



DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Bachelor's Thesis in Informatics

Evaluation of WebAssembly IoT Runtimes on a ESP32 Microcontroller

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I confirm that this bachelor's thesis in informatics is my own work and I have documented all sources and material used.

Munich, 16.03.2020

Lukas Heddendorp

Acknowledgments

Abstract

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1 Introduction

2 Background

2.1 Microcontrollers

Since this thesis is focused on the use of WebAssembly on microcontrollers, we would like to introduce the concept and limitations shortly. A microcontroller (**MCU** for microcontroller unit) is a small computer, meant to fulfill a very specific requirement without a complex operating system. They are designed for embedded applications from implantable medical devices to toys and very prominently in IoT devices. Devices will often have multiple microcontrollers, each responsible for a particular function. A car, for example, could include, amongst others, an MCU to control the mirror adjustments, one to handle fuel injection and another one for traction control.

Core elements of an MCU are the processor, memory, and I/O peripherals. The Processor (CPU) can be thought of as the brain of the MCU. It performs basic arithmetic, logic, and I/O operations. The memory is where any data is stored the processor needs to fulfill its tasks. Mainly there is program memory, which holds the MCUs instructions and Data memory, which servers as temporary storage while a program is executed. Lastly, the I/O peripherals are the controller's connection to the outside world; they allow the receiving and sending of information, such as receiving a signal from a switch and turning on a light in response.

2.1.1 ESP32

For this thesis, we want to specifically focus on the ESP32 system on a chip (SoC). A very popular low-cost, low power series of microcontrollers with integrated WiFi and Bluetooth. Developed by the Shanghai-based company Espressif Systems this successor to the ESP8266 offers a great platform for IoT and embedded projects[5]. Compared to the MCU described before, the ESP32 has the additional processing power and I/O options that make it a great platform for developing secure IoT devices. It gained popularity fast after being released in September of 2016.

The ESP32 systems family provides an excellent base for many IoT applications. There are multiple versions available from ones very well suited for hobbyists to ones usable for industrial manufactures. With a low price point and area footprint, they still provide significant performance and many operational features[10].

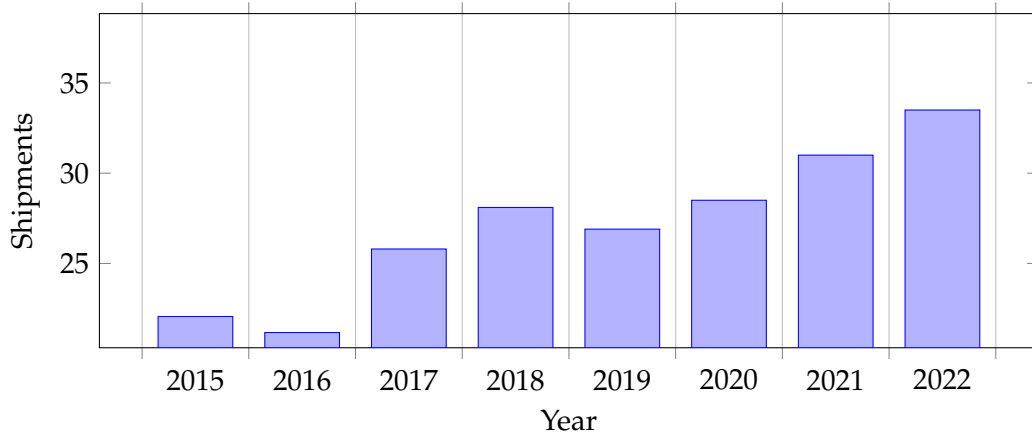


Figure 2.1: MCU shipments worldwide from 2015 to 2023 (in billions)

To reach price and power consumption targets, the ESP32 has significant hardware limitations. This introduces some constraints when working with the platform. The Operating system for example can hardly be called that. Compared to popular operating systems like windows and linux, the used FreeRTOS can be thought of as a thread library. This specialty will be further explained in the following passage.

2.1.2 FreeRTOS

Many MCUs are used in applications where throughput is less important than a guaranteed performance. This is why the ESP32 uses FreeRTOS, a real-time operating system (RTOS) is specifically intended to be used in time-critical situations. A key characteristic of such an operating system is the predictable behavior of the scheduler, the part of the operating system that decides which task should be run by the CPU at any given time. Most schedulers allow the user to set priorities for tasks in order to decide which task should be run next.

