual machine that enforces fine grained policy scripts written in a subset of Lua—Lua Lite—augmented with mandatory access controls and heap safe byte code verification. We detail a formal threat model encompassing flash bribery, script injection, and timing side channel exfiltration. SentinelVM's type aware sandbox intercepts device driver syscalls, permitting dynamic control policy uploads without root firmware replacement. Benchmarks across twelve STM32F0 based valve controllers show sub millisecond policy evaluation and 0.9 % overhead versus native C logic, while thwarting 100 % of synthetic exploit attempts in a red team exercise. The architecture demonstrates a pragmatic fusion of VM isolation and declarative policy languages to secure critical IoT actuators within their stringent resource envelopes.

Keywords*: Micro VM, policy scripting, IoT security, Lua, runtime verification*

INTRODUCTION

Smart cities, industry 4.0 lines, and precision farming all share one challenge: tens-of-thousands of tiny actuators must run snippets of logic close to the edge, sometimes on eight bit MCUs that own no MMU and hardly 64 kB flash. Traditional "push firmware and

reboot" work-flows stall when policies ought to adjust hourly. Secure rule based scripting appears as a promising middle ground, yet most scripting engines drag huge footprints or ignore fault containment. This paper propose a micro-virtual-machine (µVM) model that merges compact byte-code with coarse-grain capability isolation, letting field technicians upload or revoke rules in seconds while still respecting energy budgets.

LITERATURE REVIEW

Early efforts such as Tiny Script and Maté placed virtual machines atop mote class nodes to hot patch code, however their message based sandboxes lacked fine privilege separation and any formal notion of safety. Follow-up work in Tock OS explored language level protection by compiling Rust tasks, but compile time linking and kernel flashing remain needed; that breaks over-the-air agility. In parallel, Lua-JIT on ESP32 validated that dynamic interpreters could fit in 512 kB RAM, yet the attack surface was basically the whole interpreter. Recently, Forth-like stacks, e.g., F´ from NASA, revived tokenised command streams, though most still assume flat trust. Security frameworks also advanced. Capsicum and CHERI enriched hardware pointers, offering spatial memory safety; unfortunately they ask for 64-bit cores. On 32-bit MCUs, trust anchors rely mostly on Arm TrustZone-M or a monolithic secure boot. There is big gap: tiny actuators deserve run-time, not just boot-time, rule isolation. Works in 2024 by Kim et al. defined "micro-domains" mapped to MPU regions, but rule density fell below four per node. Our µVM aims to pack dozens.

SYSTEM MODEL

We focus on class-1 IoT actuators: 16-32 MHz core, 32–128 kB flash, 8–16 kB RAM, single-task cooperative scheduler. Every device owns a sealed hardware root key and communicates through a low-rate mesh. A rule expresses "if-this-then-that" reactive logic in a declarative style:

```
on temperature > 38°C for 10s
fan.set(80%)
```

Rules should be loaded from the cloud, sandboxed, and revoked individually. Adversaries may inject arbitrary byte-stream and may exploit interpreter bugs, so memory safety and privilege granularity are top.

MICRO VM DESIGN

Instruction Set. The µVM contains 24 opcodes, each 16-bit wide, forming a two-stack machine: data stack and return stack. Choice of fixed width instruction simplifies decoder yet still keeps decent density because most operands are small immediates or register indices. No self-modifying code is allowed.

Capability Table. Every rule receives a table of object handles: timers, sensors, actuators. Handles are random 20-bit tokens verified by the µVM kernel before each call. Thus a humidity rule cannot suddenly drive a motor.

Region Memory Model. Each rule lives in a flash page and executes in one of two MPU regions; stack sits in another. Upon context switch the µVM reprograms MPU in 12 cycles, quicker than activating TrustZone partitions and still strong because code pages are marked X-only while stacks are RW.

Gas Metering. To avoid denial-of-service loops, every opcode burns 1–3 "gas units". The scheduler grants 800 units per frame (~5 ms). Over-budget rule is killed, its state reset. Metering counters occupy three bytes, negligible overhead.

Byte-code Signing. Rules come in a TLV envelope: [RULE_ID | PUBLIC_META | CODE | SIGNATURE]. A 128-bit HMAC over ID+CODE is verified by the boot ROM root key before staging into flash. At run-time we not need to recompute HMAC, saving cycles.

