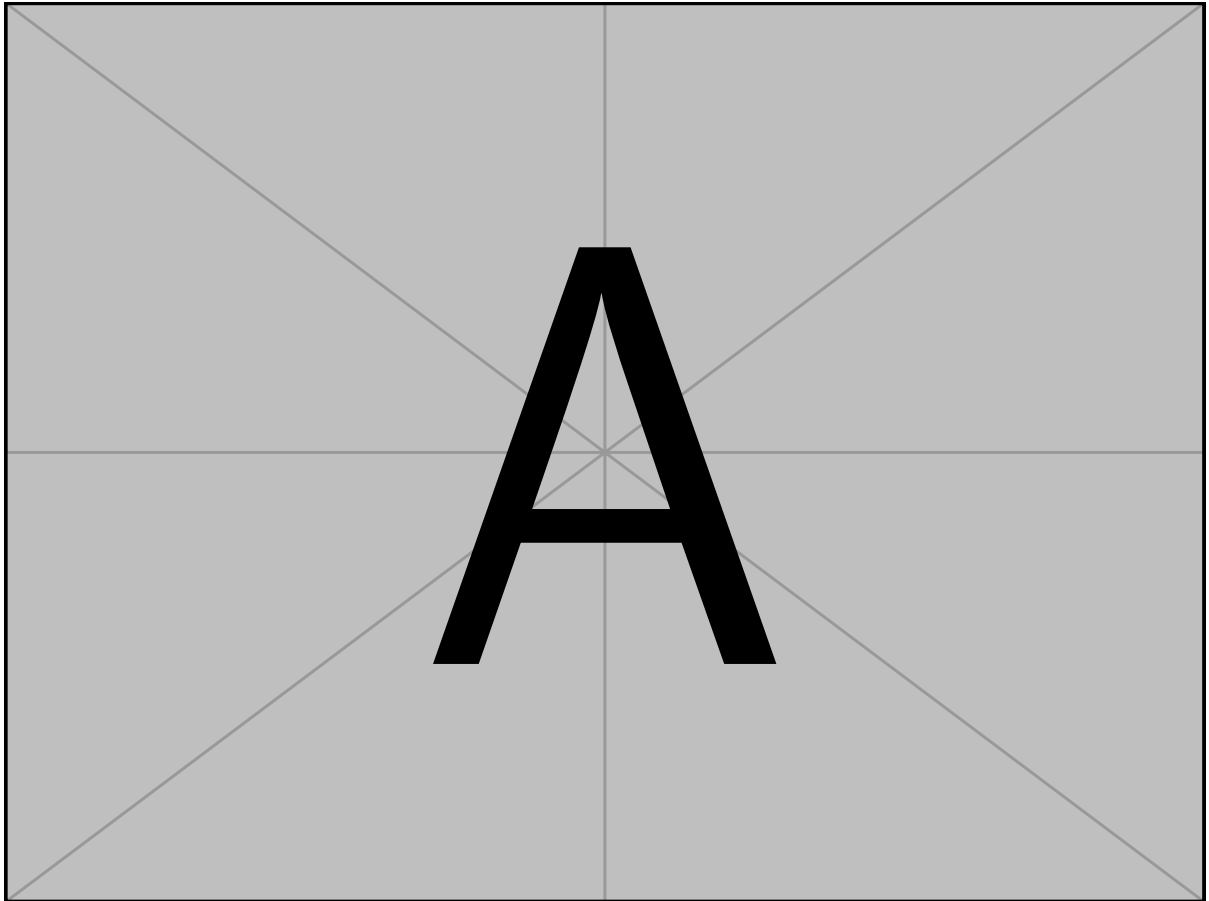

Embedded IoT for Eclipse Arrowhead



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*To my dad Bengt-Göran Martinsson a special thanks for proof reading is required.
A special thank to my little sister Hedvig Martinsson for drawing the cover image is also required.*

ABSTRACT

This thesis will investigate the possibility of connecting an embedded device, STM32 B-L4S5I-IOT01A IoT discovery node, to a local Eclipse Arrowhead framework cloud. This thesis will also compare the benefits and limitations of using the Eclipse Arrowhead framework to commercially available solutions such as Amazon's Amazon Web Services and Microsoft Azure.

The world is on the verge of a new industrial revolution, often referred to as Industry 4.0, moving towards a more decentralized and software-oriented means of production. Incorporating System of Systems, Cyber-Physical Systems, and embedded software technologies will form the backbone and be an inherent part of every value chain.

The Eclipse Arrowhead framework contains many examples in various languages and technologies but lacks an example of a specific piece of hardware connecting to a local Eclipse Arrowhead cloud. Therefore, a project with the clear intent to showcase both the capabilities and possibilities of Cyber-Physical systems and the Eclipse Arrowhead framework is needed.

The system consists of three major parts: the stm32 board, a Python flask app, and the Eclipse Arrowhead framework. The main objective of the Eclipse Arrowhead framework is to connect the consumer and the provider in a safe and structured way. The provider is built with C/C++ using ARM's mbed os.

The response time of the different frameworks, Eclipse Arrowhead framework and Amazon Web Services, was measured. We made a thousand attempts to form an adequate basis for an average response time. In addition to presenting the average response time, we will calculate the maximum and minimum response times to understand the different frameworks' performance further.

The thesis also examined the benefits of using the Eclipse Arrowhead framework compared to its competitors Amazon Web Services and Microsoft Azure. The thesis showed some benefits in terms of response time when running a local cloud instead of using a remote service such as Amazon Web Services, a 17.5 decrease in average response time was recorded. Maximum and minimum response times decreased by 1.9 and 134 times, respectively.

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CHAPTER 1

Introduction

This thesis will examine the opportunity and possibility to connect an embedded IoT device to a local Eclipse Arrowhead framework cloud. This project will use the STM32 B-L4S5I-IOT01A IoT discovery node as a development board, running the Mbed-OS 6.

1.1 Background

According to Artemis-IA, the world is on the verge of a new industrial revolution, moving towards a more decentralized and software-oriented means of production.[1] This fourth new, and in some sense planned, industrial revolution is called Industry 4.0 according to Lasi.[2] Cyber-Physical systems act as a bridge between the data-rich cybernetic world and the technology-rich physical world Artemis-IA means. Artemis-IA adds that a differentiating factor between traditional embedded systems and Cyber-Physical systems is their scale, where traditional embedded systems have a more limited scale. Cyber-Physical system, on the other hand, has a much larger scale, including interconnected embedded systems, human-, and socio-technological systems as well Artemis-IA adds.[1]

For Europe to compete with the rest of the world's larger economies with initiatives, for instance, China's Made in China 2025, Europe needs to invest in the technologies mentioned above Artemis-IA adds. A shift away from proprietary solutions towards collaborative solutions is also needed means Artemis-IA in their report Embedded intelligence.[1]

1.2 Motivation

The need for a European incentive promoting Industry 4.0 is clear. According to their website, the Arrowhead Tools project aims for digitalization and automation solutions for the European industries.[3] The Arrowhead Tools project uses the open-source Eclipse Arrowhead framework, further contributing to the collaborative solutions needed for the European economy defined in the previous section.

The Eclipse Arrowhead framework contains many examples in various languages and

technologies, mainly java. Python, C#, and C++ have client libraries and example code developed for them, which you can find on the project's GitHub page.[4]

However, there is no client library or code example for a specific piece of hardware to connect to a local Arrowhead cloud fast and easy, showcasing the capabilities of this project. Therefore, a project with the clear intent to showcase both the capabilities and possibilities of Cyber-Physical systems and the Eclipse Arrowhead framework is needed.

This thesis will examine the possibilities of having a ready-made example to compile and run on a specific hardware platform that connects a local Arrowhead cloud as a proof of concept. Much like the 'Getting started with' examples from Amazon Web Services and Microsoft Azure.[5, 6]

1.3 Problem definition

This project aims to investigate the possibilities, benefits, and limitations of using the Eclipse Arrowhead framework on embedded devices in contrast to commercially available solutions such as Amazon's Amazon Web Services and Microsoft Azure.