FreeRTOS specifically is the leading RTOS amongst MCUs and is designed to be small enough to run on a microcontroller[7]. Since most applications in which MCUs are used do not warrant the use of a full RTOS, FreeRTOS only provides the core scheduling functionality, timing, and synchronization primitives. It can, however, be extended by using add-on components, for example, to make use of a specific networking stack. FreeRTOS also built a significant community and support for many platforms in its 15-year development.

In more recent history amazon has taken over stewardship of FreeRTOS and also offers their own extension a:FreeRTOS[9]. This version additionally comes with some

direct integration into amazon's AWS service[8]. It is supposed to make the development of new IoT devices easier, especially when using amazon's platform for the server side processing, the core of FreeRTOS remains open source still.

2.2 WebAssembly

Beginning with static HTML pages, the web has since developed into a common application platform, accessible from many different devices running different operating systems. JavaScript is the only natively supported language on the web. However, even though it is universally used and made a lot of progression modern implementations, it still has some problems as a compilation target. WebAssembly addresses these issues and provides a compilation target for the web.

WebAssembly (WASM) was first announced in June 2015 and reached a cross-browser consensus in March 2017. Its goal was to provide near-native performance for browser-based applications, which could only be written in JavaScript for a long time. Since being published in March 2017, it is currently usable for about 90% of global internet users. More recently, the interest picked up around usage outside of the browser, which is also the primary concern of this thesis.

Being meant for the web, WASM has to achieve specific goals that give the platform new properties. It has to be safe since, on the web, code is loaded mainly from untrusted sources. It has to be fast as the primary motivation to introduce WebAssembly was to provide a compile target on the web with reliable performance. Other than the usual low-level code such as regular assembly, WebAssembly has to be portable and work in all the different circumstances the web is currently used. Lastly, because the code is transmitted over the network, it has to be as small as possible to reduce bandwidth and improve latency.

WASM is a low-level binary format, designed to be a portable target for high-level languages like C

C++ or Rust. It is executed on a stack-based virtual machine on which it executes in near-native speed due to its low-level design. Still, it runs in a memory-safe environment inside the browser and is subject to the same security policies as JavaScript code would be. WebAssembly modules are loaded with the application and provide bindings to JavaScript that make them usable in the browser.

Together with the binary format of WebAssembly, there is a text format that defines a programming language with syntax and structure. Every WASM binary is a self-contained module with functions, globals, tables, imports, and exports. This concept provides both encapsulation and sandboxing since modules can only interact with their environment using imports, and the client can only access the specified exports.

Inside the module, the code is organized in functions that can call each other even recursively.

2.2.1 WebAssembly for IoT

While WASM is developed for the web, it carefully avoids any dependencies on the web. It is meant to be an open standard that can be embedded in a variety of ways. The goals mentioned above, which WebAssembly achieves, make it an exciting format to explore on embedded devices. Due to its aim to be universal it would allow the use of languages on MCUs that were not previously supported and since it is already meant to be transmitted over the network, also over the air updates of code running on the controller are possible. To achieve portability, the source level interface libraries would have to map the host environments' capabilities either at build time or runtime.

While WebAssembly in an IoT context is a very promising concept it is also a brand new development. The best support for WASM right now is in the browser of course but out of browser runtimes keep surfacing, implemented in various languages and providing an interesting execution environment. Runtimes meant to be used on MCUs are much more rare and not as mature yet. Given the big interest in the idea though and the working groups avoidance of web dependencies it can be assumed that this situation will change in the future.

2.2.2 Interpreters

With our specific usecase in mind, the WASM3 engine was chosen since its specific goal is to run WebAssembly on MCUs. Other than many other engines it does not follow a just in time compilation pattern though, but instead acts as an interpreter. Thus we'd like to shortly introduce the concept and advantages.

Interpreters are computer programs that execute a program. They pose a different concept to compiled execution, where a program would be translated to machine code before being run directly on the CPU. While offering multiple advantages, the main drawback is the execution speed compared to native code execution, which is often slower by order of magnitude and sometimes more. The overhead is generated by the interpreter having to analyze the program code before it can be executed.