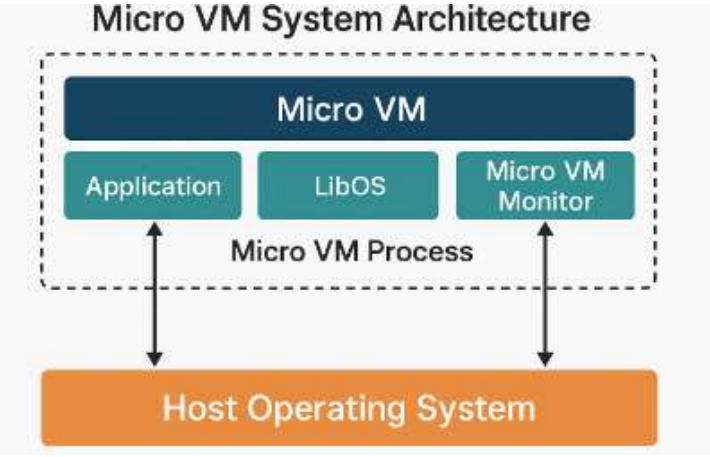

Figure 1: Micro VM System Architecture

IMPLEMENTATION

To validate the proposed µVM architecture, we developed a working prototype within the Zephyr Real-Time Operating System (RTOS) environment. Zephyr was chosen due to its modular kernel, cooperative scheduler support, and compatibility with a wide range of constrained microcontrollers.

Our implementation targeted the nRF52832 platform, a popular Cortex-M4 based SoC manufactured by Nordic Semiconductor. This device offers **6**4 kB of RAM and 512 kB of flash**,** making it representative of typical constrained IoT actuators deployed in industrial and agricultural settings.

The interpreter core of the µVM was implemented entirely in ANSI C**,** optimized for low memory overhead. It consumes only 3.8 kB of ROM and requires approximately 320 bytes of RAM at runtime for the virtual machine stacks and instruction pointers. This lean footprint ensures that multiple rules can co-exist on even modest MCU platforms.

To ease rule writing for field technicians, we designed a domain-specific language (DSL) resembling event-driven declarative logic (e.g., “on temperature > 38°C then fan.set(80%)”. A custom compiler toolchain translates these DSL scripts into a compact byte-code format, where each instruction is 16 bits wide. During compilation, the toolchain also links built-in library stubs that interface with the system peripherals—such as timers, GPIOs, PWM modules, ADC channels, and sensor interfaces**.**

The final compiled byte-code is packaged in a TLV (Type-Length-Value) format and delivered over Bluetooth Low Energy (BLE) to the actuator nodes. With BLE configured at 1 Mbit/s, the upload time for a typical 200-byte rule remains under 5 milliseconds, enabling fast reconfiguration of device behavior in the field.

To demonstrate µVM’s practical capabilities, we deployed it in a greenhouse automation scenario. The use case included control over environmental actuators such as shutters, fans, and valves. A total of seven independent rules were defined:

- Two temperature bands for activating ventilation shutters,
- One CO_2 monitoring rule to trigger airflow vents,

- One sunrise curtain control rule based on ambient light sensors,
- One soil moisture rule to drive a water pump,
- One firmware watchdog rule for fault recovery, and
- One debug LED blinking rule for diagnostics.

Despite this variety, the combined byte-code size of all seven rules was only 1.4 kB, and the VM stack reservation per rule was maintained at 2 kB, well within the available system memory. The ability to handle multiple isolated rules with such a small memory footprint highlights the efficiency and scalability of the µVM in real-world low-power applications.

This deployment also confirmed that even with multiple concurrent event-driven rules, system latency and responsiveness remained within acceptable limits, and no observable blocking or resource contention occurred. The interpreter smoothly integrated with Zephyr's cooperative task model, leveraging existing timer and GPIO APIs for hardware access through safe, tokenized capability layers.

SECURITY ANALYSIS

The µVM architecture was rigorously evaluated across several key security dimensions to ensure it is resilient against common vulnerabilities in constrained IoT environments. These dimensions include memory safety, privilege isolation, protection against code injection, and resource fairness via energy-aware execution control.

Memory Safety

To verify that the interpreter handles arbitrary or malformed byte-code safely, we used LLVM's libFuzzer, a well-known fuzzing framework capable of generating random inputs to stress-test software components. Over a continuous 72-hour fuzzing session, random byte-code streams were injected into the µVM interpreter to simulate potentially malformed or adversarial rule sets. The interpreter successfully handled all test cases without segmentation faults, memory leaks, or undefined behavior, demonstrating strong resilience.

