Diseñando un Fichador Personalizado
Designing a Customized Employee Time Tracker

Trabajo de Fin de Grado
Curso 2023–2024

Autor
Santiago Elias Rabbia

Director
Gonzalo Méndez Pozo

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Resumen

Diseñando un Fichador Personalizado

Cambios en las regulaciones modificaron el procedimiento por el cual los empleados fichan al entrar a sus trabajos en una compañía de gestión de instalaciones, volviendo obsoletos muchos dispositivos existentes. Se necesitaba una respuesta rápida, por lo que se desarrolló un dispositivo de fichaje rentable que utiliza microcontroladores, un PCB personalizado y una caja impresa en 3D.

Este dispositivo IoT debe ser responsivo, intuitivo de usar y ofrecer un servicio casi ininterrumpido, enviando información a través de WiFi o datos celulares. El intercambio de datos se realiza por medio de API alojada en la nube, desarrollada usando Java Spring, que pueden ser montada como un contenedor de Docker, o como una Google Cloud Function.

Palabras clave

fichador, microcontrolador, pcb, impresión 3D, cloud API, IoT, programación asíncrona, Docker, GCP, Java Spring

Abstract

Designing a Customized Employee Time Tracker

Regulatory changes have prompted a shift in employee clock-in procedures at a facility management company, rendering many existing devices obsolete. A swift response was necessary, leading to the development of a cost-effective clocking device utilizing microcontrollers, a custom PCB, and a 3D-printed case.

This IoT device has to be responsive, intuitive to use and offer close-to uninterruped service, sending information through WiFi or cellular data. Data exchange is facilitated through cloud-hosted APIs developed using Java Spring, hostable as Docker containers or as Google Cloud Functions.

Keywords

clocking device, microcontroller, pcb, 3D print, cloud API, IoT, asynchronous programming, Docker, GCP, Java Spring

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Chapter 1

Introduction and objectives

Recent legislative changes introduced by both the European Union and the Spanish government have mandated alterations to employee clocking procedures. Notably, Spain now requires employees to clock in upon arrival at work, necessitating the implementation of reliable time-tracking systems. Additionally, the European Union has banned the use of clocking devices employing biometric identification methods such as fingerprint scanning or facial recognition.

A particular company manages many thousands of employees throughout Spain, and it was of utmost importance to expeditely replace the non-compliant devices for different ones, as many companies were already being imposed hefty fines, from tens to hundreds of thousands of Euros, for not meeting the new regulatory requirements.

The company already had providers for many types of clocking devices, and many of them were compliant, but were priced in the hundreds of Euros each. Now, faced with having to replace them, the prospect of replacing *thousands* of units at considerable expense loomed large. Moreover, outsourcing these devices often meant committing to complex time-tracking ecosystems, adding further complications and increasing the complexity of the data the company manages.

These issues were brought to light to the innovation team at the company, and were then tasked with bringing a solution to market.

1.1. Objectives

Given the preceding challenges and considerations, the development of a cost-effective device and the establishment of a cloud infrastructure were deemed necessary.

The objectives of this project are as follows:

- **Design and Prototyping**: Design a device utilizing microcontrollers and additional electronic modules, such as LCD displays and NFC readers, to fulfill the specified requirements.

- **PCB Design**: Develop a Printed Circuit Board (PCB) layout to facilitate easy interconnection of the various electronic modules used in the device, ensuring efficient and reliable performance.
- **API Development**: Create an Application Programming Interface (API) capable of deployment as a Docker container or Google Cloud Function, enabling seamless communication between the device and cloud-based services.
- **Microcontroller Research**: Investigate the constraints and capabilities of microcontrollers, particularly RP2040-based microcontrollers, to inform design decisions and optimize performance.
- **3D Printing and Modeling**: Explore the fundamentals of 3D printing and 3D modeling necessary for designing a suitable enclosure for the device. Additionally, provide an overview and comparison of various materials suitable for enclosure fabrication, considering factors such as durability, cost, and aesthetic appeal.

Chapter 2

Breadboard Prototype

The first phase of developing the new clocking device involved thorough research into available components and microcontrollers in the market. Factors such as cost, functionality, and potential drawbacks were carefully evaluated to inform the selection process. Subsequently, selected components were tested by constructing a basic prototype on a breadboard to assess functionality and performance. Demonstrating the viability of the project at this stage was crucial for ensuring its continued development and success.

2.1. Hardware selection

Firstly, considering that the development was urgent, it would only be possible to use an already made controller. There were two routes to take:

- Using a **single-board computer**.
- Using a **microcontroller**.

The team's familiarity with *Raspberry Pi* products and their reputation for reliability led to the decision to utilize their offerings for the project. Given the lightweight processing requirements, the *Raspberry Pi Zero 2 W*, a cost-effective single-board computer with built-in WiFi capabilities, emerged as a suitable option. Alternatively, the *Raspberry Pi Pico W*, a microcontroller, presented another viable choice.

However, it's important to note that while the *Pi Zero* offers more features and functionality, it comes at a higher cost compared to the *Pi Pico*. In fact, it costs almost three times as much. Therefore, careful consideration is warranted to determine whether the additional expense justifies the benefits.

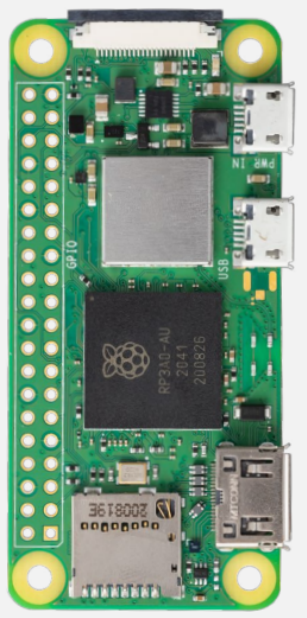

Figure 2.1: Raspberry Pi Zero 2 W

Figure 2.2: Raspberry Pi Pico WH

2.1.1. Single-board Computers

A single-board computer (*SBC*) is a complete computer built on a single circuit board. It integrates all the necessary components required for a functional computer system, including a central processing unit (CPU), memory (RAM), storage (usually in the form of a MicroSD card), input/output ports, and sometimes additional features such as networking capabilities (e.g., Ethernet or WiFi), audio/video output, GPIO (General Purpose Input/Output) pins for connecting external devices, and even USB ports.

SBCs are designed to be compact and efficient, which is the case of the *Pi Zero*, measuring about 65mm by 30mm while drawing about one Watt of power. Additionally, SBCs can run an operating system, such as Ubuntu.

This ability to run an entire operating system significantly enhances their versatility compared to microcontrollers out-of-the-box. Many peripheral devices can simply be plugged into a USB port and function seamlessly without requiring additional configuration. For instance, a 3G SIM card adapter, which will be necessary for future stages of the project, can be effortlessly integrated into the system, letting the operating system take charge of the communication with the mobile network, abstracting all these problems from the programmer.

2.1.2. Microcontrollers

A microcontroller is a compact integrated circuit (IC) that contains a central processing unit (CPU), memory (both volatile RAM and non-volatile flash memory), input/output peripherals (such as digital and analog I/O pins), and various other hardware components necessary for interfacing with external devices. Unlike single-board computers, microcontrollers are typically designed for specific tasks and embedded applications, often with real-time requirements.