Interpreters thus offer benefits in development speed since the code does not have to be recompiled to run and in portability because the same code could be run on multiple platform-specific interpreters without the need to compile it into the native machine code of multiple platforms. For our use-case, the interpreter executes WASM instructions, allowing the dynamic loading of modules and running them in the chosen environment.

2.3 Microbenchmarking

Benchmarking is any form of measurement to qualify the behavior of a system. The most obvious examples would be measuring performance, energy or memory consumption, but also reliability and temperature stability could contribute to a benchmark. Building good benchmarks is hard, because a program has to be created that yields repeatable and consistent results. A major effort in the world of microcontroller benchmarking is the EEMBC.

The embedded microprocessor benchmark consortium is an industry association that has been designing benchmarks for over 20 years. The consortium offers multiple benchmarks, all meant to cover specific usecases of embedded controllers from ultra-low power IoT applications, over processor performance measurements to a recent benchmark designed to assess machine learning performance.

3 Methodology

3.1 Running WebAssembly

The goal of this thesis is to evaluate the use of WebAssembly for programming an ESP 32 Microcontroller. After we have introduced the concepts around MCUs and WebAssembly, we would like to explain our approach of evaluation WebAssembly.

Firstly, as explained earlier, WebAssembly always needs a runtime, which is usually provided by the browser. In this case, we do not need all the features a browser would provide, just a way to execute WASM. Since the momentum around running WASM outside of a browser environment is picking up recently, more and more runtimes become available. A big push for WebAssembly on new platforms came in November of 2019 in the form of the Bytecode Alliance [2]. An open-source community dedicated to creating the foundations needed to run WASM on multiple platforms in a secure way.

The Bytecode Alliance maintains a couple of different compilers and runtimes for WebAssembly. This project includes the WebAssembly Micro Runtime (WAMR), which is an interpreter based runtime, specifically meant to run on embedded devices such as the ESP32 [3]. While looking at this project, we had to find out that the OS used by the ESP32 (FreeRTOS) was not yet supported, with no current plans to change that.

While a couple of other WebAssembly runtimes are available, [1] WAMR used to be the only one capable of running on an embedded device. In late 2019 the second runtime for embedded devices was released in WASM3 [12]. This runtime is the first one we know of to support the ESP32 and FreeRTOS. It also performs significantly better than WAMR in benchmarks [11]. Thus we decided that using WASM3 was the way to go about running WASM on the ESP32.

According to the developers' measurements, WASM3 is currently the fastest available WebAssembly interpreter, being about 4x slower than current just in time compiling runtimes and about 12x slower than native execution. Because of the strict constraints that embedded devices have, WASM3 uses an interpreter model, which is more memory efficient and provides better startup times than JIT compilation. It also makes portability and security much easier to achieve and maintain.

3.2 Comparing the platform

After finding a way to run WebAssembly on the ESP32 and verifying it with basic tests, we had to find a way to measure how well that works. In order to compare different platforms, a popular tool is benchmarking, in which the same workload is run on multiple platforms to generate values to compare those platforms by.

While most benchmarks are meant to provide a comparison of two hardware platforms, in this specific case, we are not interested in the performance of the platform. Instead, we are interested in the performance of different execution models on the same platform, being the default native execution of code explicitly compiled for the ESP32 and the interpreted execution of the WASM code that could run anywhere.

Our desired comparison makes the test setup quite simple, the basic idea is to run the same code on the ESP32 twice, but once compiled to WASM. This approach has worked for the most part, with small detours being made when testing the import of outside functions into WebAssembly. All tests consist of a run method, which is once called from the main file and once loaded into the engine and run as a WASM function.

In line with how benchmarks work, we set out to design a couple of workloads we could run in both the native and the WebAssembly environments and compare the way they execute. In order to generate meaningful results, we tried to find simple tests that are not too far from what an MCU would execute. Keeping the tests limited and simple also allows us to look at the WASM output and understand a little more about the new concepts introduced.

3.2.1 Specialized Workloads

The first and most basic test is recursively calculating a Fibonacci number, while extensive recursive calls are not a part of most applications, functions calls in general are. This also shows some WebAssembly specific features since it does not only have jumps available but allows functions and function calls in the assembler code.

Secondly, switch and if statements are an integral part of any application. So comparing the performance of a switch statement is another indicator of how good applications would perform.

