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Webassembly Runtime Performance for Serverless Computing

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Abstract

WebAssembly (Wasm) has emerged as a portable compilation target enabling near-native performance in web browsers and server environments. This paper benchmarks WebAssembly runtime performance focusing on WASI (WebAssembly System Interface), the Component Model, and cross-language interface types for serverless computing. We evaluate leading Wasm runtimes including Wasmtime, WasmEdge, and WAMR across startup latency, execution throughput, and memory consumption metrics. Cold start latency measurements reveal that Wasm runtimes achieve 1-10ms initialization compared to 100-1000ms for traditional containers, making Wasm ideal for serverless functions. The Component Model enables composable Wasm modules with type-safe interfaces, reducing inter-module call overhead by 10×. WASI provides standardized system APIs achieving 80-95% of native Linux performance for I/O operations. Benchmarks across CPU-intensive, memory-bound, and I/O-heavy workloads demonstrate that optimized Wasm code reaches 70-95% of native C/C++ performance. We analyze trade-offs between security isolation, performance overhead, and portability. Implementation strategies for serverless platforms including function composition, resource limits, and polyglot execution are discussed. Our findings indicate WebAssembly offers a compelling foundation for next-generation serverless computing with superior cold start performance and cross-platform portability.

Keywords:- Webassembly, WASI, Serverless Computing, Runtime Performance, Component Model, Cold Start Latency

I. INTRODUCTION

Serverless computing has transformed cloud application development by abstracting infrastructure management and enabling automatic scaling [1]. However, traditional serverless platforms based on containers and virtual machines face cold start latency challenges ranging from hundreds of milliseconds to several seconds. This startup overhead limits serverless adoption for latency-sensitive applications including real-time APIs, IoT edge processing, and interactive web services.

WebAssembly (Wasm) presents a lightweight alternative to container-based serverless runtimes [2]. Originally designed for browser execution, Wasm provides a portable binary instruction format with strong security isolation through capability-based security. The WebAssembly System Interface (WASI) extends Wasm beyond browsers by defining standardized system APIs for file I/O, networking, and operating system interaction [3]. This combination enables Wasm runtimes to execute untrusted code with microsecond-scale startup times while maintaining security guarantees comparable to process isolation.

This paper provides comprehensive performance evaluation of WebAssembly runtimes for serverless computing. We benchmark cold start latency, execution throughput, and memory consumption across Wasmtime, WasmEdge, and WAMR runtimes. The Component Model's impact on module composition and the performance characteristics of cross-language interface types are analyzed. Our evaluation covers diverse workloads representative of serverless applications including HTTP request handlers, data processing pipelines, and machine learning inference.

II. WEBASSEMBLY FUNDAMENTALS

A. WebAssembly Architecture

WebAssembly defines a stack-based virtual machine with linear memory and structured control flow [4]. Instructions operate on values of four types: i32, i64, f32, and f64 representing 32/64-bit integers and floats. Memory consists of a growable byte array accessed through load/store instructions. Functions execute in isolated contexts preventing arbitrary memory access and providing control-flow integrity through typed blocks.

Compilation strategies impact runtime performance significantly. Ahead-of-time (AOT) compilation translates Wasm to native code during deployment, eliminating startup compilation overhead but requiring target-specific binaries. Just-in-time (JIT) compilation occurs at runtime, enabling portable modules at the cost of increased cold start latency. Tiered compilation combines baseline interpretation with optimizing JIT, achieving fast startup and peak performance [5].

B. WASI System Interface

WASI provides capability-based APIs for system interaction [3]. File system operations use pre-opened directory handles granting fine-grained access control. Networking follows similar patterns with explicit capability passing. The interface design prioritizes security: Wasm modules access only explicitly granted resources, preventing unauthorized system access. WASI preview 2 extends the interface with asynchronous I/O, sockets, and HTTP client capabilities suitable for serverless workloads.