1.4 Equality and ethics

The ability to own and control your data is becoming rarer and rarer these days, with giant corporations establishing their cloud services. As a consumer, one always takes a risk when pushing sensitive data to a cloud owned by someone else. Corporations should not infringe the right to possess your data. The Eclipse Arrowhead framework and the use of local clouds move the storage of your data from giant corporations to your own.

1.5 Sustainability

The use of small embedded devices instead of monolithic machines today provides a much-needed decrease in energy consumption for more immense industries. On a greater scale, the use of IoT devices would also enable preventive maintenance of components, reducing both the cost and materials required for maintenance later on.

1.6 Delimitations

1.6.1 Security

This thesis does not cover a solution to the numerous security risks and issues associated with IoT devices.

1.6.2 Core systems

This thesis will also only cover the three core systems of the Eclipse Arrowhead framework, which are the service registry, authorization, and orchestrator. The STM32 B-L4S5I-IOT01A IoT discovery node will not host the Arrowhead framework on the board itself since the Arrowhead framework is too resource-heavy for such a small device. Instead, the board will connect to a local Arrowhead cloud hosted by another computer in the same network.

1.6.3 Intercloud connection

It will also only cover connection within the same local Arrowhead cloud, intracloud, instead of using multiple clouds, intercloud. Intercloud connection requires two more Arrowhead systems, gateway and gatekeeper, to operate and the configuration of those systems is beyond the scope of this thesis.

1.7 Thesis structure

Chapter 2 presents related work and conducts a literature review of IoT, Industry 4.0, security, and the Eclipse Arrowhead framework. Chapter 3 covers theory, describing what technologies and scientific methods this thesis uses. Chapter 4 covers implementation, describing the design of different systems used in this thesis from a software engineering perspective. Chapter 5 presents an evaluation of the experiment conducted. Chapter 6 contains a discussion about the solution to the problem stated in chapter 1, possible alternative solutions, and how the results affect the industry. Chapter 7 presents the conclusion of the work done in this thesis. The chapter also describes how to investigate further the questions raised in this thesis. In chapter 8, there is a list of references used in this thesis.

CHAPTER 2

Related work

2.1 Internet of things

Cluster of European research projects regarding the Internet of Things:

'Things' are active participants in business, information and social processes where they are enabled to interact and communicate among themselves and with the environment by exchanging data and information sensed about the environment while reacting autonomously to real/physical world events and influencing it by running processes that trigger actions and create services with or without direct human intervention.[7]

Gubbi et al. define the Internet of Things as:

Interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications. Achieved by seamless large scale sensing, data analytics, and information representation using cutting edge ubiquitous sensing and cloud computing.[7]

2.2 Industry 4.0

Lasi argues that the term industry 4.0 was coined beforehand as a planned fourth industrial revolution.[2] The use of internet of things devices, IoT devices from now on, and cyber-physical systems, CPS from now on is what defines the fourth industrial revolution Vaidya means.[8] See figure x for a short historic overview of previous industrial revolutions.

According to Vaidya, industry 4.0 promotes connecting sensors and devices to the internet and other sensors or devices.[8]

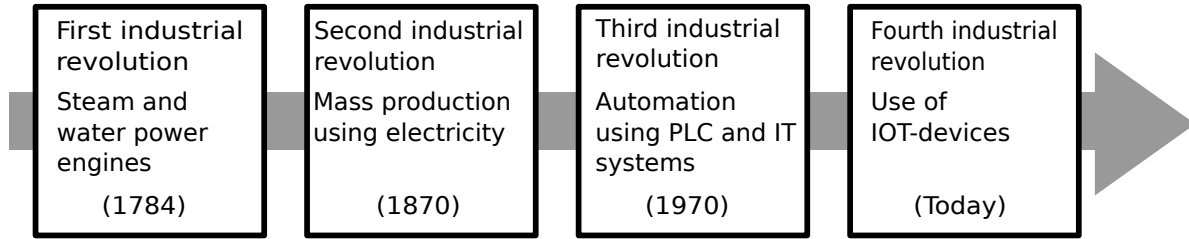


Figure 2.1: Historic overview of previous industrial revolutions

Hozdić states that a sensor is a device capable of providing an appropriate output in response to a measured value. One key feature of an intelligent sensor is that it increases information processing, and it processes the information at a logical level, Hozdić argues. An Intelligent sensor is capable of executing actions based on the measured value in contrast to regular sensors, making them easier to set up and use means Hozdić.[9]

Hozdić defines a cyber-physical system, CPS, as a new generation of a system that integrates physical and computer abilities. A cyber-physical system consists of two parts, one cybernetic and one physical. The cybernetic aspect of the system is a summation of logic and sensor units. In contrast, the physical part of the system is the summation of the actuator units, Hozdić adds. Xu et al. state that cyber-physical systems are a vital part of Industry 4.0. In contrast to the simple embedded systems of today will be exceeded due to advances in CPS that enable enhanced capability, scalability, adaptability, resiliency, safety, usability, and security.[10] Hozdić argues that the CPS can share and receive information from intelligent sensors connected to digital networks, enabling and forming an internet of things.[9]

2.3 Arrowhead framework

Delsing defines a local cloud as a self-contained network with at least the three mandatory systems deployed, more on those in a later paragraph. Delsing et al. also argue that the three mandatory core systems running a local cloud also need at least one application system deployed.[11]

To further understand what the Eclipse Arrowhead framework aims to accomplish, introducing the terms services and systems is necessary. Delsing et al. define a system as providing or consuming a service. Furthermore, Delsing et al. define a service as conveying information between a provider and a consumer.[11]

The Eclipse Arrowhead framework, Arrowhead from now on, consists of three mandatory core systems according to Delsing et. al. To fully operate a local cloud as defined in the previous section it must, according to Delsing, contain:

- Service registry system.

- Authorization system.
- Orchestration system.[11]

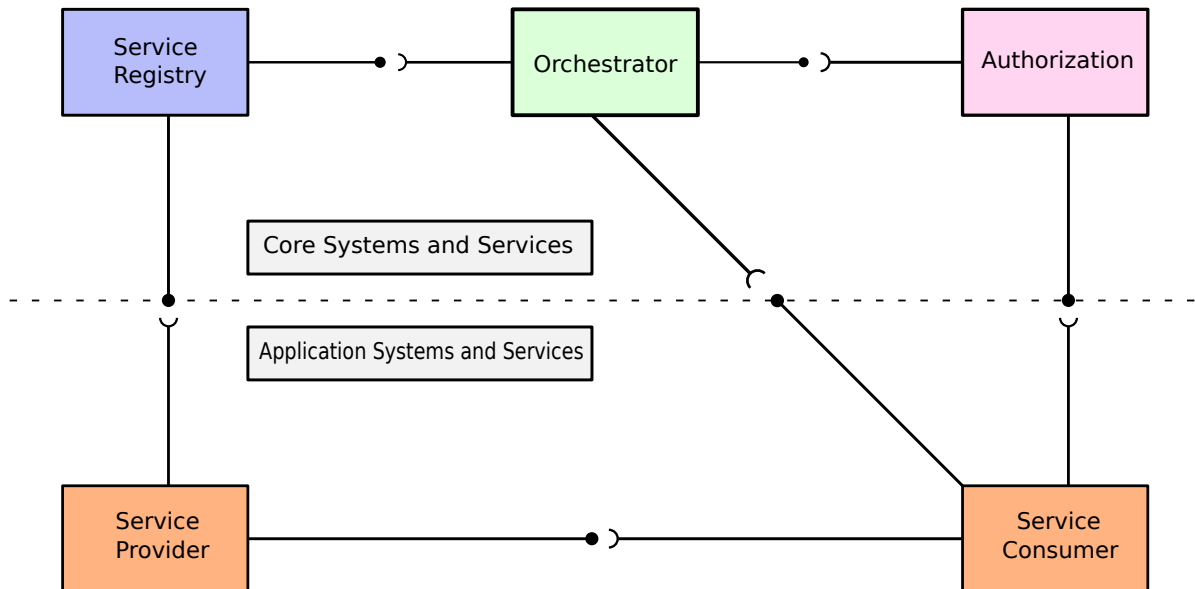


Figure 2.2: The core systems of the Eclipse Arrowhead framework

The dynamics between the consumer and provider system will follow in the theory section.