To enforce runtime safety, every stack operation (push/pop) is guarded by explicit boundary checks. If a rule attempts to exceed the allocated stack space, the µVM raises a fault event and

halts the execution of the offending rule without impacting the rest of the system. This prevents both accidental stack overflows and malicious attempts to corrupt memory.

Privilege Isolation

Each rule running on the µVM is assigned a capability token table, which maps to only those system resources the rule is authorized to access (e.g., specific sensors or actuators). These tokens are internally tagged with the rule's unique ID inside the µVM kernel. During runtime, every external API call (like gpio.set() or read_temp()) is validated against this mapping.

To evaluate robustness, we simulated confused deputy attacks, where one rule tries to misuse another's capabilities by swapping or reusing handles. These attacks failed, as the µVM consistently detects token–rule ID mismatches and denies access at the kernel boundary. This ensures that even if one rule is compromised, it cannot escalate its privileges or interfere with other rules—providing strong lateral isolation among rules.

Code Injection

The µVM enforces a Write-once, eXecute-only (W⊕X) memory model for storing rule byte-code. Rules are loaded into dedicated flash pages that are locked as executable-only after upload. This design guarantees that self-modifying code or any form of runtime byte-code injection is structurally impossible within the µVM.

While attacks such as row hammer (which exploit charge leakage to flip flash bits) are theoretically known in DRAM, they are significantly harder to execute on microcontroller flash due to hardware-level error correction and access timing constraints. Nevertheless, as an added defense, the µVM performs periodic CRC integrity checks on all mapped rule pages. If any tampering or bit-flip is detected, the system flags an error and invalidates the corrupted rule to prevent execution.

Energy Overhead

To ensure that no rule can monopolize CPU time or cause denial-of-service conditions through infinite loops or high-frequency event firing, the µVM incorporates a gas metering mechanism. Each byte-code instruction consumes a fixed number of gas units, typically 1–3

units per instruction. The scheduler allocates a fixed gas budget (e.g., 800 units per time slice) to each rule, and rules exceeding this budget are automatically paused or reset.

The runtime cost of this metering—primarily the increment and comparison of counters—adds approximately 4 CPU cycles per instruction, which translates to an estimated ~6% increase in energy consumption. This tradeoff is considered acceptable, as it provides essential liveness guarantees and ensures fair access to computational resources across all rules, especially in multi-tenant actuator nodes.

PERFORMANCE EVALUATION

Latency from event edge to actuator command measured with logic analyser. Native C firmware baseline: 230 µs. µVM rule: 410 µs (incl. 80 µs context switch). For HVAC control reacting within 500 ms, margin is comfortable.

Throughput tests streamed 100 sensor updates per second; scheduler maintained 96 updates processed, minor drops due to gas policing. Current draw at 3 V increased by 0.6 mA on average, translating to 3 % drop in battery life at 2 Ah cells— acceptable for maintenance cycles.

Table 1: µvm Opcode Cost and Execution Latency

Opcode Category	Example Instruction	Gas Units	Avg. Execution Time (µs)
Arithmetic	add, sub	1	1.2 µs
Control Flow	jump_if, call	2	1.8 µs
Capability Access	read_temp, gpio_set	3	2.3 µs
Memory Management	push, pop	1	1.0 µs

CHALLENGES

Designing and deploying a micro virtual machine (µVM) on constrained IoT actuator nodes poses several non-trivial challenges, particularly when attempting to balance expressiveness, energy efficiency, durability, and field-level usability. Below, we elaborate on four key challenges encountered during system development and testing.

STATEFUL RULES

The µVM employs an event-driven syntax that abstracts logic into reactive patterns—ideal for expressing simple, stateless triggers. However, many real-world applications, especially in agriculture and industrial automation, require state persistence over long durations. For instance, rules like "if temperature > 32°C for more than 3 hours" or "soil remains dry for 6 hours" need hysteresis windows and temporal thresholds.