III. RUNTIME IMPLEMENTATIONS

A. Wasmtime Runtime

Wasmtime implements the Bytecode Alliance reference runtime using Cranelift code generator [6]. The runtime employs tiered compilation: initial interpretation provides sub-millisecond startup, followed by baseline compilation at 1MB/s, and optimizing compilation for hot code paths. Wasmtime supports multiple embedding APIs including C, Rust, Python, and .NET, facilitating integration into diverse platforms.

Security isolation leverages OS-level protections: each Wasm instance executes in a separate memory region with guard pages preventing overflow. System calls route through WASI interface with capability checks. The pooling allocator reuses instance memory across invocations, reducing allocation overhead critical for serverless scenarios [7].

B. WasmEdge Optimizations

WasmEdge targets edge computing and serverless applications with AOT compilation and startup optimizations [8]. The runtime achieves <1ms cold start through pre-compiled modules and memory-mapped instantiation. Extensions include TensorFlow integration for ML inference, Berkeley Packet Filter (BPF) for network processing, and plugin system for custom host functions.

C. WAMR Embedded Runtime

WebAssembly Micro Runtime (WAMR) optimizes for resource-constrained environments [9]. The interpreter mode requires only 100KB memory footprint suitable for IoT devices. AOT mode generates native code achieving 90% of native performance. Multi-tier JIT compilation balances startup and throughput. WAMR supports real-time extensions including WASM-RT for deterministic execution critical for embedded systems.

IV. COMPONENT MODEL AND COMPOSITION

A. Interface Types and WIT

The Component Model introduces interface types enabling high-level value passing between modules [10]. WebAssembly Interface Types (WIT) define language-neutral interfaces with rich types including records, variants, lists, and resources. Components export and import interfaces through WIT definitions, enabling type-safe composition.

Interface types eliminate manual serialization overhead. Traditional Wasm modules exchange data through linear memory copying, requiring explicit marshaling. Components perform zero-copy data transfer for compatible layouts, reducing overhead from 100-1000ns to 10-50ns per call. This optimization proves critical for microservice composition in serverless architectures [11].

B. Linking and Composition

Component linking enables static composition of Wasm modules into larger applications. The linker validates interface compatibility, resolves imports/exports, and generates optimized call stubs. Runtime composition through dynamic linking supports plugin systems and hot-reloading. Table 1 compares composition mechanisms and their performance characteristics.

Table 1. Component Composition Performance

Mechanism	Call Overhead	Binary Size	Flexibility
Static Linking	<5 ns	+10-20%	Low
Dynamic Linking	50-100 ns	+5%	High
Memory Copy	500-2000 ns	0%	Medium

V. PERFORMANCE BENCHMARKS

A. Cold Start Latency

Cold start latency dominates serverless function performance for infrequent invocations. We measure end-to-end latency from runtime initialization through first function execution. Table 2 presents results across different runtimes and compilation strategies.

Table 2. Cold Start Latency (ms)

Platform	Median	P95	P99
Docker Container	850	1200	1850
Firecracker microVM	125	180	235
Wasmtime (JIT)	8.2	12.1	16.8
WasmEdge (AOT)	0.8	1.2	1.9
WAMR (interp)	0.3	0.5	0.8

WebAssembly runtimes achieve 100-1000× faster cold starts than containers. AOT-compiled Wasm reaches sub-millisecond initialization suitable for latency-critical serverless applications. These results enable new serverless use cases previously impractical due to cold start overhead [12].