Of course, every application needs memory access, so we decided to implement two memory tests. One using linear access and one using random access to see if there is any impact on performance. Combining memory access and calculation, we also ran a matrix multiplication. This algorithm is the basis for many more complex algorithms, and the tight inner loop offers itself for optimization on the hardware and during compilation.

Lastly, it is essential for embedded devices to also have hardware access. Currently,

WebAssembly does not have a model of specific hardware features, network stack, or even CPU cores. All this functionality is assumed to be in the browser environment. The runtime we selected offers a mechanic to link external functions that can then be called from the WASM code, so we designed tests to see if outside calls came with a significant overhead that would impact applications using them.

3.3 Running tests

All tests were run on the ESP-WROOM-32 using the IDF provided by espressif. The same code was compiled to WebAssembly and also imported into the test program to allow for native execution. Then the test code was run multiple times to spot inconsistencies between the runs. The results from these tests will be explained in more detail in a specific section for each test.

3.3.1 Testing setup

All tests share a very similar main program to execute and time the tests, which we would like to explain now.

Listing 3.1: Main testing method

```
1 extern "C" void app_main(void) {
2     // Variable initialization
3
4     setup_wasm();
5
6     for (long long &wasm_time : wasm_times) {
7         int64_t start_time = esp_timer_get_time();
8         for (int j = 0; j < 10; ++j) {
9             run_wasm("20");
10        }
11        int64_t end_time = esp_timer_get_time();
12        wasm_time = (end_time - start_time) / 10;
13    }
14
15    for (long long &native_time : native_times) {
16        int64_t start_time = esp_timer_get_time();
17        for (int j = 0; j < 10; ++j) {
18            long value = run(20);
19        }
```



```

20     int64_t end_time = esp_timer_get_time();
21     native_time = (end_time - start_time) / 10;
22 }
23
24     printf("|Run|WASM|NATIVE|\n|---|---|---|\n");
25     for (int i = 0; i < sizeof(wasm_times) / sizeof(wasm_times[0]); ++i) {
26         printf("|%d|%lld|%lld|\n", i + 1, wasm_times[i], native_times[i]);
27     }
28     sleep(100);
29     printf("Restarting...\n\n\n");
30     esp_restart();
31 }

```

The main testing method starts with setting up the WebAssembly runtime, which will be further explained with Listing 3.2. This process is timed to see how much overhead the runtime initialization introduces. Next, there are two arrays set up to hold the test results. Then the test is run for the WASM with the function described in listing 3.3, by taking the average time over ten runs and saving that into the previously declared array. Following, the same is done for the native version of the test code. Lastly, the results are printed to the console, and the controller is eventually restarted to rerun the tests.

Listing 3.2: Runtime setup

```

1  IM3Environment env;
2  IM3Runtime runtime;
3  IM3Module module;
4  IM3Function f;
5
6  static void setup_wasm() {
7      M3Result result = m3Err_none;
8
9      auto *wasm = (uint8_t *) wasm_test_cpp_wasm;
10     uint32_t fsize = wasm_test_cpp_wasm_len - 1;
11
12     env = m3_NewEnvironment(); // Error output omitted
13
14     runtime = m3_NewRuntime(env, 2048, NULL);
15
16     result = m3_ParseModule(env, &module, wasm, fsize);
17
18     result = m3_LoadModule(runtime, module);

```

```
19
20     result = LinkThesis(runtime);
21
22     result = m3_FindFunction(&f, runtime, "run");
23 }
24 }
```

Setting up the runtime is pretty straight forward, initially, the WASM module is imported from a header file, together with its length. Then the environment and runtime are created, followed by parsing the module. If the runtime has to provide functions that the WASM module relies upon, they are linked after loading the module. An example can be found in section 3.3.6 in which lines 24 and 25 of listing 3.2 are not commented out. Once the runtime is fully set up, the function itself is searched for. In our case, the functions name is always "run".

Listing 3.3: WASM execution

```
1 static void run_wasm(const char *input1) {
2     M3Result result = m3Err_none;
3
4     const char *i_argv[3] = {input1, NULL};
5     result = m3_CallWithArgs(f, 1, i_argv);
6
7     if (result) FATAL("m3_CallWithArgs: %s", result);
8
9     long value = *(uint64_t *) (runtime->stack);
10 }
```

The execution of the WASM function is a matter of calling the previously found function with the runtimes `m3_CallWithArgs()` method and supplying it with the input arguments. The return value of the operation can be found on the virtual machines stack afterward.