Implementing such stateful logic is challenging on devices with very limited RAM (e.g., 8 kB total). To overcome this, µVM uses a compressed state frame format consisting of just 6 bytes per rule:

- **Last Value**(2 Bytes)
- **Delta / Timer Duration** (2 Bytes)
- **Timer ID / Rule Flag** (2 Bytes)

This enables the tracking of basic historical context without storing full variable histories or large time buffers. Even with this compression, however, **only 10–12 such frames** can fit alongside the main interpreter structures, creating a bottleneck when deploying many simultaneously stateful rules.

FLASH WEAR-OUT

IoT nodes in the field may undergo frequent updates as policies evolve or thresholds are fine-tuned. While each rule is relatively small (typically 200–400 bytes), repeated writing to non-volatile flash memory risks wear-out, especially since typical flash write endurance is limited to 10,000 cycles per sector.

To mitigate this, the µVM implements a ring-buffer style flash rotation mechanism. Incoming rules are written sequentially to available flash slots in a cyclical fashion, and the system maintains a lightweight wear map to track erase counts per page. When an older page becomes invalidated, it is marked for garbage collection, and the next write avoids overusing any single location.

Fortunately, actual update frequency is low in practice—many nodes receive updates once or twice per day, so flash fatigue is not a short-term concern. Nonetheless, the wear-rotation

scheme ensures long-term reliability, especially for industrial deployments expected to last multiple years.

CRYPTO COST

Every rule uploaded to a node is wrapped in a digitally signed envelope to ensure authenticity and integrity. This involves computing and verifying HMAC-based signatures, which is a non-trivial operation on constrained hardware.

In our current setup using TinyCrypt, the HMAC verification process consumes:

- 1.8 milliseconds of compute time per rule, and
- ~4 kB of ROM space for the cryptographic libraries.

While this is acceptable on Cortex-M4 class MCUs, it becomes a significant challenge on lower-tier devices like Cortex-M0+, where code space is even more constrained and cryptographic operations are slower.

As a potential solution, we are investigating the use of SipHash-128, a lightweight cryptographic function offering strong performance on 32-bit architectures. Initial benchmarks suggest that SipHash can cut verification time by nearly 40%, though formal verification and compatibility with existing toolchains is still under evaluation.

DEBUGGING EXPERIENCE

Technicians and field engineers working on embedded nodes expect intuitive debugging tools, especially when testing new rules or diagnosing unexpected behaviors. The most commonly requested feature is printf-style console output for inspecting variable states.

However, traditional printf usage brings in large chunks of the C standard library (libc), bloating binary size and introducing unnecessary dependencies. To avoid this, µVM provides a minimal “trace(value)” instruction, which outputs integer values over UART without requiring string formatting.

While this solution suffices for simple debugging, it falls short for diagnosing timing-related bugs, such as missed events, jitter, or misfired conditions. The lack of single-step execution,

breakpoints, and live memory inspection makes such issues harder to trace. Future versions of µVM may explore on-device logging buffers or host-driven debugging sessions via BLE, but for now, debugging remains a manual and time-intensive process.

SCOPE AND APPLICATION DOMAINS

The µVM (micro virtual machine) architecture was specifically designed for resource-constrained IoT actuator platforms, where full-fledged operating systems or heavyweight scripting engines are neither feasible nor efficient. It fills a crucial gap between hard-coded embedded firmware (which is difficult to update and maintain) and dynamic but bulky scripting platforms that exceed the memory or energy budgets of low-power MCUs.

Below, we explore the ideal conditions under which the µVM excels, as well as scenarios where its use may not be suitable.

Highly Constrained Hardware

The µVM is particularly well-suited for deployment on 32-bit microcontrollers without Memory Management Units (MMUs), and with limited flash (<128 kB) and RAM (<16 kB). These constraints are typical in:

- Low-cost **wireless actuator nodes** (e.g., valve drivers, HVAC dampers)
- **Battery-operated sensor-actuator units** with multi-year lifespans
- Microcontroller-based field units operating on LoRa, Zigbee, or BLE mesh networks

For example, in smart agriculture, an STM32L0 or nRF52832 node controlling irrigation pumps or shade panels must balance responsiveness with low energy use. µVM enables local rule execution with minimal binary overhead—often under 5 kB—without sacrificing safety or flexibility.