2.4 Amazon Web Services

According to the Amazon webpage, the AWS IoT Core connectivity services consist of the device gateway, message broker, and rules engine.

The device gateway enables devices to securely, via X.509 certificates, and efficiently communicate with AWS IoT Amazon.

Amazon states that the message broker provides a secure way for devices and AWS IoT applications to publish or receive, subscribe as known in MQTT, messages from each other. The message broker also distributes device data to devices that have subscribed to it and to other AWS IoT Core services, such as the rules engine Amazon adds.

The Rules engine connects data from the message broker to other AWS services, such as Amazon Simple Storage Service (Amazon S3), Amazon DynamoDB, and AWS Lambda, according to Amazon.[12]

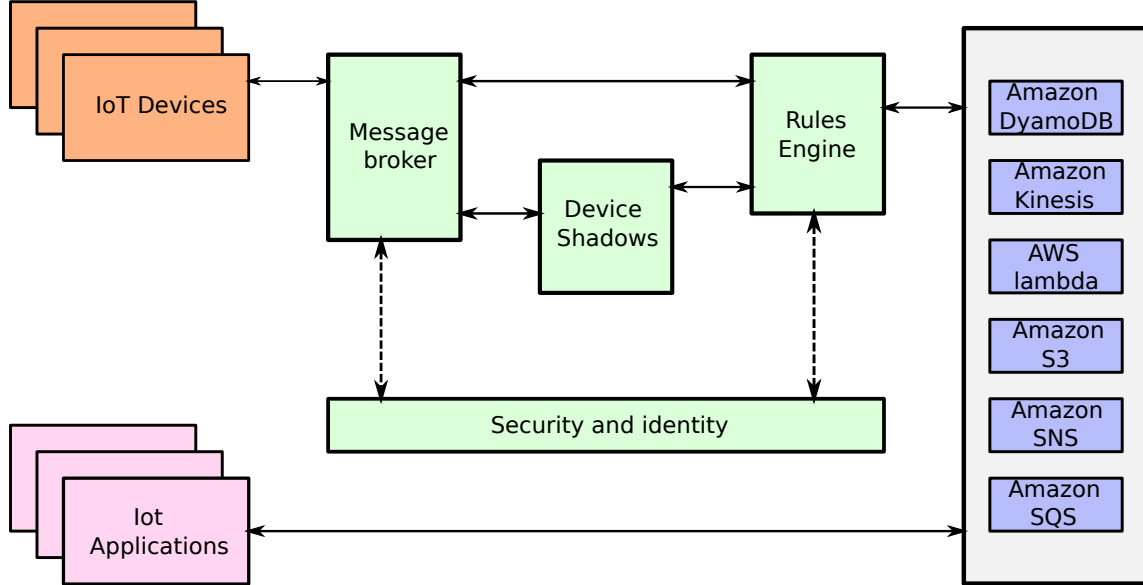


Figure 2.3: The core systems of the Amazon Web Services

2.5 Security

Meneghello et al. argue that the increasing number of IoT devices and the pervasive nature of new smart home or healthcare devices can pose a real threat to the users' integrity. Meneghello et al. define sensitive information as a video recording of the user's home, location, access to buildings, health monitoring, and industrial processes.[13]

Meneghello et al. divide the security requirements of an IoT system into three different operational levels: the information, access, and functional level. The information level should guarantee the preservation of the system's integrity, anonymity, confidentiality, and privacy. To maintain integrity, no alteration of the messages can occur during transmission. The identity of the data source and the clients' private information remains hidden. Third parties cannot read that data, Meneghello et al. argue. The access level guarantees that only legitimate users can access the network and the devices associated with that network. It also guarantees that users within the network only use resources they can use, Meneghello et al. state. The functional level should guarantee the continued functionality of a network even in the case of malfunction or a malicious attack, Meneghello et al. add.[13]

Zhang also argues that privacy is a big concern with IoT devices and suggests two solutions data collection policy and data anonymization. A policy that describes how data collected from the devices would restrict data flow, ensuring privacy preservation, Zhang

states. Data anonymization means that private information sent by the IoT devices is either encrypted or conceals the relation of the data and its owner according to Zhang.[14]

Meneghello et al. argue that one of the main aspects of security within IoT is to ensure that the data sent is the data received and that the data has not been tampered with or read during transmission. The most critical operation to guarantee is encryption, which converts the message sent in plain text to an encrypted message only readable with a decryption key, Meneghello et al. state. Meneghello et al. state that there are two mechanisms for encryption, symmetric and asymmetric. Symmetric encryption uses the same key for encryption and decryption, sharing it with both the sender and receiver. On the other hand, asymmetric encryption only shares the public key, and the sender and receiver have their private keys Meneghello et al. means.[13]

Hassija et al. state the importance of end-to-end encryption and its challenges for IoT systems. End-to-end encryption is required to ensure the confidentiality of the data. The application should not let anyone except the intended recipient read the messages sent Hassija adds.[15]

Noor, Meneghello, and Zhang state the importance of authentication in IoT systems.[16, 13, 14] Noor adds that 60% of all IoT systems use authentication to grant access to the user.[16] Zhang argues that public key cryptosystem provides more security than symmetric encryption schemes but has the drawback of having high computational overhead.[14]

Noor argues that conventional cryptographic primitive is unsuitable for IoT devices due to their lack of computational power and limited battery life and memory capacity.[16] With IoT devices lacking capabilities as background Noor, Meneghello, and Zhang all agree that a push for lightweight cryptography is required to ensure the security of these devices.[16, 13, 14]

2.6 Communication

MQTT, Message Queue Telemetry Transport, is a lightweight messaging invented by IBM suitable for IoT according to Wukkadada.[17] MQTT is a publish/subscribe protocol that requires a minimal footprint and bandwidth to connect an IoT device according to Hivemq.[18] MQTT consists of an MQTT broker and MQTT clients, where the broker is responsible for sending messages between the sender and its recipients.[17] On the other hand, a client publishes a message to the broker that other clients can subscribe to Hivemq add.[18]

HTTP, HyperText Transfer Protocol, is a request/response protocol consisting of clients and servers that communicate by exchanging individual messages. The clients are responsible for the requests, and the servers are responsible for the response Mozilla developer network clarifies. [19] In contrast to the lightweight MQTT protocol with low overhead and bandwidth, HTTP can cause serious bandwidth issues, Wukkadada adds. [17] The most significant benefits to using HTTP are that it supports the RESTful Web architec-

ture and a globally accepted web messaging standard Naik suggests. [20]

Naik argues that HTTP exceeds MQTT in message size, message overload, power consumption, resource requirements, bandwidth, and latency. All things that are considered adverse for a protocol. On the other hand, HTTP exceeds MQTT in interoperability, standardization, security, and provisioning, Naik adds.[20] All things that are considered positive for a protocol. Shariatzadeh argues that that HTTP may be expansive for many IoT devices, but it can be beneficial due to the interoperability since initially developed for the web.[21] Wukkadada also points out the lower power consumption of the MQTT protocol but adds that the more lengthy HTTP protocol can be easier for developers to understand. Wukkada drives home the point of choosing MQTT for IoT devices.[17]

CHAPTER 3

Theory

The theory behind the implementation in this thesis consists of performing correct SQL queries to appropriate tables in the Eclipse Arrowhead framework database with the help of Swagger UI REST API.

3.1 Eclipse Arrowhead framework

As mentioned in the related work section, the Eclipse Arrowhead framework consists of three mandatory core systems

- Service registry system.
- Authorization system.
- Orchestration system.

3.1.1 Service registry system

The service registry system is responsible for enabling discovery and registering services, Delsing et al. state. According to the Eclipse Arrowhead projects own GitHub page, the service registry system provides the database which stores the offered services in the local cloud.[22] The Github page also states the three main objectives of the service registry system are:

- To allow the application system to register available services to the database.
- Remove or update available services from the database.
- Allow application system to use the lookup functionality of the registry.