3.3.2 Testing matrix multiplication

To test performance during matrix multiplication, then function takes one argument, the matrix size. It then creates two $n \times n$ matrices and multiplies them. In the end, it returns one value of the resulting matrix. This is to prevent the compiler from deleting the actual calculation during compilation.

Listing 3.4: Matrix multiply test

```
1 uint32_t run(uint32_t n) {
```

```
2     uint32_t a[n][n], b[n][n], mul[n][n];
3
4     for (uint32_t i = 0; i < sizeof(a) / sizeof(a[0]); ++i) {
5         for (uint32_t j = 0; j < sizeof(a[0]) / sizeof(a[0][0]); ++j) {
6             a[i][j]=i+1;
7             b[i][j]=i+2;
8         }
9     }
10
11    for (uint32_t i = 0; i < sizeof(a) / sizeof(a[0]); ++i) {
12        for (uint32_t j = 0; j < sizeof(a[0]) / sizeof(a[0][0]); ++j) {
13            mul[i][j] = 0;
14            for (uint32_t k = 0; k < sizeof(a[0]) / sizeof(a[0][0]); ++k) {
15                mul[i][j] += a[i][k] * b[k][j];
16            }
17        }
18    }
19    return mul[n-1][n-1];
20 }
```

Running this function in the main program described in section 3.3.1 results in the following measurements for the average execution times of 100 runs.

3.3.3 Testing memory performance

Of course the memory performance is an important aspect of any computing platform so we designed a test to compare it between native and WASM execution.

Listing 3.5: Linear memory test

```
1 uint32_t run(uint32_t n) {
2     uint32_t array1[n];
3
4     for (int i = 0; i < n; ++i) {
5         array1[i] = i+1;
6     }
7     array1[n-1] = 0;
8     uint32_t nextStep = 1;
9     while(nextStep){
10         nextStep = array1[nextStep];
11     }
```

```
12     return nextStep;
13 }
```

The setup is fairly simple, an array is created and filled with the indices of the respective following elements, imitating a linked list. Then it is read from, starting at index 1 and saving whatever index was found there into a variable that defines the next index to be read until finally the next index ends up being 0. Lastly the next index is returned to prevent compiler optimization.

3.3.4 Testing recursive calls

The test of recursive calls is run by calculating Fibonacci numbers with the following code.

Listing 3.6: Recursive calling test

```
1 uint32_t run(uint32_t n) {
2     if (n < 2) {
3         return n;
4     }
5     return run(n - 1) + run(n - 2);
6 }
```

Listing 3.7: WASM code excerpt

```
1 (module
2   (type $t1 (func (param i32) (result i32)))
3   (func $run (export "run") (type $t1) (param $p0 i32) (result i32)
4     (block $B0
5       (br_if $B0
6         (i32.lt_u
7           (local.get $p0)
8           (i32.const 2)))
9       (return
10        (i32.add
11          (call $run
12            (i32.add
13              (local.get $p0)
14              (i32.const -1)))
15          (call $run
16            (i32.add
17              (local.get $p0)
```

```
18         (i32.const -2))))))
19     (local.get $p0)))
```

Listing 3.7 shows the WebAssembly text format generated for the Fibonacci function in listing 3.6 and we would like to take a closer look at what the WASM module looks like for this specific example. After the module opening, the type of our `uint32_t run(uint32_t n)` function is defined and reused in the function definition in line 3, in this line the functions input and return types are also defined. The input is assigned to the `$p0` variable for later use. In line 4 the block `$B0` is started, it contains the main function body. In line 5, we can see a `br_if` instruction; this is a conditional break that breaks the execution of the passed block if the condition is true. The condition, in this case, is the rest of the instructions included in the parentheses. Namely the comparison of the accepted parameter with 2 to see if it is smaller if that is the case the remaining block is skipped and code execution would continue in line 19 where the parameter is pushed on the stack, as the topmost value of the stack after the execution is the return value of a WASM function. Alternatively, the execution could continue in line 9 with the `return` instruction, which executes the instructions inside the parentheses and prevents any further code execution after that, mirroring the common `return` instruction in C. the Value `return` is the result of the two recursive calls of line 5 in the C listing. The `run` function is called again by using the `call` instruction in lines 11 and 15.