One key characteristic of microcontrollers is their ability to execute dedicated firmware or software code stored in their internal memory. This code typically controls the behavior of the microcontroller, processes inputs from sensors or other external devices, and generates outputs to control actuators or display information.

The *Raspberry Pi Pico W* is a development board that utilizes the *RP2040* microcontroller chip. This board offers a range of features beyond its microcontroller, including onboard flash memory for program storage, versatile GPIO pins for interfacing with external devices, built-in USB connectivity for programming and power supply, and WiFi connectivity.

In comparison to single-board computers, the *Pi Pico* does not have an operating system. Instead, firmware can be loaded onto it, and it is this firmware that provides functionality to the board. This firmware allows the programmer to use programming languages such as C or MicroPython, which then control the microcontroller's behavior and interactions with external devices.

The absence of an operating system reduces the overhead associated with system management and resource allocation, resulting in faster boot times and improved reliability for time-critical tasks.

Taking into account our previously established requirements, which prioritize minimal points of failure, low computational demands, and cost-effectiveness, the logical preference leans towards the utilization of a microcontroller. For instance, single-board computers often rely on SD cards for storage, which can be prone to failure after prolonged use due to factors such as wear and tear or data corruption. In contrast, microcontrollers typically have simpler storage mechanisms, such as onboard flash memory, which are less susceptible to such issues. Thus, lower operating costs.

As a conclusion, a **microcontroller will be used**, and in particular, the ***Raspberry Pi Pico W***.

2.1.3. Electronic Modules

Now that the microcontroller has been selected, additional components are necessary to meet the project's requirements. Specifically, the device must integrate an NFC reader and an LCD screen. Additionally, other peripherals, such as a buzzer or LED, may also be evaluated.

We need to take into account the available buses and choose modules accordingly.

Relying solely on the datasheet alone is not enough to determine the buses that are usable concurrently, since if two different buses use the same pin, then they cannot be used simultaneously. Referring to the pinout diagram of the *Raspberry Pi Pico W* provided below, we can identify the available buses:

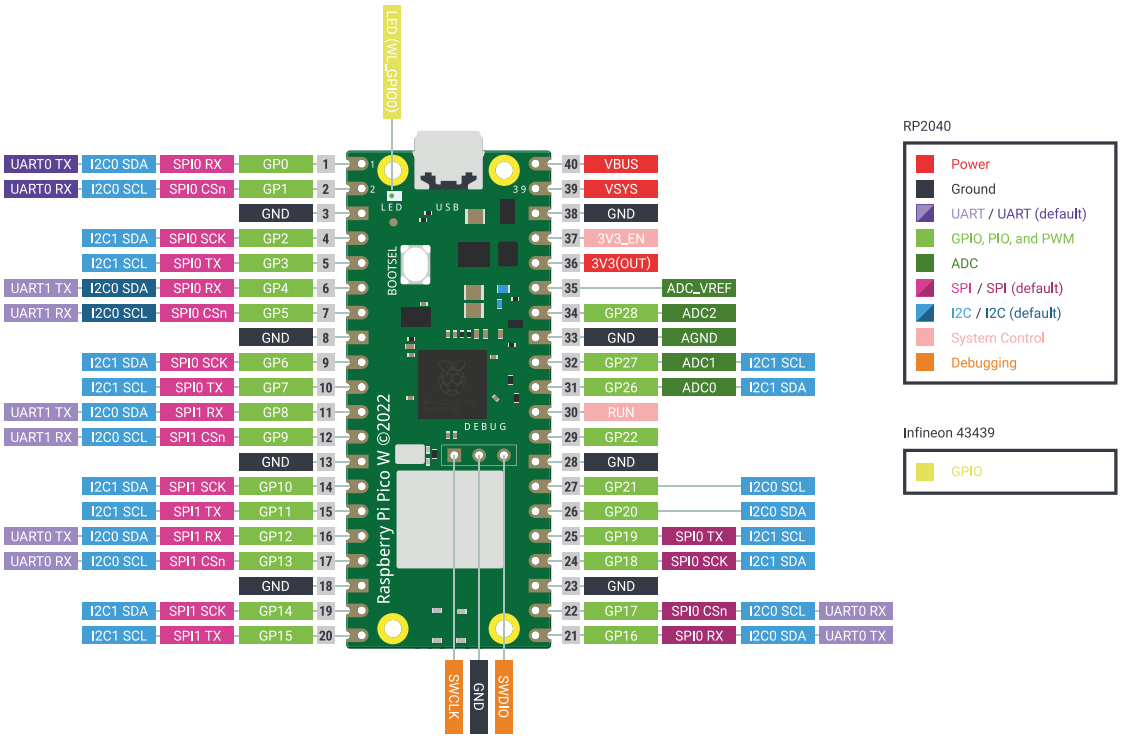

Figure 2.3: Raspberry Pi Pico W's Pinout

For example, each UART bus conflicts with I2C buses. Therefore, when selecting components, it's crucial to ensure compatibility with this layout [1].

NFC Module

Various NFC boards are available on the market. Ideally, the desired NFC board would offer extended range, compact form-factor, low power consumption, and support for multiple communication protocols such as UART, I2C, SPI, among others.

The *PN532* chipset produced by *NXP* offers all three types of buses mentioned before, that is: High Speed UART, I2C and SPI. Numerous boards utilizing this chipset are available on the market, with *ElecHouse*'s offering standing out for its excellent form-factor (about 4cm×4cm) and impressive range [8]. This specific board has been extensively replicated and is accessible at a low cost, and various providers offer open-source code for controlling it.

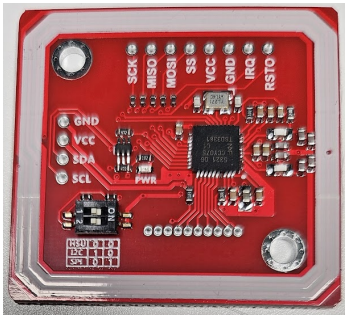

Figure 2.4: PN532 board

LCD Module

Initially, the idea of utilizing a black and white OLED display seemed appealing. However, as the size increased, so did the price, and even then, the displays were still too small. Consequently, the most practical decision was to adhere to LCD technology.

Upon researching LCD modules, the *LCD1602* module emerged as a suitable choice. It offers sufficient size, accommodating up to 16 characters per row across 2 rows, and provides satisfactory contrast. Additionally, it is available with I2C adapters for simplified control, requiring fewer pins on the microcontroller.

Figure 2.5: LCD1602 board

Buzzer

Beyond just relying on visual cues displayed on the screen to convey the device's status, it's essential to enhance the user experience by incorporating auditory feedback. When employees clock in to work, providing a distinct sound signal from a buzzer ensures they receive immediate confirmation of their action.

There are two types of buzzer:

- **Active buzzers**: they incorporate an internal oscillator circuit that generates the sound signal when voltage is applied. They are self-contained and do

not require external circuitry to produce sound. They are commonly used in applications where simplicity and ease of use are prioritized, as they can be directly connected to a power source to emit sound.

- **Passive buzzers**: they require an external oscillating circuit to produce sound. An alternating current is applied to create vibrations that produce sound waves. They offer more flexibility in sound frequency and intensity control but require additional circuitry for operation.