3.1.2 Authorization system

According to the projects Github page, the Authorization system contains two databases for keeping track of which system can consume services from which other systems, de-

pending on whether the Application system is in the same cloud or not. The GitHub documentation also states that if the authorization happens within the same cloud, it is called intra-cloud authorization, and if it happens across two local clouds, it is called inter-cloud authorization.[22]

3.1.3 Orchestrator system

The Orchestration system is responsible for pairing and finding service providers and consumers, Delsing et al. declare. Delsing et al. continue to state that the orchestrator also stores the orchestration requirements and the resulting orchestration rules.[11] The project's documentation argues that the main objective of the orchestrator system is to find an appropriate provider for the requesting consumer system.[22]

The documentation also states that there are two types of orchestration, store orchestration and dynamic orchestration. Store orchestration uses the database orchestration store to find predefined orchestration rules. On the other hand, dynamic orchestration searches the entire local cloud, or even other clouds, to find the matching provider.[22]

3.2 Arrowhead database

The Eclipse Arrowhead framework can be viewed as a series of database tables that have to be linked with each other. One table relevant to all the core systems is the `service_interface` table. It correlates a connection interface, i.e., HTTP-INSECURE-JSON, HTTP-SECURE-JSON, and HTTPS-SECURE-JSON, to a specific ID used later on.

3.2.1 Service registry system tables

The tables in the Arrowhead database relevant to the service registry system are

- `system_` keeps the information about consumers and providers.
- `service_registry` contains information about the different services.
- `service_definition`, stores service definition name, and ID.
- `service_registry_interface_connection` correlates a service registry ID to an interface ID.

3.2.2 Authorization system tables

The tables in the Arrowhead database relevant to the authorization system are

- `authorization_intra_cloud`, adds authorization rules for the provider, consumer, and service definition. Dictates which consumers are allowed to connect to which providers and the services they are allowed to use.

- `authorization_intra_cloud_interface_connection` correlates an intracloud authorization ID to an interface ID.

3.2.3 Orchestration system tables

The tables in the Arrowhead database relevant to the orchestrator system are

- `orchestrator_store`, contains orchestrator store entry, with information about which endpoints the consumers can use.

3.3 Swagger UI

The Eclipse Arrowhead framework has integrated Swagger UI into their core services. This means that the databases can be accessed and altered using HTTP methods instead of SQL queries. Each core system has its swagger UI page, which serves as a visual, user-friendly REST API. A REST API, Representational state transfer, is a way to structure an API and consists of the following main principles according to Wikipedia.[23]

- Each resource has its own URI.
- The resources have a common interface for commands between client and server. These are
 - POST creates a new state for a resource.
 - GET requests the state of a resource.
 - PUT replaces the state of an already created state.
 - DELETE deletes a resource state.

Instead of sending SQL-queries, the Swagger UI also enables the use of JSON, JavaScript Object Notation, and the construction of theses will be covered in the implementation section.

3.4 ARM Mbed

The STM 32 board needs to be connected to the internet to enable the use of the Swagger UI. The ARM mbed OS 6 provides the functionality needed for this.

Mbed OS 6 uses a hardware abstraction layer, HAL, to enable the essential parts of a microcontroller, such as timers. Using hardware supported by Mbed OS 6 libraries, drivers, and, support for standard peripherals for microcontrollers are automatically imported upon compilation. This foundation enables the user to write applications against a shared set of APIs. Another advantage of using supported hardware is the retargeting layer and boot process integration, so application development feels similar to C or C++ development.

ARM Mbed OS enables the user to use a range of connectivity tools and suits. In this thesis, Wi-Fi is used, but there is support for Bluetooth, NFC, and much more. Mbed OS connectivity and network stack offer a stable core of existing connectivity technologies, perfect for even the most demanding and versatile IoT applications.

The Mbed online compiler allows the user to develop their code online, independent of the platform. The online compiler also supports the importation of code from GitHub, making it easier for the users to import this code and genuinely use this as a 'Getting started with the Eclipse Arrowhead framework' example.

3.5 Performance measurement

Response time is measured to compare the performance of the three different IoT frameworks. Due to the vastly different implementation of the three frameworks, Amazon Web Services, Microsoft Azure, and Eclipse Arrowhead framework, the only thing worth measuring is the response time when pinging the different frameworks.

The Test-Connection command in power-shell sends four 32-bit packets to the specified destination. This will be iterated 250 times, resulting in 1000 measured values that are significant enough to produce an average response time. The average is calculated with $\frac{\sum \text{response times}}{\text{number of response times}}$. In addition to presenting the average response time, the maximum and minimum response times will be calculated to give further understanding of the performance of the different frameworks. The results of these calculations will be presented in detail in Chapter 5.

CHAPTER 4

Implementation

The system consists of three major parts, the provider on the stm32 board, a Python flask app as a consumer, and the Eclipse Arrowhead framework. The main objective of the Eclipse Arrowhead framework is to connect the consumer and the provider in a safe and structured way. The provider is built with C/C++ using ARMs' mbed os, and mainly the mbed-http library.

4.1 System architecture

4.1.1 Services

The provider offers two services to the consumer. The first one is sending the temperature from the LPS22HB temperature and pressure sensor. The service URI of this service is /temperature, and when performing a GET request, the temperature reading will be returned as an integer. A sequence diagram visualizing how the temperature service is implemented.

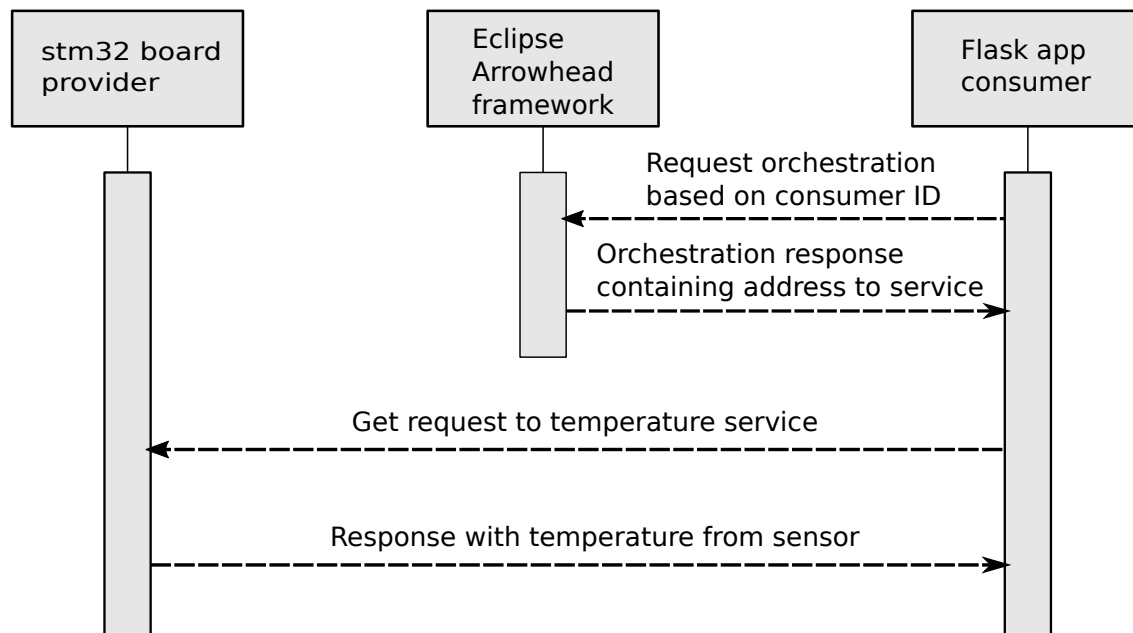


Figure 4.1: Sequence diagram of the process of connecting the consumer and provider through the temperature service.

The second one is turning on and off a LED based on the state of that LED. The service URI of this server is /LED, and the desired state of the LED, ON or OFF, is specified in the payload of that call. It returns the new state of the LED and performs that action on the LED. A sequence diagram was drawn to visualize how the LED service was implemented.

4.1.2 Sequence of execution

Since the core systems are dependent on each other, the order of execution of the queries to the database matters a lot. To have the board act as a part of an Arrowhead system and registering that to the local cloud, the following order of execution has to be used.

- Register provider.
- Register consumer.
- Register a service definition.
- Add intracloud authorization rules.
- Create an orchestration store entry.
- Recieve orchestration information based on consumer ID.