It is important to note that this text format is not strictly WebAssembly, but one version to make it readable for humans. To make it more similar to the look of common programming languages for this listing, code folding was applied. To make the difference visible, listing 3.8 shows the WASM code without folding.

Listing 3.8: WASM code without folding

```
1  (func $run (export "run") (type $t1) (param $p0 i32) (result i32)
2    block $B0
3      local.get $p0
4      i32.const 2
5      i32.lt_u
6      br_if $B0
7      local.get $p0
8      i32.const -1
9      i32.add
10     call $run
11     local.get $p0
12     i32.const -2
13     i32.add
```

```
14     call $run
15     i32.add
16     return
17 end
18 local.get $p0)
```

3.3.5 Testing switch statements

As previously motivated, switch statements are a very common occurrence in software running on microcontrollers and thus a thing to be tested. The test method for this is a big switch statement that is looped over. The result of this is secondary and just included to guarantee compilation.

3.3.6 Testing native calls

A very important function of the runtime is to expose outside functions to the WASM module and allow the interaction with other libraries from within the WASM code. For this we designed two fairly simple tests that call functions not defined in the WASM code.

Listing 3.9: Outside call test code

```
1 #include "test_api.h"
2
3 WASM_EXPORT
4 void run(uint32_t n) {
5     mark();
6 }
```

As is obvious from listing 3.9, the test code just calls the outside `mark()` function. There is also an import of the test api header in which the external function is defined to make the testcode compile.

Listing 3.10: Test api definition

```
1 #ifndef WASM3_TEST_API_H
2 #define WASM3_TEST_API_H
3
4 #include <stdint.h>
5
6 #define WASM_EXPORT extern "C" __attribute__((used)) __attribute__((visibility ("default")))
7 #define WASM_EXPORT_AS(NAME) WASM_EXPORT __attribute__((export_name(NAME)))
```

```

8 #define WASM_IMPORT(MODULE, NAME) __attribute__((import_module(MODULE))) __attribute__((im
9
10 extern "C" {
11
12 WASM_IMPORT("thesis", "sendValue") uint32_t sendValue (void);
13 WASM_IMPORT("thesis", "mark") void mark (void);
14
15 }
16
17 #endif //WASM3_TEST_API_H

```

The resulting WASM code does not include the mark method but instead imports it from the thesis module that is expected to be available at runtime.

Listing 3.11: WASM code for the outside call

```

1 (module
2   (type $t0 (func))
3   (type $t1 (func (param i32)))
4   (import "thesis" "mark" (func $thesis.mark (type $t0)))
5   (func $run (export "run") (type $t1) (param $p0 i32)
6     (call $thesis.mark)))

```

As displayed in listing 3.11 line 4 the mark function from the thesis module is imported as defined in listing 3.10. The run function then just calls the imported function in line 6.

In order to provide this imported function at runtime the setup for our tests has to be changed slightly, namely it has to be linked during the runtime setup in listing 3.2.

Listing 3.12: Function linking

```

1 int64_t native_timestamp;
2
3 m3ApiRawFunction(m3_thesis_mark) {
4   native_timestamp = esp_timer_get_time();
5   m3ApiSuccess();
6 }
7
8 M3Result LinkThesis(IM3Runtime runtime) {
9   IM3Module module = runtime->modules;
10   const char *thesis = "thesis";
11
12   m3_LinkRawFunction(module, thesis, "mark", "i()", &m3_thesis_mark);

```

```
13     return m3Err_none;
14 }
15
16 void mark() {
17     native_timestamp = esp_timer_get_time();
18 }
```

In listing 3.12 line 1 we introduce a variable to hold a timestamp after the mark function was called. In line 3 we define the function, which just saves the current timestamp and ends with success. This is then linked into the runtime in line 12. To compare native execution this time we can not call the exact same function, since it was not compiled to WASM at all, so we implement a similar function in line 16 that is called during the test of native execution.

4 Evaluation

4.1 Running benchmarks

In order to collect results we ran all the tests described in the previous section on an ESP32 and gathered the timings here. As expected, running the code in a interpreter produces a significant slowdown. We want to analyze the the different test results and their impact of the usefulness of WASM on MCUs.