Due to the project's time constraints and the preference for simplicity, **active buzzers will be employed**. Additionally, since a single sound frequency suffices for the intended use, active buzzers are well-suited for the task.

Cellular Connectivity Module

In certain locations, access to WiFi networks may be limited or unavailable altogether. Even in areas where WiFi is accessible, signal strength may vary, leading to instances of poor connectivity. Consequently, it becomes imperative to incorporate cellular connectivity options to ensure internet access across diverse environments and conditions. By integrating cellular connectivity capabilities into the system, users can rely on alternative means of internet access, mitigating the limitations posed by WiFi availability and signal quality fluctuations.

Considering the time limitations, it would be benefitial to opt for a ready-made solution. However, it's worth noting that the Raspberry Pi Pico, being a microcontroller, cannot simply utilize a USB dongle with a SIM card adapter for cellular connectivity. A more intricate solution is necessary. Fortunately, there exists a module specifically designed for compatibility with the Pi Pico, developed by *Waveshare*. This module integrates the *SIM7020E* module, manufactured by *SIMCOM*, a prominent provider of wireless modules and electronics.

The *SIM7020E* module, known for its affordability and low power consumption, is specifically designed for NB-IoT[1] applications, making it an optimal choice for M2M[2] communication scenarios. Integrated into the *Waveshare* board, this module establishes communication with the Pi Pico through UART, using *AT*[3] commands for control and data exchange [15].

However, a significant tradeoff exists as this module only supports NarrowBand IoT. NB-IoT operates within the LTE (Long-Term Evolution) spectrum and is tailored for narrow bandwidths, making it ideal for low-power, wide-area IoT applications. While NB-IoT typically utilizes the 4G LTE spectrum, it operates at reduced data rates compared to conventional LTE, facilitating efficient communication with IoT devices while minimizing power consumption and costs.

[1] NB-IoT, short for Narrowband Internet of Things, is a low-power cellular technology designed for efficient communication between IoT devices and networks.

[2] M2M stands for Machine-to-Machine, and encompasses a wide range of applications where devices or machines communicate and exchange data without human intervention.

[3] AT commands are a standardized set of instructions used to communicate with and control modems and other serial devices.

Nonetheless, this limitation poses challenges as the range constraints of LTE networks persist, potentially leading to signal issues in underground facilities. In an ideal scenario, a module supporting 2G and NB-IoT would be preferable for the project. However, such modules are not readily available on the market for seamless integration with the Pi Pico. While *SIMCOM* does offer several variants of these modules with diverse capabilities, developing a custom solution would necessitate significant investment in terms of both time and resources.

However, the downside of this approach is that the module requires soldering of fourteen pins (the ones whose text is highlighted in white in Fig. 2.7), introducing an additional layer of complexity to the device assembly process. Furthermore, it is important to note the stacking headers featured in Figures 2.6 and 2.7, which consist of female headers with extended male pins. These pins are designed to penetrate the PCB and connect to another female header underneath. While this setup may appear standard, improper soldering, with excess tin reaching too high on the male part of the header, can lead to faulty connections with the PCB or breadboard. Therefore, if the team intends to assemble the device on-site, careful soldering is a must.

Figure 2.6: Waveshare's SIM7020E module, top view

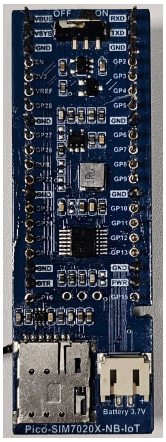

Figure 2.7: Waveshare's SIM7020E module, bottom view

Buses

As previously mentioned, various buses are available for interconnecting components. While the LCD is already set up for I2C, the NFC reader offers more flexibility in bus selection. However, to maintain simplicity, the NFC reader will also utilize the I2C bus.

I2C, short for Inter-Integrated Circuit, is a serial communication protocol commonly utilized for connecting microcontrollers and peripheral devices. It operates using two wires: *SDA* (Serial Data) and *SCL* (Serial Clock). Devices connected to the bus are addressed individually by unique addresses, and communication follows a master-slave configuration. The master device initiates communication and controls the bus, while one or more slave devices respond to commands. Data is trans-

ferred sequentially, with the master device generating clock pulses to synchronize communication [11].

However, I2C does have limitations. It operates at relatively low speeds compared to other protocols, which can impact performance in applications requiring high data transfer rates. The length of the I2C bus is also limited due to signal integrity issues, typically to a few meters, which may restrict the physical layout of devices in larger systems. In any case, none of these limitations affect this project's use case.

The *Pi Pico* features two I2C buses, providing an additional bus beyond what is required. It's important to mention that the two modules can share the same I2C bus since they have different I2C addresses. For instance, the PN532 always uses the *0x48* address, which cannot be modified. Consequently, two PN532 readers cannot share the same bus and must be placed separately. However, this is not an issue for the LCD as it uses a different address.

Note: While the PN532 produced by *NXP* does allow for the modification of the I2C address [12], it is conventionally maintained at *0x48* [13].

Matrix Keypad

A matrix keyboard offers an alternative means for employees to clock in or out by entering a numeric code, which can be particularly useful if an employee forgets or misplaces their card. The working principle of matrix keyboards is straightforward: as illustrated in Figure 2.9, they consist of intersecting rows and columns. Each key on the keyboard is positioned at the intersection of a row and a column. When a key is pressed, it creates a connection between a specific row and column, resulting in a unique electrical signal that can be interpreted by the microcontroller.

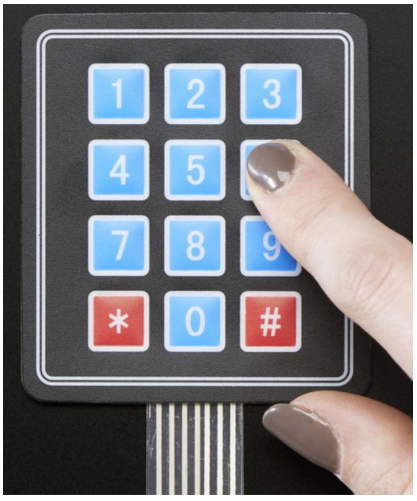

Figure 2.8: Matrix keypad

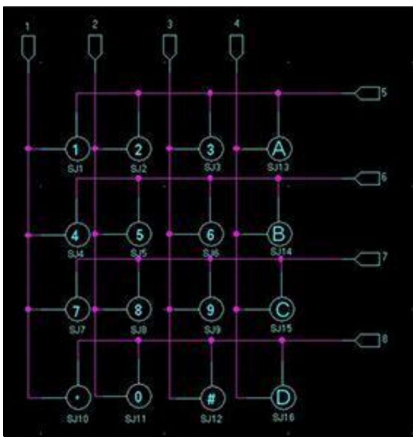

Figure 2.9: Matrix keypad's schematics

Matrix keyboards utilize a scanning technique to detect key presses. The microcontroller sequentially activates each row, while monitoring the columns for any

signals. If a signal is detected, the microcontroller identifies the corresponding key based on the activated row and column, allowing it to register the key press.