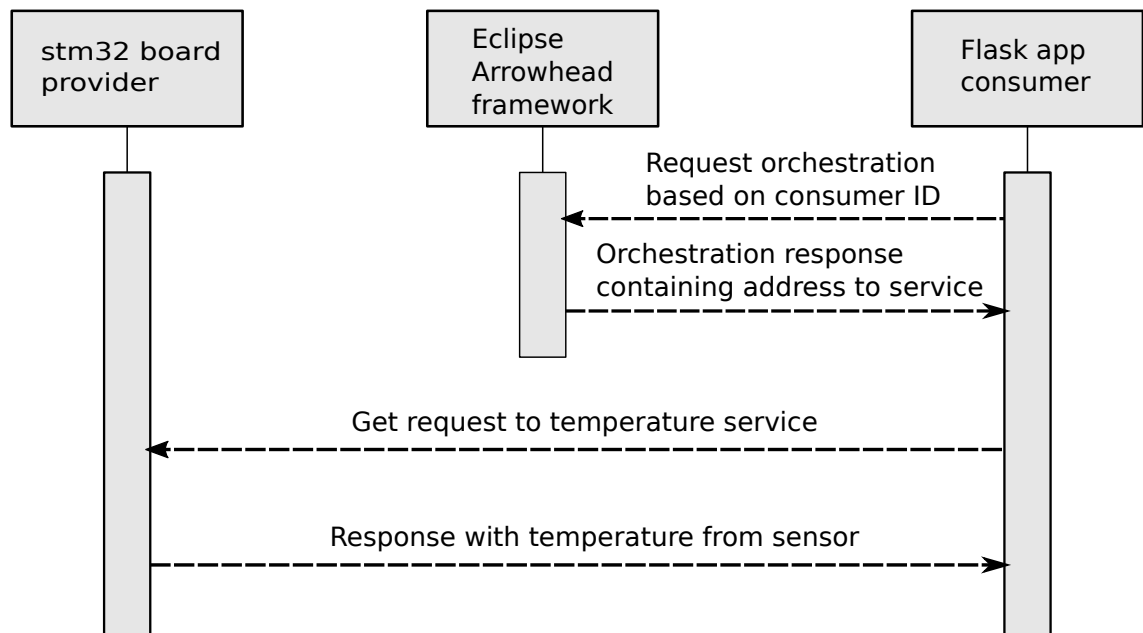


Figure 4.2: Sequence diagram of the process of connecting the consumer and provider through the LED service.

A sequence diagram visualizing the order of execution in the core systems.

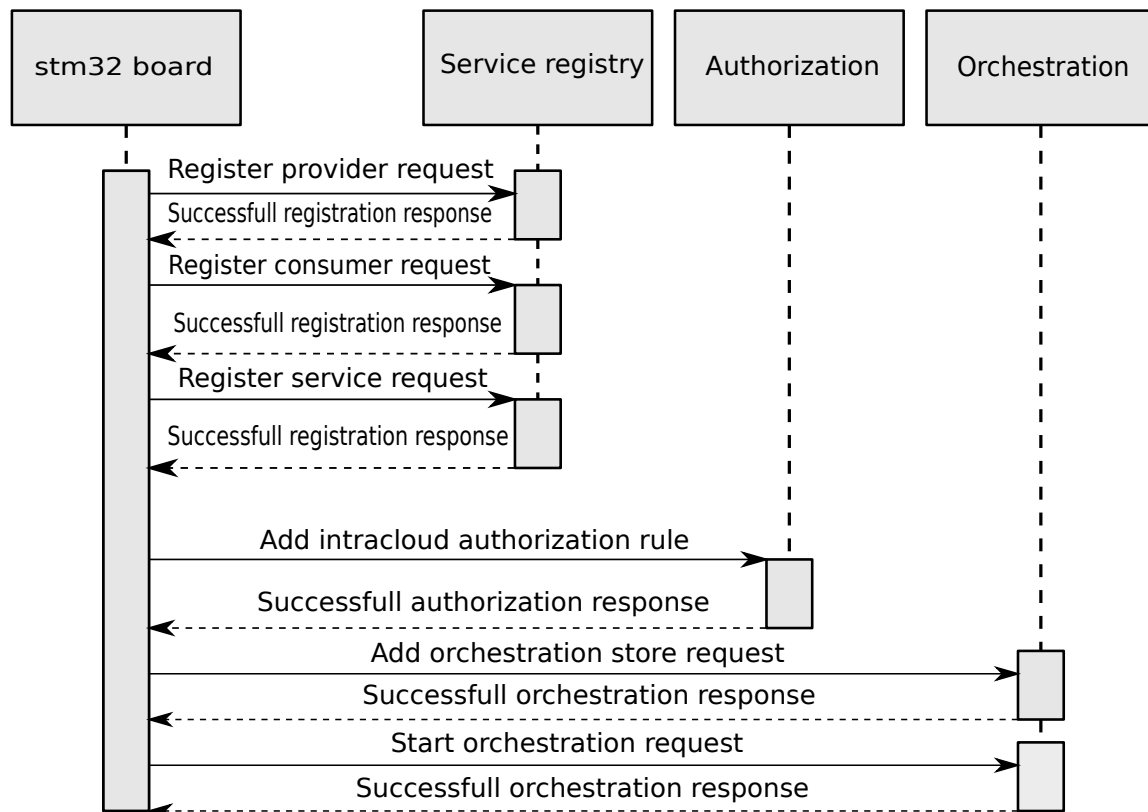


Figure 4.3: Sequence diagram of the process of using the Eclipse Arrowhead framework.

4.2 System components

Based on the architecture described in the previous section, it is clear that the software components have two main tasks

- Send and receive information using HTTP POST and GET methods.
- Constructing correct JSON strings to act as payload in the POST and GET methods.

4.2.1 HTTP post using the mbeb-HTTP library

The first function performs an HTTP post with a constructed JSON body as a payload. It does that with the help of the network interface object defined in the setup and sends that post to the appropriate URL.

```

1  std::string http_post_request_with_response(NetworkInterface* _net, std
  ::string url, std::string body)
2  {

```

```

3      HttpRequest *post_request = new HttpRequest(_net, HTTP_POST, url.
c_str());
4      post_request->set_header("Content-Type", "application/json");
5      HttpResponse *post_response = post_request->send(body.c_str(),
strlen(body.c_str()));
6      if (!post_response) {
7          printf("HttpRequest failed (error code %d)\n", post_request->
get_error());
8          return std::to_string(post_request->get_error());
9      }
10     printf("\n—— HTTP POST response ——\n");
11     std::string response_body = post_response->get_body_as_string();
12     delete post_response;
13     return response_body;
14 }

```

4.2.2 HTTP get using the mbeb-http library

The second function is similar to the first one with the main difference that it performs an HTTP get with a JSON payload. It also uses the network interface to send it to the appropriate URL. It does that with the help of the network interface object defined in the setup and sends that post to the appropriate URL.

```

1 std::string http_get_request_with_response(NetworkInterface* _net, std::
string url)
2 {
3     HttpRequest *get_request= new HttpRequest(_net, HTTP_GET, url.c_str());
4
5     HttpResponse *get_request_response = get_request->send();
6
7     if (!get_request_response) {
8         printf("HttpRequest failed (error code %d)\n", get_request->
get_error());
9         return std::to_string(get_request->get_error());
10    }
11    printf("\n—— HTTP GET response ——\n");
12    std::string response_body = get_request_response->get_body_as_string();
13    delete get_request_response;
14    return response_body;
15 }

```

4.2.3 Constructing appropriate JSON strings

To use the POST and GET function defined in the previous section, a correct JSON payload, or HTTP body, has to be created. To register a system, consumer, or provider, a body similar to the one defined underneath should be used.

```

1     std::string register_system_body = "{\"address\": \"192.168.0.101\", \"
authenticationInfo\": \"\", \"port\": 1234, \"systemName\": \"
system_name\"}";

```

The next operation is to register a service, and just as when registering a system, a correct JSON payload is required. The previously defined provider system is passed as a parameter here an interface, has to be defined as well.

```
1 std::string register_service_body = "{\"serviceDefinition\": \"
  service_definition\", \"providerSystem\": {\"systemName\": \"
  system_name\", \"address\": \"192.168.0.101\", \"port\": 1234, \"
  authenticationInfo\": \"\" }, \"interfaces\": [\"HTTP-INSECURE-JSON\"],
  \"serviceUri\": \"temperature\"}\r\n\";
```

These three calls should all be made to the service registry core system.