4.2 Benchmark results

Similar to the tests, we want to look at the results by the functional requirement they describe.

4.2.1 Recursive calls

Calling functions is an integral capabnlty of any application, so this is the first test to compare WASM with the native execution of our code.

As is obvious from the measured times the variance is very low here, this is to be expected since the tests ran without any other load on the MCU and the dterministic nature of FreeRTOS as mentioned in section 2.1.2.

Run	WASM Execution	Native Exectuion
10	41766	1000
11	41767	1000
12	41766	1000
13	41767	1000
14	41766	1000
15	41767	1000
16	41766	1000
17	41766	1000

Table 4.1: Exerpt of the measured times for recursive calls

Run	WASM exection	native exection
1	26283	285
2	26277	281
3	26277	282
4	26277	281
5	26277	281
6	26277	282

Table 4.2: Exerpt of the measured times for matrix multiplication

Even though the actual applicatins running on an MCU might not do recursive calculations it does provide an insight into the overhead vreated by executing function calls in the interpreter. This overhead causes a slowdown of about 41x which is consinistent through ultiple tests with other numbers to calculate.

As seen in the WASM code of listing 3.7 it's actually very simple but requires the runtime to manage the execution of the same functions many times over.

4.2.2 Swicth statements

TODO: FIX SWITCH TEST BEFORE WRITING

4.2.3 Memory access

TODO: REIMPLEMENT SHUFFLE

4.2.4 Matrix multiplication

TODO: UPDATE MATRIX CODE TO NOT USE SIZEOF() As is evident from the measurements, the interpreter introduces a 90x slowdown of the WASM execution compared to the native one.

4.2.5 Calling of native code

Of course not all functionality can be included in the WASM module, especially native platform features will have to make use of cuntions only avialiable outside of the engine.

Run	WASM Execution	Native Exectuion
15	33	7
16	33	8
17	33	7
18	32	8
19	33	8
20	32	8
21	33	8
22	32	7
23	33	8
24	32	7
25	33	8

Table 4.3: Exerpt of the measured times for external calls

4.3 Learnings

4.3.1 Drawbacks of WASM execution

The very obvious drawback of executing WebAssembly on a microcontroller is the performance loss that comes with it. We have shown this with all our tests and even though the slowdown varies from test to test, code compiled to WASM and executed by an interpreter will run an order of magnitude slower than the same code directly compiled into the main program and executed on the MCUs CPU.

Next to the perforamnce decrease the longer runtime also means that more energy will be used to achieve the same result. Using about 40x more power for one task is an important consideration for applications with MCUs running on a battery insteads of having a stable power connection. For reference, enabling WiFi on the ESP32 can increase power consumption by up to six times compared to regular usage[6].

Apart from impact on the running of program code on the MCU we also noticed other limitataions. The availability of certain expected functionality in WASM is very limited. For example, the use of `malloc()` is not possible if comoilng code to WASM and running it in our runtime. In webbrowsers this functionality is avaliable for import from the environment and implemented such that it can be used as expected. WASM3 however does not offer any functions for import and implementing dynaic memory management would be a major effort.

Since the problem of system access outside the beowser is very common, a subgroup of the WASM community group is working on specifying a system interface for WASM[4]. The WebAssembly system interface (WASI) is meant to provide a foundation

for developers to build upon when targeting non-browser platforms. Once specified, code compiled for WASI will run in any WASI-compliant runtime, truly enabling WASMs portability.

4.3.2 Usecases for WASM on ESP32

From our tests we can see that WASM comes with major downsides right now, that is slower execution across the bench of any kind of task. This does not mean however that it's unusable in an embedded context, but that its usage should be carefully evaluated. If the MCU is continually working and collecting data for example it might not be a good fit, since the use of WASM would limit the efficiency of the MCU.

From what we saw in our tests, we think that WASM is an option to be considered especially for projects that only need short program to be run in longer intervals. Here the disadvantages of lower performance and higher execution time do not have much of an impact. One example for such an application is a sensor monitoring the rooms temperature and possibly taking action such as adjusting the heating. In this scenario the longer execution time would not pose any issue since the reaction is not affected by a small delay.

5 Conclusion

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