One important consideration when using matrix keyboards is the potential for key ghosting or masking. Ghosting occurs when multiple keys are pressed simultaneously, causing the keyboard to register unintended key presses. Masking, on the other hand, happens when certain key combinations prevent other keys from registering. To mitigate these issues, careful design and debounce techniques must be employed to ensure reliable key detection.

During testing, it was observed that with sufficiently fast scanning and debouncing, the occurrence of ghosting or masking on the keyboard would likely not present a problem in practical usage scenarios. This assessment stems from the understanding that the likelihood of multiple key presses happening simultaneously on a wall-mounted device, such as the one being developed, is minimal.

Another challenge arises from the substantial use of GPIO pins on the microcontroller. The 4×4 keyboard depicted in Figure 2.8, consisting of 4 rows and 4 columns, requires 8 GPIO pins for operation. Considering that the Pi Pico offers a total of 29 GPIO pins, this allocation accounts for nearly 30 percent of available pins.

2.2. Prototype Assembly

Once the components have been selected and basic schematics drawn, the assembly process can commence. All components can be interconnected on a breadboard using jumper wires. It is important to highlight that the Raspberry Pi Pico WH comes with pre-soldered headers, facilitating easy integration for testing purposes. Only minimal soldering is required for certain components, such as the four pins on the NFC module and the fourteen pins for the Waveshare module.

Many of the components necessary for this prototyping phase can be obtained by purchasing a basic electronics kit, which typically includes a breadboard and jumper wires, and other basic components such as a matrix keyboard and buzzer.

In addition to the minor soldering required, the majority of components were effortlessly connected to the breadboard using jumper wires. The small footprint of the Pi Pico further simplified the connections to its pins.

In the subsequent sections, detailed explanations of the wiring configurations for all modules will be provided, offering insights into their respective functionalities and interconnections within the system.

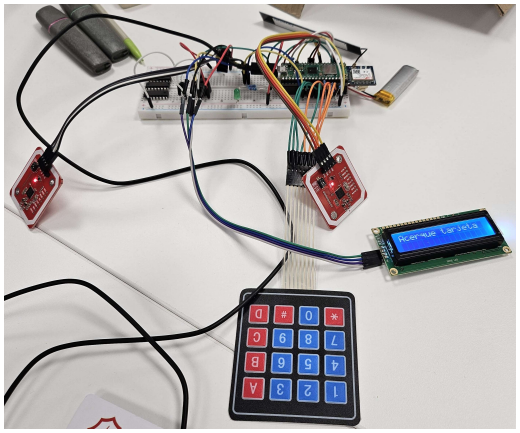

Figure 2.10: First prototype mounted on a breadboard

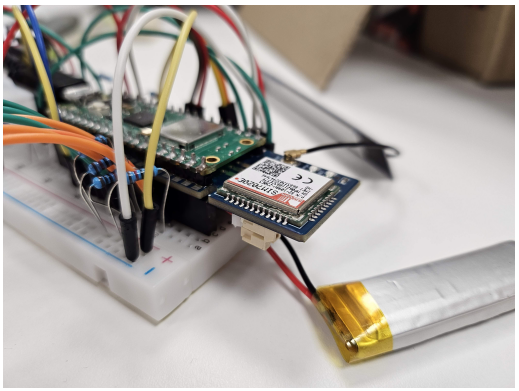

Figure 2.11: Zoom in on the Pi Pico and SIM7020E module

2.2.1. Matrix keypad wiring

Row Pins Configuration

- The 4 row pins are configured as INPUT with PULL-UP resistors enabled. This configuration allows the microcontroller to detect changes in voltage on these pins.
- Each row pin is connected to the positive supply voltage (3V) through a 10kΩ resistor. This ensures that when no button is pressed, the row pins maintain a high voltage level due to the PULL-UP resistors.
- When a button in a particular row is pressed, it creates a connection between the row and column pins, effectively pulling the voltage level of the corresponding row pin down to ground.

Column Pins Configuration

- The 4 column pins are configured as OUTPUT. During scanning, each column pin is individually set to false (logic low), one at a time, while the others remain at a high logic level (logic high or true).
- By setting a column pin to false, it creates a path to ground for the corresponding row pins. If a button in the corresponding column and row is pressed, the voltage on the row pin is pulled low, indicating a button press.

Button Press Detection

- When a button is pressed, it forms a connection between a row and column pin. During scanning, when the corresponding column pin is set to false, it effectively pulls the voltage on the row pin down to ground.

- The microcontroller continuously scans each column pin, one by one, and if it detects changes in voltage on one row pin, then it already pinpointed the row-column pair, corresponding to a key press.

In summary, this configuration allows the microcontroller to detect button presses on the keypad by scanning each column and monitoring the voltage levels on the row pins. When a button is pressed, it creates a connection between a row and column pin, causing a change in voltage on the row pin, which is detected by the microcontroller.

2.2.2. Devices on the I2C bus

Thanks to the straightforward nature of I2C communication, connecting both the LCD display and the NFC reader requires just two wires each: one for the Serial Data Line (SDA) and the other for the Serial Clock Line (SCL), in addition to the necessary VCC and GND connections. With the Pi Pico offering two I2C buses, either or both buses can be used. This versatility is possible because the two devices possess distinct I2C addresses, as specified in their respective datasheets.

I2C Pull-up

Ensuring proper signal integrity is crucial for the reliable operation of I2C communication. One essential consideration in this regard is the implementation of pull-up resistors on both the SDA and SCL of the bus.

Pull-up resistors serve to maintain the default high logic level on the SDA and SCL lines when they are not actively being driven by the master or slave devices. Without pull-up resistors, the I2C lines may float, leading to undefined voltage levels and potential communication errors.

The pull-up resistors effectively "pull" the voltage level of the I2C lines to the high logic level when they are not actively being driven low by a device. This ensures clear signal transitions and prevents signal distortion or noise interference that could disrupt communication.

Typically, pull-up resistors are connected between the SDA and SCL lines and the positive supply voltage (VCC) of the system. The value of the pull-up resistors determines the strength of the pull-up effect and should be chosen carefully to balance signal integrity with power consumption.

During the initial stages of the project, pull-up resistors were manually added to the SDA and SCL of the I2C bus to ensure proper signal integrity. However, it was later discovered upon examination of the device schematics that both the LCD display and NFC reader modules already incorporated pull-up resistors on their respective boards, with voltage level translation from 5V to 3.3V.

This unintentional duplication of pull-up resistors led to a reduction in the overall resistance of the pull-up network and an increase in the strength of the pull-up

effect on the I2C lines. The existing 4.7kΩ resistor in both the NFC reader and LCD modules inadvertently paralleled with an additional 10kΩ resistor, effectively reduced the overall resistance to approximately 3.2kΩ [7]. While this theoretically could result in faster signal transitions, it also heightened susceptibility to noise and interference, potentially leading to signal integrity issues. Additionally, the increased current draw from the additional pull-up resistors slightly elevated the power consumption of the system.

Despite these consequences, it is important to note that the unintentional duplication of pull-up resistors is unlikely to cause permanent damage to the devices involved.