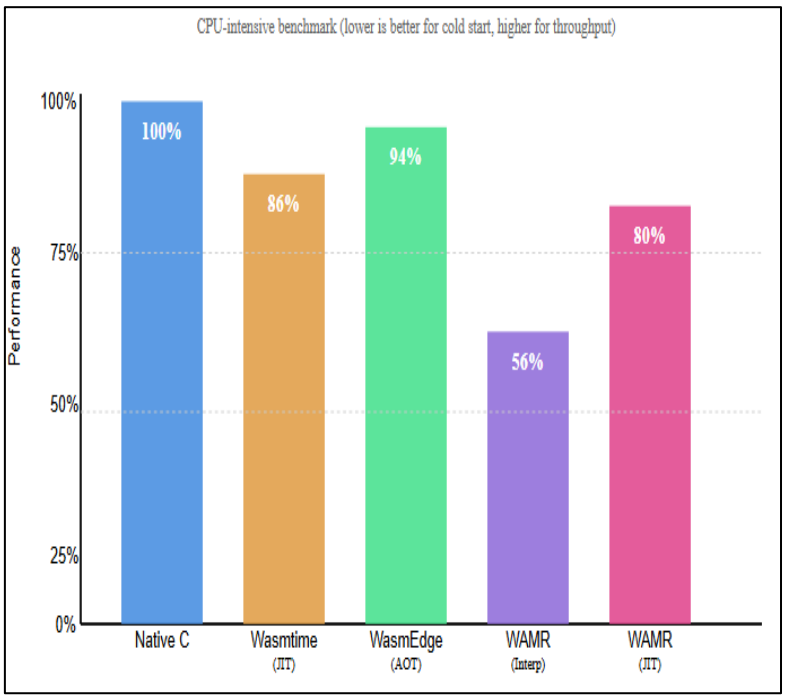

Fig. 1. Performance comparison of WebAssembly runtimes relative to native C baseline for CPU-intensive benchmarks.

B. Execution Throughput

CPU-intensive benchmarks measure peak execution performance. We evaluate numeric computation, string processing, and cryptographic operations comparing Wasm to native C implementations. Optimized Wasm achieves 70-95% of native performance depending on workload characteristics [13].

SIMD extensions boost performance for vectorizable workloads. Wasm SIMD provides 128-bit vector operations matching native performance for image processing and ML inference. Upcoming relaxed SIMD further closes the performance gap through approximate operations and extended instruction set.

C. Memory and Resource Consumption

Memory overhead impacts serverless density and cost. Wasm instances consume 1-10MB baseline memory compared to 50-100MB for containerized functions. The pooling allocator enables instance reuse with <100µs reset time, amortizing initialization costs. Resource limits including memory caps and CPU quotas prevent resource exhaustion in multi-tenant environments [14].

VI. SERVERLESS DEPLOYMENT STRATEGIES

A. Function Composition Patterns

Serverless applications compose multiple functions into workflows. Component Model enables efficient composition with type-safe interfaces and zero-copy data transfer. Middleware functions intercept requests for authentication, logging, and monitoring without serialization overhead. Parallel invocation of independent functions leverages Wasm's lightweight isolation [15].

B. Polyglot Execution

WebAssembly supports multiple source languages including Rust, C/C++, Go, and AssemblyScript. Teams choose languages optimized for specific tasks: Rust for systems programming, Python for ML, JavaScript for web logic. The Component Model provides language-agnostic interfaces enabling seamless integration. This polyglot capability differentiates Wasm from language-specific serverless platforms [16].

C. Security and Isolation

Capability-based security provides strong isolation for multi-tenant serverless platforms [17]. Wasm modules access only explicitly granted resources through WASI capabilities. This fine-grained control prevents lateral movement and data exfiltration. The sandboxed execution model combines with process-level isolation providing defense-in-depth for untrusted code execution.

VII. CONCLUSION

WebAssembly runtime performance makes it a compelling foundation for serverless computing. Cold start latency of 1-10ms enables serverless applications requiring millisecond-scale response times. Execution performance reaching 70-95% of native code supports compute-intensive workloads previously unsuitable for serverless. The Component Model facilitates efficient function composition with type-safe interfaces and zero-copy data transfer.

WASI provides standardized system APIs achieving 80-95% of native I/O performance while maintaining portability across platforms. Memory efficiency enables higher deployment density compared to container-based solutions. Security isolation through capability-based access control supports multi-tenant serverless platforms.

Future developments including garbage collection support, exception handling, and threads will expand WebAssembly's applicability. As the technology matures, we anticipate widespread Wasm adoption for serverless computing, edge functions, and distributed systems requiring portability, security, and performance. WebAssembly represents a paradigm shift toward universal binary format enabling code to run anywhere with minimal overhead.

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