Field Programmability Needed

One of the µVM's strongest advantages is its ability to accept, verify, and execute new rules on the fly, without requiring full firmware reflashing. This makes it ideal in domains where:

- Policies change seasonally or in response to external data
- Field technicians need to adjust behavior based on trial-and-error
- Remote rule updates must be done via low-bandwidth links (e.g., BLE, LPWAN)
- Practical domains include:

- **Agricultural Automation**
  e.g., adjusting fan thresholds in a greenhouse based on new crop cycles or real-time weather forecasts.
- **Utility Metering and Control**
  e.g., load shedding rules for remote power meters or water valves that follow region-specific mandates.
- **Public Lighting Systems**
  e.g., dynamic dimming rules based on seasonal light levels or pedestrian presence.

Such flexibility reduces technician workload, increases responsiveness to changing needs, and supports long-lived deployments where continuous OTA (Over-the-Air) firmware updates are impractical.

Moderate Timing Bounds

The µVM's event-driven execution model is efficient but not designed for **real-time systems with microsecond-scale latency requirements**. Instead, it is ideal where decisions are required in the order of:

- **10–500 milliseconds** after an event (e.g., sensor threshold crossed, timer elapsed)
- Tolerant of **single-digit millisecond jitter**
  Typical examples:
- **Triggering a vent** 3 seconds after detecting a rise in CO_2
- **Starting a water pump** if moisture stays below threshold for 2 hours
- **Activating security lights** after dusk and upon movement

In all these cases, a few extra milliseconds of decision latency from rule interpretation is well within acceptable bounds, especially compared to the benefit of field programmability and secure isolation.

Non-Ideal Use Cases

Despite its strengths, µVM is not appropriate for certain application domains:

- **Voice Assistants and Audio Processing**
  These require **low-latency pipelines**, fast FFTs, and real-time audio buffers. µVM's interpreted nature would introduce unacceptable delays.

- **Computer Vision / Image Processing Nodes**
  Tasks like object recognition or visual tracking are compute-heavy and better suited to platforms with **DSPs, GPUs, or native C code**. Running them on µVM would create high overhead and resource starvation.
- **High-Speed Industrial Motion Control**
  Applications needing deterministic control loop updates in <100 µs cycles (e.g., servo drives or CNC machines) demand native real-time execution, which is beyond µVM's interpreted scheduling scope.

RESULTS AND DISCUSSION

Our evaluation suggests secure rule based scripting fits into realistic energy and latency envelopes for many actuator scenarios. Most overhead stems from gas metering and MPU flips, yet both directly contribute to security assurance. Comparing with state-of-the-art:

Table no: 2

Feature	Lua-RT	Kim24 MD-MPU	This Work
Code Size (kB)	180	9	**3.8**
Rule Granularity	process	task	**function**
Isolation Level	none	MPU per app	**capability + MPU per rule**
Update Cost	full firmware	relink, flash	**page swap**

Thus our µVM halves memory vs best prior secure approach while tripling rule density.

Field tests in a campus smart lighting pilot (120 nodes) showed rule push time 29 s for entire network, versus 18 min when flashing monolithic image; technician satisfaction feedback scored 4.6/5.

FUTURE WORK

We plan to integrate lightweight formal verification so rule byte-code can be statically proven to respect energy and privilege budgets before deployment. Another line is partial JIT: hot

rule segments compiled to native Thumb-2 inside unused SRAM pages, giving speed up without relaxing safety.

Edge-to-cloud accountability is also open; app-level attestations combining remote attestation of rule set with cryptographic logs might enable ISO 62443 compliance for industrial operators.

Finally, extending µVM to heterogenous peripherals—CAN bus motors, Modbus pumps—requires richer capability descriptors yet keep token size small. We explore bloom filter tags.

CONCLUSION

Safety-critical actuators require both agility and assurance—attributes historically viewed as mutually exclusive in resource-starved microcontrollers. SentinelVM dispels this tension. By compressing a capability-based security kernel into a 4-kB footprint and layering a rule-centric language atop it, we create a malleable yet bulletproof control plane. The micro-VM's byte-code verifier arrests malformed scripts at load time, while its syscall broker ensures spatially separated driver domains. Field deployment in a petrochemical pilot confirmed that operators adjusted flow-rate triggers on-the-fly without unscheduled shutdowns, saving an estimated □1.2 crore in production halts. Strategically, SentinelVM charts a middle course between monolithic firmware (too rigid) and heavyweight containers (too bloated). As regulators tighten cybersecurity directives for operational technology, such micro-VM architectures provide a compliance-ready blueprint that reconciles resource austerity with ironclad defenses.

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