Problems with the NFC reader

During a later phase of the project, an issue surfaced wherein the NFC reader would cease to respond after prolonged periods of operation. The only indication of this malfunction was rapid flickering of its red LED. Attempts to command the reader yielded no response, needing a power cycle to restore functionality. This could be achieved either by disconnecting and reconnecting the power source or by pulling down the "RSTPD_N" pin on the board. To mitigate this recurring problem, a solution involving the insertion of a transistor between the microcontroller and the VCC pin on the NFC board was devised. This approach was favored over direct soldering onto a minuscule 1-millimeter pin on the NFC board, which presented challenges and fitting problems.

2.2.3. The SIM7020E board

With the Waveshare board purposefully engineered to align with the pinout of the Pi Pico, no wiring is necessary beyond connecting the two components. This module interfaces with the microcontroller via UART for communication and utilizes additional GPIO pins for auxiliary functions such as power management.

A critical consideration is to avoid utilizing any pins already allocated by the SIM7020E board. This precaution can be ensured by referencing the datasheet and wiki documentation provided by the manufacturer [18].

Although the device includes a 3.7V Li-Po battery in the box, it was decided against its utilization due to concerns about introducing an additional point of failure to the device. Furthermore, its presence impedes the Raspberry Pi from undergoing a hard reset when disconnected from the power source.

2.2.4. Buzzer and other components

The active buzzer, requiring minimal setup, simply needs a transistor to toggle its state using a control signal from the microcontroller. It's essential to note that it must still be connected to a 5V source, as the 3.3V from the GPIO pins is insufficient, hence the requirement for the transistor.

Adding an LED to the project is similarly straightforward, as it can be controlled directly by a GPIO pin due to its lower voltage and current requirements. When paired with a 50Ω resistor, the LED emits sufficient brightness, even in well-lit conditions. However, ultimately, it was deemed unnecessary and excluded from the final design.

2.2.5. Considerations

The initial prototype incorporated two NFC modules, as can be seen on figure 2.10, intending to use one module for clocking in and the other for clocking out. This approach was adopted initially to streamline compatibility with a specific provider. However, this strategy was subsequently abandoned in favor of a simpler solution, whereby the worker's entry or exit status is determined through software processing.

Initially, the matrix keyboard was contemplated as an alternative method for clocking in or out by entering a numeric code. However, this approach was deemed impractical due to several concerns. Using the worker's national identification number as the input code would involve handling sensitive information, which was not ideal. Additionally, distributing individual codes to each worker would present logistical challenges. As a result, this approach was ultimately abandoned.

Chapter 3

PCB Design

Following the initial development on a breadboard, the natural progression in the design evolution was to transition to a perfboard assembly. This intermediate step not only served to condense the device's footprint but also offered a preliminary glimpse into its form and functionality. Subsequently, the culmination of this iterative process involved the design and fabrication of a PCB tailored to the project's specifications, marking a significant milestone in its realization.

3.1. Assembling on a Perfboard

Perfboards, short for perforated boards, are commonly used prototyping platforms in electronics. They consist of a board with a grid of holes spaced at regular intervals. These holes are surrounded by copper pads or traces that can be connected using solder to create electronic circuits. Perfboards allow electronic components, such as resistors, capacitors, integrated circuits, and other discrete components, to be soldered onto the board, facilitating the creation of temporary or semi-permanent circuits for testing and development purposes [5]. They serve as a practical and versatile tool for electronics hobbyists, engineers, and designers to quickly prototype and iterate on circuit designs before moving to more permanent solutions like printed circuit boards (PCBs). Examples can be seen in Figures 3.1 and 3.2.

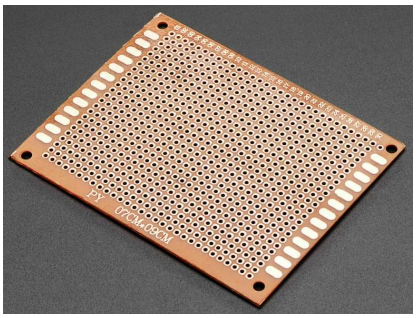

Figure 3.1: Back side of a perfboard

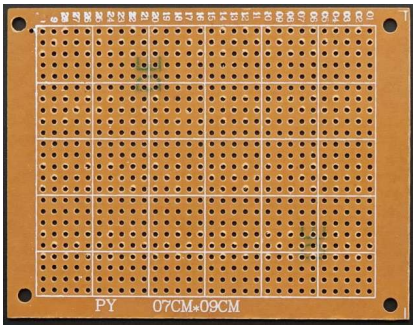

Figure 3.2: Front side of a perfboard

In the context of this project, transitioning to a perfboard prototype served multiple crucial purposes. Firstly, it offered a tangible visualization of the future device's physical footprint, providing executives with a concrete representation of the project's direction and potential. This visual aid not only conveyed the scale and form of the device but also showed its feasibility and progress, instilling confidence in its development trajectory.

To commence this phase, a diagram detailing the placement of each component and its connection to the corresponding pins on the microcontroller was drafted. This diagram served as a blueprint, guiding the subsequent assembly process.

With the schematic as a roadmap, the assembly of the perfboard prototype commenced. Components were transitioned from the breadboard to the perfboard, ensuring each element found its designated place. Careful consideration was given to the layout, optimizing spatial organization for efficient circuitry and minimal interference.

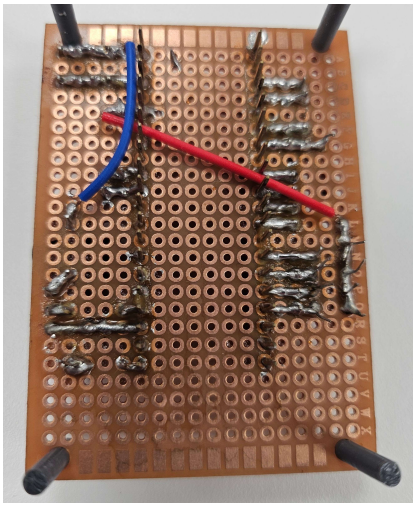

Figure 3.3: Back side of the assembled perfboard

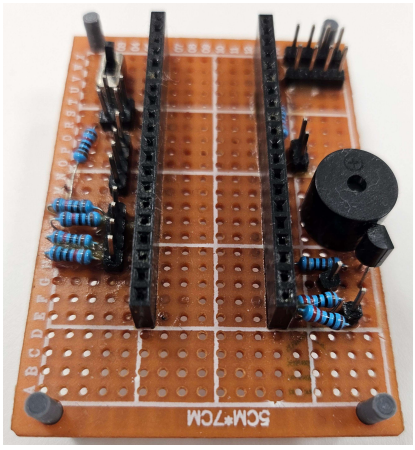

Figure 3.4: Front side of the assembled perfboard

3.2. Designing the PCB

Now that the perfboard provided a good idea of how the PCB would be, now it has to be properly designed. As it could be seen before, the perfboard's main job was to bring all components together, and that will also be the case for the PCB. It would give a much cleaner look than the perfboard, and be much more comfortable to plug components into, since on the perfboard traces could not overlap, limiting design possibilities. Now, with a multi-layer PCB, traces could go above and below each other, allowing for the placement continuous male headers for each component.

Having used the perfboard as a preliminary platform to consolidate components and understand the spatial dynamics of the circuit, the focus now shifts towards the meticulous design of the printed circuit board (PCB).