To create intracloud rules, provider, consumer, and service definition ids must be passed as parameters. Two helper functions were implemented to achieve this. The first one parses the response from registering a system, finds the substring containing the systems id and returns that as a character pointer. The second one parses the response from registering a service, finds the substring containing the service definition id, and returns that as a character pointer. The field interfaceIds can be looked up in the table system_interface in the Arrowhead database and should correlate with the selected interface.

	id	interface_name	created_at	updated_at
1	1	HTTP-SECURE-JSON	2021-02-03 11:56:35	2021-02-03 11:56:35
2	2	HTTP-INSECURE-JSON	2021-02-03 11:56:35	2021-02-03 11:56:35
3	3	HTTPS-SECURE-JSON	2021-02-16 17:45:57	2021-02-16 17:45:57

The correct JSON can now be constructed and posted to the authorization core system.

```
1 std::string add_intracloud_authorization_body = "{\"consumerId\": \" +
  std::to_string(consumer_id) + \", \"interfaceIds\": [3], \"providerIds\":
  [\" + std::to_string(provider_id) + \"], \"serviceDefinitionIds\": [\" +
  std::to_string(service_id) + \"]}\r\n\";
```

The previously defined consumer and provider system and the consumer id have to be provided to create an orchestration store rule. Information about the operating cloud and interface has to be defined, and posted to the orchestrator core system.

```
1 std::string create_orchestration_store_body = "[{ \"serviceDefinitionName
  \": \"service_definition\", \"consumerSystemId\": \" + std::to_string(
  consumer_id) + \", \"providerSystem\": { \"systemName\": \"system_name
  \", \"address\": \"192.168.0.101\", \"port\": 1234, \"
  authenticationInfo\": \"\" }, \"cloud\": { \"operator\": \"aitia\", \"
  name\": \"testcloud2\" }, \"serviceInterfaceName\": \"HTTP-INSECURE-
  JSON\", \"priority\": 1}]\r\n\";
```

A get request is sent to the orchestrator with the consumer's id as a parameter. The response from the orchestrator contains information about the address, port, and service URI of the provider the consumer wants to connect to. To parse the response from the

orchestrator, a helper function was created. It takes the response as a parameter and returns the address, port, and service URI as a string. If every step is successful, the consumer can connect to the provider.

4.3 Error handling

From the sequence diagram above, it can be seen that the success of each subsequent operation is dependent on the success of the previous one. Without adequately defined and registered systems, a service definition can not be registered. If one command fails, the chain of commands is broken. The commands will still execute but return an appropriate error code and error message describing the error.

For instance, a provider system with the same name as a previous one in the database is trying to register itself to the service registry. This will throw an error stating that such a system already exists and not return the system id, which will cause the command to add intracloud rules to fail since the id of the provider system is required. The orchestrator can not be performed if the systems are not authorized correctly, causing the GET method to the orchestrator returning a blank response, which causes the consumer not to be able to connect to a provider.

CHAPTER 5

Evaluation

The objective of this thesis was to investigate the possibilities, benefits, and limitations of using the Eclipse Arrowhead framework on embedded devices in contrast to commercially available solutions such as Amazon's Amazon Web Services and Microsoft Azure. The previous chapter showed that it was possible to connect the STM32 B-L4S5I-IOT01A to an Eclipse Arrowhead framework local cloud. Tests to figure out which IoT framework had the shortest response time were carried out and the results of those will be presented later on in this chapter.

5.1 Incorporating an Eclipse Arrowhead framework local cloud

For the implementation to be seen as successful it has to be able to connect the system and services in compliance with the Eclipse Arrowhead framework. It has to be able to send the temperature data from the STM32 B-L4S5I-IOT01A board to the flask app running on another device. The implementation should be easy to use which due to the use of an online compiler and the ability to import the code, requiring minimal setup for the end-user, proved to be the case. The implementation presented in the previous section managed to do that successfully.

Based on the previous section it seems possible to successfully use an Eclipse Arrowhead local cloud together with an embedded device connected to the internet. The benefits of using the Eclipse Arrowhead framework will be presented in the next chapter which presents the test results. The limitations of using the Eclipse Arrowhead framework will be covered in the next chapter.

5.2 Performance test result

The performance measurement, as described in the theory section, pinged the different IoT framework 1000 times and calculated the average, minimum and maximum response

times. Line diagrams of the response time and average response time are presented below for the different IoT frameworks are presented below.