The primary function of the PCB mirrors that of the perfboard: to integrate and interconnect all components seamlessly. However, unlike the perfboard, the PCB offers advantages in terms of aesthetics, functionality, and ease of assembly.

Moreover, the transition to a multi-layer PCB introduces a realm of design possibilities previously unattainable with the perfboard. By using multiple layers, traces can now traverse both above and below the surface, allowing for more flexibility in component placement and routing. This feature allows for the implementation of continuous male headers for each component, which were not easily implemented with the perfboard.

3.2.1. Requirements

As mentioned earlier, this PCB is designed primarily as an interconnection platform for the various components of the device, making its complexity relatively low.

The SIM7020E board would be positioned beneath the Pi Pico using stacking headers, as illustrated in Figure 2.6, thereby reducing the number of interconnections required.

Additionally, it requires integration of the buzzer and its transistor, while certain parts were retained in case of future requirements, given their minimal cost. These include the matrix keyboard's header, the additional NFC reader's header, and the LED's header. Further details on the cost will be provided in the next section.

Another critical requirement driving the development of a custom PCB is the need to streamline the device's assembly processes. In line with this objective, it's essential for the PCB to arrive pre-assembled. While it's common for boards to be sold without soldered components, pre-assembled PCBs are a must for this project to be economically and logistically viable. Thus, an ideal provider would offer both manufacturing and assembly services.

3.2.2. Design and Production

In the quest for a user-friendly PCB design program, *EasyEDA*[1] emerged as a promising option. Offering a schematic design tool, it facilitated the transition from hand-drawn schematics to digital diagrams. EasyEDA allows users to seamlessly translate these diagrams into PCB layouts, enabling the placement of components, definition of board dimensions, and automatic routing of traces to interconnect all elements. Thanks to its simplicity, a final design was swiftly achieved within a matter of days.

It was discovered that EasyEDA has a partnership with *JLCPCB*[2], a company offering comprehensive PCB manufacturing and assembly services. Additionally,

[1] EasyEDA's website: `https://easyeda.com/`
[2] JLCPCB's website: `https://jlcpcb.com/`

EasyEDA seamlessly integrates with *LCSC*[3], a supplier providing a comprehensive parts catalog with detailed specifications for each component used in the project. Notably, the final pricing was highly competitive, and with all these providers working together, support extended throughout the entire production process, from schematic design to the final product.

A few considerations regarding part selection:

- Since active buzzers can only be turned on or off, the sound's frequency is already pre-determined. This has to be taken into consideration when choosing one.
- The transistor responsible for controlling power to the buzzer must meet the power specifications and respond to changes in voltage from a GPIO pin (3.3V). Fortunately, given that the voltage at the drain is 5V and the current is in the milliamp range, virtually any transistor would be suitable for this purpose.
- Since regular *DuPont* jumper wires will be used, each one of the headers' pins have to be 2.54mm apart (which is the equivalent to 0.1 inches), thus compatible headers need to be selected.
- Mounting holes would be needed on each corner to attach it to a box, which would be designed in the future.

After navigating through a learning curve with the parts catalogue and sorting through dozens of providers for each component, all necessary parts were successfully chosen, and the PCB was prepared for production.

Figure 3.5: PCB's top view

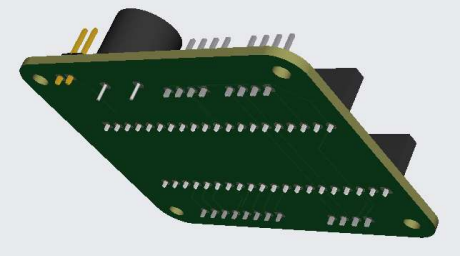

Figure 3.6: PCB's bottom view

During the ordering process, a 3D model of the PCB with the selected parts is displayed, similar to Figures 3.5 and 3.6. It's important to note that the PCBs are manufactured in China and then shipped internationally. Factors such as import tariffs and shipping costs need to be taken into account. Despite these considerations, the price remained competitive compared to local alternatives, even after factoring in customs duties and shipping fees. Remarkably, the PCBs arrived within a week of ordering.

[3]LCSC's website: `https://www.lcsc.com/`

The quality of construction exceeded expectations, with all components fitting perfectly on the first try. The selected buzzer emitted the expected pitch, and everything functioned as intended. Executives were pleasantly surprised by the remarkably low price per unit.

Chapter 4

Code Implementation and Development Challenges

The software development phase represents a significant portion of the project timeline, demanding meticulous attention to detail and thorough problem-solving skills. In the forthcoming sections, an overview of the software requirements will be provided, shedding light on how these requirements were effectively addressed. Additionally, detailed insights into the encountered challenges and the corresponding solutions devised will be explored.

One crucial decision made early on was the selection of CircuitPython as the programming language for the device. This decision stemmed from several key factors, including its open-source nature, extensive library support, and the availability of pre-existing libraries with MIT licenses, particularly those essential for handling NFC readers. Furthermore, CircuitPython's user-friendly syntax and simplified microcontroller programming paradigm were deemed advantageous compared to alternatives like MicroPython, contributing to smoother development workflows.

However, it's important to note that despite the benefits of CircuitPython, the project encountered limitations imposed by the microcontroller's memory capacity, capped at 264kB. This constraint was exacerbated by the use of Python, a high-level language known for its memory-intensive nature. Throughout the development process, various memory optimization strategies were implemented to mitigate these limitations. These optimizations will be thoroughly explained, providing valuable insights into managing resource constraints in microcontroller-based projects.

In addition to the aforementioned aspects, it's crucial to highlight the iterative nature of software development, where frequent testing, debugging, and refinement cycles were integral to achieving desired functionality and performance. This iterative approach enabled the project team to address emerging issues promptly and iteratively enhance the software's robustness and reliability.

Furthermore, a detailed examination of the software architecture and design decisions made will offer valuable insights into the project's development methodology and the rationale behind specific implementation choices.

4.1. CircuitPython: Advantages and Disadvantages

CircuitPython is an open-source programming language designed specifically for microcontroller-based development. Developed primarily by Adafruit Industries, CircuitPython is built on top of the Python programming language, offering a simplified yet powerful platform for programming microcontrollers. Unlike traditional embedded programming languages, CircuitPython abstracts many low-level complexities, making it more accessible to beginners and hobbyists while still providing advanced features for experienced developers.

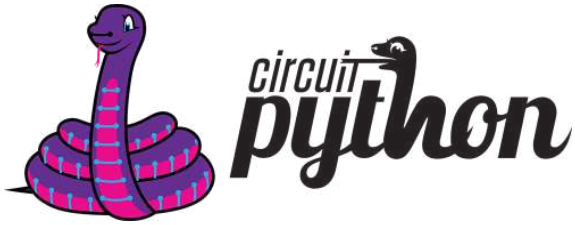

Figure 4.1: CircuitPython's logo

One of the key advantages of CircuitPython is its user-friendly syntax and high-level abstractions, which resemble those of Python, a language renowned for its readability and simplicity. This makes CircuitPython particularly attractive to beginners and educators, enabling them to quickly grasp programming concepts and develop projects without being bogged down by intricate syntax or complex setup procedures.

Furthermore, CircuitPython simplifies the process of interacting with hardware peripherals and sensors commonly used in embedded systems. It provides a consistent and intuitive API (Application Programming Interface) for accessing GPIO pins, I2C and SPI interfaces, analog inputs, and other hardware features, streamlining the development process and reducing the learning curve associated with embedded programming.

Another notable advantage of CircuitPython is its extensive library support, particularly for popular microcontroller boards and peripherals. Adafruit maintains a vast repository of CircuitPython libraries, covering a wide range of sensors, displays, actuators, communication modules, and other components commonly used in electronics projects[1]. These libraries abstract the complexities of interfacing with specific hardware, allowing developers to focus on application logic rather than low-level hardware details.

Despite its numerous advantages, CircuitPython does have some limitations and drawbacks. One notable limitation is its higher memory footprint compared to lower-level languages like C or assembly, which can be a concern for projects with strict memory constraints. Additionally, while CircuitPython abstracts many hardware complexities, it may sacrifice some performance compared to bare-metal or lower-level programming approaches.

[1] Adafruit's Library Bundle: `https://github.com/adafruit/Adafruit_CircuitPython_Bundle`

Overall, CircuitPython offers a compelling combination of simplicity, accessibility, and versatility for microcontroller-based development, making it an excellent choice for a wide range of projects, from educational endeavors to commercial products. Its rich ecosystem of libraries, ease of use, and strong community support contribute to its popularity among hobbyists, educators, and professional developers alike[2].

For this project, CircuitPython version 9.0.0 will be used.

4.2. Code Requirements

The device must prioritize responsiveness and intuitive usability for all employees. This ensures that the device can be easily operated by users of varying technical proficiency levels, promoting efficient and accurate clocking processes.

Furthermore, the device must maintain the highest possible uptime to ensure continuous operation without interruptions. This is crucial for accurate time tracking and prevents any disruptions that could lead to discrepancies in employee attendance records.

Data integrity is of paramount importance, as any loss of data could result in unfair deductions from employees' wages. Therefore, the device must be designed to prevent data loss under any circumstances, even in the event of power outages or connectivity issues. It should have the capability to store clockings locally and reliably transmit them to the server once connectivity is restored.

In situations where internet connectivity is temporarily lost, the device must continue to store clockings and transmit them as soon as connectivity is regained. This ensures that no clocking data is lost and enables seamless operation regardless of network conditions.

Efficient data transmission is essential for real-time monitoring and analysis of employee attendance. Therefore, the device should send clocking data as soon as it is available, without any delays, to ensure timely reporting and accurate statistics.

Flexibility is also key, as the device must be capable of operating using either WiFi or cellular data connectivity, depending on the specific configuration and deployment requirements.

Moreover, the device should incorporate a mode-switching feature, allowing it to display relevant information such as the device's ID and enabling easy implementation of additional modes in the future. This ensures scalability and adaptability to changing needs and requirements.

Additionally, the device must display the current time on the screen to provide users with real-time information and facilitate accurate clocking processes.

To enhance user experience and ensure successful clocking operations, the device should provide visual and audible cues to indicate successful clockings. It should also alert users to errors, such as attempting to clock in multiple times with the same keycard.

Finally, all clocking data should be securely transmitted to an API using POST requests, ensuring that it is reliably delivered to the server for processing and storage. This maintains data integrity and enables seamless integration with existing systems and workflows.

4.3. Overview

In this section, a brief overview of the main workings of the code will be provided, with more detailed explanations to follow in subsequent sections.

The code operates two main tasks running asynchronously, which share CPU time efficiently.

- **Main Loop**: This task continuously listens for NFC cards. When a card is detected, it adds the clocking data to the device's storage. Additionally, this task periodically instructs the second task to send a "keepalive" message to the server.
- **Data-Sending Task**: This task reads the device's storage for any stored clockings. When it finds clocking data, it sends a POST request to the server. This task manages all internet communications.

This division of labor ensures that the device remains responsive and does not hang. If a worker had to wait for a POST request to complete before clocking in, the delay could range from 10 seconds to a few minutes (due to the NB-IoT's network slow responses), which is unacceptable. By making the main loop independent from the data-sending task, the system maintains its responsiveness and efficiency.

4.4. Code Implementation

4.4.1. Asynchronous Programming

Asynchronous programming is a programming paradigm that allows multiple tasks to be executed concurrently, without the need for explicit parallelism or multithreading. It enables programs to perform non-blocking operations, where tasks can be started and completed independently of each other, leading to improved performance and responsiveness.

In CircuitPython, asynchronous programming is achieved using the `asyncio` module, which provides a framework for writing asynchronous code using coroutines. Coroutines are functions that can be paused and resumed during execution, allowing for efficient task scheduling and coordination.

The key concept in asynchronous programming in Python is the `async` and `await` keywords. Functions defined with the `async` keyword are called asynchronous

functions, and they can be paused with the `await` keyword when they encounter an operation that may block, such as I/O operations or network requests.

When an asynchronous function is awaited, it returns control to the event loop, allowing other tasks to continue executing in the meantime. Once the awaited operation completes, the function resumes execution from the point where it was paused.

The event loop is a central component of asynchronous programming in Python and CircuitPython. It manages the execution of asynchronous tasks and ensures that they are scheduled and executed efficiently. The event loop continuously checks for tasks that are ready to run, executes them until completion or until they are paused, and then moves on to the next task [2].

The code extensively utilizes asynchronous programming to enhance the perception of concurrency and prevent the device from becoming unresponsive. This is crucial, especially considering that the device displays the time, including seconds, on the screen. However, while this approach offers significant benefits, it also introduces certain drawbacks, which will be addressed later.

Later on, this aspect will be further explored. Essentially, two tasks will run within the event loop: one managing the main loop, waiting for workers to approach the device with their keycards, while the other will handle the transmission of clockings to the internet.

4.4.2. Main Loop and Operating Modes

The main loop executes functions on the current operating mode. These modes, essentially Python classes, implement an interface containing four functions: `enter_mode`, `exit_mode`, `card_received`, and `no_card_found`. Depending on the event, one or more of these functions may be invoked.

Initially, the device starts in a default mode. When the "configuration keycard" is detected by the NFC reader, the mode transitions to a different one, triggering the `exit_mode` function on the mode that is being exited, and `enter_mode` in the mode that entered execution.

As part of its operation, the NFC reader is configured with a timeout to detect the presence of any card near its antenna. Upon successful detection, it reads the UID of the card.

Additionally, the main loop is responsible for sending a periodic "keepalive" message to the server to maintain connectivity.

4.4.3. Interchangeable WiFi and Cellular Data Operation

In certain deployment locations, access to WiFi may not always be available. Furthermore, even in areas with existing WiFi coverage, circumstances can change, requiring the device to be relocated to areas without such connectivity. In such scenarios, cellular data operation becomes essential.

To facilitate internet usage, an interface was created with fundamental functions for internet communication. Essentially, the primary requirement was the capability to send POST requests, or a series of them. Consequently, two classes were designed to adhere to this interface: one serving as a controller for WiFi connectivity, and the other for the SIM7020E module.

Either of these controllers could be employed seamlessly, with the device operating without any noticeable difference.