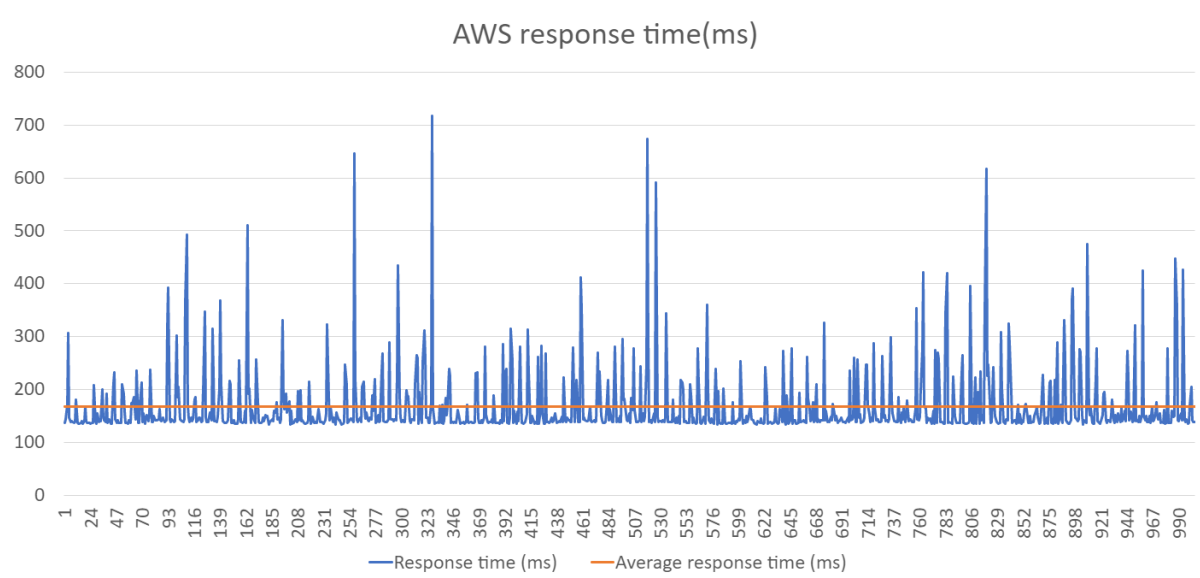


Figure 5.1: Response time and average of AWS

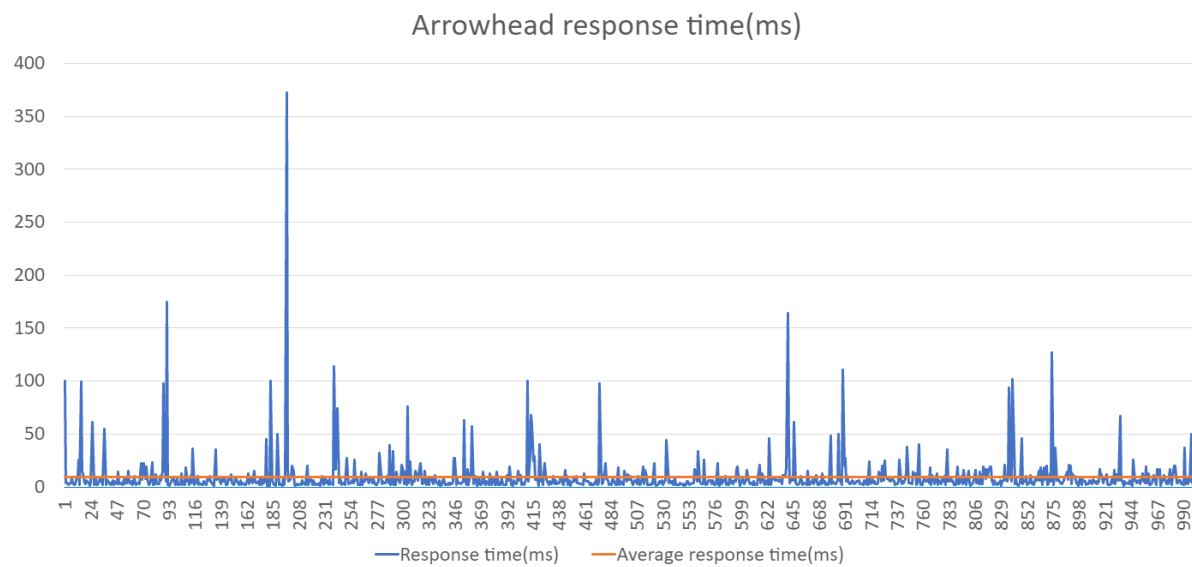


Figure 5.2: Response time and average of Arrowhead framework

To give a clearer picture of the results in the test the following table was constructed.

Parameters	AWS	Arrowhead	Azure
Average response time(ms)	166.94	9.5105	0
Max response time(ms)	717	372	0
Min response time(ms)	134	1	0

The table above shows that the Eclipse Arrowhead framework has the shortest average response time, 17.5 times faster than Amazon Web Services. The table also shows that Amazon Web Services has a max response time 1.9 times greater than the Eclipse Arrowhead framework. The largest difference can be seen in the minimum response time where the Eclipse Arrowhead framework is 134 times faster than Amazon Web Services. The advantages of having a lower response time will be covered in the next chapter.

CHAPTER 6

Discussion

This thesis aimed to investigate whether it was possible to use an embedded device in conjunction with the Eclipse Arrowhead framework. If that was possible, this thesis also aimed to show the advantages and limitations of using the Eclipse Arrowhead framework on embedded devices. Another goal of this thesis was to show that using the Arrowhead framework on embedded devices provides a ready-to-make example for people to try out the framework. To fill a void in the Arrowhead project GitHub with a complete example ready to compile and using an online compiler.

6.1 Choice of development environment

The IDE, integrated development environment, chosen for this thesis stood between the Mbed online compiler and the STM CUBE IDE. The STM cube IDE requires setup on the local machine, installing C and Cmake, but provides shorter compilation time. The Mbed online compiler requires no setup on the local machine but takes much longer to save and compile the code.

Both compilation time and an easy setup are favorable attributes for an IDE, and it all depends on the end goal. If the goal were to try out multiple different iterations of the same source code, then STM cube IDE would be the best choice. On the other hand, if the goal was to provide an example of a framework or concept and get the users started as quickly and painless as possible, the Mbed online compiler is the obvious choice. The latter fitted the goals of this thesis better and was therefore chosen.

Both IDEs provide ready to run example that features different aspects of the development boards, and both contain an example of connecting the board to the internet. The Mbed online compiler, in conjunction with arm Mbed OS, provides an easy and intuitive way to get started on desired projects. The Mbed online compiler has its drawbacks as well. When using it, the user is pushed into using libraries integrated into the Mbed OS 6. It is possible to use outside libraries but more often than not, resulting in a rabbit hole of including header files. On the other hand, STM Cube IDE works similarly to a

local C-program. If the header files are in the include folder or installed locally, they can be used without much effort.

The STM Cude IDE also supports code generation from Cube MX, letting the user choose which peripherals to be included and adding initiation code before developing a project. Cube MX also supports importing supported libraries, generating the required include folders and header files for the user beforehand. When using the Mbed online compiler, all the peripherals, sensors, and libraries have to be initialized by the user. It will result in a trade-off between ease of use, performance, and customizability.

One disadvantage of using the STM cube IDE is that all applications will become platform-dependent. STM cube IDE requires the user to have a Windows computer. Mbed online compiler, on the other hand, builds everything in the browser. When the build is done, the Mbed online compiler prompts the user to download a .bin file that can be dragged to the STM32 B-L4S5I-IOT01A board, as if storing a file on a flash drive. The STM32 B-L4S5I-IOT01A board compiles the .bin file and outputs the result to the user, no need to install Cmake or other toolchains.

6.2 Provider architecture

The implementation in this thesis follows the publish/subscribe model, as described in the related work section. The STM32 B-L4S5I-IOT01A board is the publisher, and the remote computer will act as the subscriber. The board has to find where to send the temperature data and sends it in predefined intervals after that. The implementation made in this thesis lacks the functionality of acting as a server, serving a request from a consumer.

In the Eclipse Arrowhead system, a provider system will typically be passive, reacting to requests. When speaking of it in an HTTP sense, the provider will act as a server. A consumer will usually act as a client and find the provider's address to request services from the provider. In this implementation, the provider will find the consumer's address and send the temperature information. The service it provides is sending the reading from the temperature sensor in specific time intervals. It is important not to get hanged upon the terminology as both a provider and a consumer are considered systems in the Eclipse Arrowhead framework. In essence, they are the same thing and can be used interchangeably. It all depends on how the service is defined.

Depending on the application, it might be more efficient to send the data when the consumer demands it. It is possible to imagine the opposite as well. If a system relies on past information, it might be more efficient to send the data at a specified rate. If the system has to process the data and perhaps depends on a lot of data, it may be more efficient to use the subscribe/publish model. Negating the need for the embedded device to respond to requests can increase energy efficiency by having it boot at specific times to send the data. If a system relies on real-time data creating a REST API to handle these requests would be the next logical step for developing this example. This will be

covered in the future work section in the next chapter.

6.3 Comparing different frameworks

The previous chapters showed that it was possible to use the Eclipse Arrowhead framework with embedded devices. It also showed the advantages of using the framework. The main advantage was the response time, having on average 17.5 times faster response time than its competitors. A faster response time could be a great advantage when dealing with real-time applications when a fast response is as essential as a correct one.

One disadvantage of using the Eclipse Arrowhead could be the lack of supported hardware. This thesis was the first example to show that it was possible to connect to the arrowhead framework on embedded devices. In contrast, Amazon Web Services have many examples of using different hardware. Amazon Web Services also has examples showcasing the different sensors and connection possibilities of their supported boards. Creating an open-source example of using the Eclipse Arrowhead framework could inspire others to start developing embedded Arrowhead applications, expanding the functionality of this implementation.

The eclipse Arrowhead Framework requires hardware to run on, a service that has to be paid for with Amazon Web Services. It is probably cheaper to purchase hardware and run the Eclipse Arrowhead on a larger scale, but that requires an upfront cost. In smaller-scale applications or when trying out a proof of concept, the prices offered by Amazon Web Services are hard to beat. When using Amazon Web Services, the user relies on that their hardware and network runs continuously, an issue which magnitude showed its face this fall.

One significant advantage of using Amazon Web Services is its services offered out of the box. Lambda functions, S3 buckets, and all the functionality that follows with them is something the user will have to implement on their own if choosing the Eclipse Arrowhead framework. On the other hand, if the user wants to do something not supported by Amazon Web Services, they will be constrained. As with the choice of IDE, it will result in a trade-off between ease of use and customizability.

Another significant advantage of Amazon Web Services is the support for and enforcement of using HTTPS. When deploying a 'Thing' to the AWS IoT Core, a certificate is generated and has to be included in the source code. The security issues raised in the related work section illustrate the need for HTTPS and other security measures for IoT devices in production. When developing a proof of concept, as this thesis has been doing, the requirement of HTTPS might be overstated. It becomes a trade-off between usability, development time, and security. If the intent is to demonstrate that the Eclipse Arrowhead framework works on embedded devices, the use of HTTPS and all the extra steps for implementing that might do more harm than good.

The Eclipse Arrowhead framework supports HTTPS and encourages its users to use it.

There is documentation for generating Arrowhead compliant certificates and support for it in the Java implementation of a client. However, it proved to be challenging to implement and beyond the scope of this thesis. The attempts of implementing HTTPS will be covered more in the future work section in the next chapter.

CHAPTER 7

Conclusions and future work

This chapter summarizes the thesis by outlining what was accomplished and what remains to be done. Section 7.1 contains the conclusion, and a description of work to be done can be found in section 7.2.

7.1 Conclusion

This thesis examined the possibility of using an Eclipse Arrowhead framework local cloud on an embedded device, namely the STM32 B-L4S5I-IOT01A board. It was possible to implement functionality for the Eclipse Arrowhead framework on the STM32 B-L4S5I-IOT01A board, having the board send temperature readings to a computer within a local network.

Another goal of this thesis was to provide an easy-to-run example of the Eclipse Arrowhead framework that could be compiled by anyone wanting to give the framework a try, a feature that is missing right now for embedded devices. The implementation was done with usability in mind, making it easy for users to try the code. This was achieved with the Mbed online compiler's code importation and minimum setup development environment, allowing users to try out the Eclipse Arrowhead framework on the STM32 B-L4S5I-IOT01A board.

The thesis also examined the benefits of using the Eclipse Arrowhead framework compared to its competitors Amazon Web Services and Microsoft Azure. The thesis showed some benefits in terms of response time when running a local cloud instead of using a remote service such as Amazon Web Services, a 17.5 decrease in average response time was recorded. Maximum and minimum response times decreased by 1.9 and 134 times, respectively.

7.2 Future work

The research presented in this thesis can take many different directions moving forward. Two main issues were raised during this thesis, security and having the STM32 B-L4S5I-IOT01A board act as a server. These two issues will be addressed in the following sections.

7.2.1 Security

The security issues raised in both the related work and the previous chapter need to be addressed for this implementation ever to be used by the industry in production. Several attempts were made at implementing HTTPS; the Mbed-HTTP library has support for HTTPS, and STM cube IDE has support for wolfSSL.

The problem that has to be solved before this could be implemented and used in the Eclipse Arrowhead framework is how certificates are handled in languages other than Java. Both Mbed and STM cube has examples using HTTPS that works, and getting started with Amazon Web Services uses HTTPS with a user-generated certificate. One of the main issues is that the certificates are self-signed, meaning no trusted certificate authority has signed them. This proved to be the main obstacle for implementing HTTPS using C. None of the libraries, Mbed-HTTP or wolfSSL, could trust the certificate from the Eclipse Arrowhead framework.

Further research on using the certificates generated by the Eclipse Arrowhead framework on embedded devices needs to be conducted. One area of research could be to move away from the .pk12 format, generally used by java applications, and include more support for the .pem format used by C and many other languages. Another area of research needed is lightweight cryptography and possible ways to move away from the idea that an IoT device has its certificate. A concept that quickly becomes unbearable when dealing with thousands of devices in one network.

7.2.2 Server implementation

The need to have the STM32 B-L4S5I-IOT01A board as a passive component reacting to requests is also an issue that has to be resolved before the industry will use the results from this thesis in production. Both the Mbed online compiler and the STM Cube IDE have a working example of an HTTP server that can request the temperature data from a generated webpage. Those examples use pure HTTP requests and responses, leading to very verbose and challenging messages to parse. Future research that promotes the same usability as Mbed-HTTP and the ability to respond to the request would greatly benefit the Eclipse Arrowhead framework.

A server implementation on the STM32 B-L4S5I-IOT01A board could also have great educational potential by using it in courses for young adults or aspiring engineers. With the number of IoT devices connecting to the internet only increasing, understanding

connected embedded devices is crucial for future engineers. Introducing concepts like IoT and embedded system programming early in an engineering degree and real-life examples could enhance knowledge and spike interest for those subjects, making aspiring engineers ready for the future.

REFERENCES

- [1] Artemis-IA News Embedded Intelligence: Trends & Challenges book release. <https://artemis-ia.eu/news/embedded-intelligence-trends-challenges-book-release.html>, accessed 2021-04-21.
- [2] Heiner Lasi, Peter Fettke, Hans Georg Kemper, Thomas Feld, and Michael Hoffmann. Industry 4.0. *Business and Information Systems Engineering*, 6:239–242, 8 2014.
- [3] Arrowhead tools. <https://arrowhead.eu/arrowheadtools/>, accessed 2021-04-22.
- [4] Arrowhead consortia. <https://github.com/arrowhead-f>, accessed 2021-03-10.
- [5] User Guide and Freertos Qualification. User manual Getting started with X-CUBE-AWS STM32Cube Expansion Package for Amazon Web Services (®) IoT. (September):1–31, 2020.
- [6] Getting started with the STMicroelectronics B-L475E-IOT01A / B-L4S5I-IOT0A1 Discovery <https://docs.microsoft.com/en-us/samples/azure-rtos/getting-started/getting-started-with-the-stmicroelectronics-b-l475e-iot01a--b-l4s5i-iot0a1-discovery> accessed 2021-04-22.
- [7] Jayavardhana Gubbi, Rajkumar Buyya, Slaven Marusic, and Marimuthu Palaniswami. Internet of things (iot): A vision, architectural elements, and future directions. *Future Generation Computer Systems*, 29:1645–1660, 9 2013.
- [8] Saurabh Vaidya, Prashant Ambad, and Santosh Bhosle. Industry 4.0 - a glimpse. volume 20, pages 233–238. Elsevier B.V., 1 2018.
- [9] Elvis Hozdić. Smart factory for industry 4.0: A review, 2015.
- [10] Li Da Xu, Eric L. Xu, and Ling Li. Industry 4.0: State of the art and future trends. *International Journal of Production Research*, 56:2941–2962, 2018.
- [11] Delsing Jerker. Iot automation: Arrowhead framework - 1st edition - jerker delsing -. 2017.
- [12] How AWS IoT works - AWS IoT Core. <https://docs.aws.amazon.com/iot/latest/developerguide/aws-iot-how-it-works.html>, accessed on 2021-04-24.

- [13] Francesca Meneghello, Matteo Calore, Daniel Zucchetto, Michele Polese, and Andrea Zanella. Iot: Internet of threats? a survey of practical security vulnerabilities in real iot devices. *IEEE Internet of Things Journal*, 6:8182–8201, 10 2019.
- [14] Zhi Kai Zhang, Michael Cheng Yi Cho, Chia Wei Wang, Chia Wei Hsu, Chong Kuan Chen, and Shiuhpyng Shieh. Iot security: Ongoing challenges and research opportunities. pages 230–234. Institute of Electrical and Electronics Engineers Inc., 12 2014.
- [15] Vikas Hassija, Vinay Chamola, Vikas Saxena, Divyansh Jain, Pranav Goyal, and Biplab Sikdar. A survey on iot security: Application areas, security threats, and solution architectures, 2019.
- [16] Mardiana binti Mohamad Noor and Wan Haslina Hassan. Current research on internet of things (iot) security: A survey. *Computer Networks*, 148:283–294, 1 2019.
- [17] Bharati Wukkadada, Kirti Wankhede, Ramith Nambiar, and Amala Nair. Comparison with http and mqtt in internet of things (iot). pages 249–253. Institute of Electrical and Electronics Engineers Inc., 12 2018.
- [18] Getting Started with MQTT. <https://www.hivemq.com/blog/how-to-get-started-with-mqtt>, accessed 2021-03-18.
- [19] An overview of HTTP. <https://developer.mozilla.org/en-US/docs/Web/HTTP/Overview>, accessed 2021-03-10.
- [20] Nitin Naik. Choice of effective messaging protocols for iot systems: Mqtt, coap, amqp and http. Institute of Electrical and Electronics Engineers Inc., 10 2017.
- [21] N Shariatzadeh, T Lundholm, L Lindberg, G Sivard Procedia Cirp, and undefined 2016. Integration of digital factory with smart factory based on internet of things. *Elsevier*.
- [22] eclipse-arrowhead/core-java-spring. <https://github.com/eclipse-arrowhead/core-java-spring>, accessed 2021-03-10.
- [23] Representational state transfer - Wikipedia. https://en.wikipedia.org/wiki/Representational_state_transfer accessed on 2021-04-29.