Regarding the WiFi functionality, Adafruit offers comprehensive code for executing requests via WiFi under an MIT license. This code was subsequently modified to operate asynchronously, aiding in preventing device hang-ups. Details regarding the SIM7020E code will be provided in the subsequent subsection.

4.4.4. SIM7020E Module

The SIM7020E module, which facilitates cellular data connectivity, operates using *AT commands*.

AT commands, short for "Attention commands", are a standardized set of instructions used to communicate with modems, including those integrated into cellular modules like the SIM7020E. These commands are typically sent from a host device, such as a microcontroller or computer, to the modem via a serial communication interface (such as *UART*, which is the case for this Waveshare board).

AT commands follow a specific syntax, starting with the characters "AT" (hence the name), followed by a command mnemonic and optional parameters. They are used to configure various settings, initiate actions (such as making a phone call, sending a text message or sending a POST request), query status information, and handle other modem-related tasks.

For example, to check the signal strength of a cellular connection, the command "AT+CSQ" may be sent to the modem, which would respond with a value indicating the signal quality. Similarly, to establish a data connection, the command "AT*MCGDEFCONT" may be used, followed by parameters specifying the APN (Access Point Name) and other connection details. It is worth noting that some of these commands may vary depending on the module used, and some are manufacturer specific [14].

AT commands provide a standardized interface for interacting with modems, allowing developers to integrate modem functionality into their applications without needing to understand the intricacies of the underlying hardware.

SIMCOM offers a specific manual for the SIM7020E, delineating the AT commands, their parameters, usage instructions, and responses. This manual proved indispensable for using the module, especially considering the scarcity of code examples available online for this specific module, apart from the brief code snippets provided by Waveshare as illustrative examples.

Commands are transmitted to the transmit UART buffer, where they await processing by the SIM7020E module. Following a command transmission, the module

responds, and its responses are stored in the designated memory region allocated for the receive UART buffer.

Subsequently, the receive UART buffer must be periodically checked to ascertain whether the entire response has been received. This periodic monitoring is essential since not all responses may be promptly received without any delay, potentially leading to device hang-ups. This necessity for asynchronous programming arose primarily from this requirement. Consequently, with asynchronous programming implemented, a command is dispatched, and the response is continuously read until the entire message is received, allowing for subsequent commands to be processed.

It's crucial to note that only one "thread" is engaged in communication with the SIM7020E module, obviating the need for locks or synchronization mechanisms to prevent the dispatch of additional commands while awaiting a response. Such simultaneous command dispatch would risk causing errors within the module.

Certain commands, particularly those related to establishing connections with the internet and external servers, inherently entail longer execution times, necessitating longer wait times during the response retrieval process.

Regarding POST requests, a sequential series of steps must be meticulously followed to ensure successful transmission. These steps will be explained to provide a clearer understanding of the module's interaction mechanisms.

CHTTPCREATE

First, an HTTP or HTTPS client instance must be created within the module. Here, the host is specified:

```
AT+CHTTPCREATE="https://example.com"
```

And after waiting for the corresponding response, the following will be read:

```
+CHTTPCREATE: 0\r\n\r\nOK\r\n
```

Notice the appearance of "`\r`" and "`\n`", due to the use of Python's byte strings.

Most commands end with the appearance of "`OK\r\n`", which allows for easily checking if a command has finished executing, to then send the following one.

CHTTPCON

The next step is to establish the HTTP connection with the server, by executing the following:

```
AT+CHTTPCON=0
```

Notice the "0" used in the command. That number has to be the same one as the one returned as a response in the `CHTTPCREATE` command. What that number means,

is the slot that the host is occupying in the module's memory. In the SIM7020E, there can be only 5 hosts in total (numbers 0 to 4). Thus, by connecting to the index "0", the device will establish the connection with the host just created.

The following response will be received in case of success:

```
\r\nOK\r\n
```

CHTTPSEND

Now, the actual POST request can be sent. The structure of the command is the following: "`AT+CHTTPSEND=<httpclient_id>, <method>, <path>, <header>, <content_type>, <content_string>`".

The values for this command will be the following:

- `httpclient_id`: "0", as explained before.
- `method`: the number "1" corresponds to the POST method, as explained by the commands manual.
- `path`: this is the endpoint. The host's URL must not be specified.
- `header`: the header contents, encoded in hexadecimal.
- `content_type`: the content type, as in any regular POST request. For example: "application/json".
- `content_string`: the data contained in the POST request, encoded in hexadecimal.

In the following example, the following headers will be sent, encoded in hexadecimal:

```
Accept:  */*
Connection:  Keep-Alive
User-Agent:  RPI_PICO
```

And the following data:

```
{"data":  "some information"}
```

This is the resulting command:

```
AT+CHTTPSEND=0,1,"/some_endpoint",
4163636570743a202a2f2aa436f6e6e656374696f6e3a204b65657
02d416c697665a557365722d4167656e743a205250495f5049434fa,
"application/json",
7b2264617461223a22736f6d6520696e666f726d6174696f6e227d
```

CHTTPDISCON

The last command to be executed is the disconnection from the HTTP server:

```
AT+CHTTPDISCON=0
```

The number sent in the command is a "0" again, and the response will be another OK. With this, the POST request will have been sent, and the connection terminated.

The HTTP field could be destroyed with the `CHTTPDESTROY` command, but this is not needed, since it will be reused, and would only increase inefficiencies in sending a new request. In fact, if there are many POST requests queued to be sent, then they could even be sent continuously before sending the `CHTTPDISCON`.

4.5. Challenges

This section examines the challenges faced during the development process. From technical obstacles to unforeseen setbacks, each hurdle provided an opportunity for problem-solving and refinement.

4.5.1. Lack of Multithreading

While CircuitPython incorporates asynchronous programming via the `asyncio` library, it's essential to note that this differs from traditional multithreading, a feature that is in fact supported by MicroPython. Asynchronous programming with `asyncio` allows for concurrent execution of tasks, but it operates within a single thread, managing task switching based on input/output operations or explicit yields. In contrast, multithreading involves the simultaneous execution of multiple threads, each running independently and potentially executing different code segments concurrently.

One significant challenge arises from the nature of CircuitPython's asynchronous programming model. While `asyncio` allows for the concurrent execution of tasks within a single thread, certain code segments lacking explicit yields may monopolize the event loop, hindering task switching and potentially causing sluggish performance. This becomes particularly evident in scenarios where tasks, such as establishing a WiFi connection, encounter delays. In such cases, where CircuitPython lacks native support for asynchronous WiFi operations, the device may become unresponsive for extended periods, up to 15 seconds, before timing out.

Regrettably, there exists no straightforward solution to address this challenge within the current framework. A potential avenue for improvement involves migrating the codebase to MicroPython, which offers multithreading capabilities. However, this approach necessitates significant reworking of existing libraries, presenting a formidable task exacerbated by time and budget constraints.

4.5.2. Memory Constraints and SSL Certificates

Python's inherent memory footprint, compared to C, is often larger, which poses a challenge given the limited 264kB of RAM available. Upon loading CircuitPython during startup, approximately 120kB of memory remains free. However, once all libraries are loaded and devices initialized, this dwindles to around 60kB.

While this may seem sufficient, complications arise when attempting to send a POST request to an HTTPS server over WiFi. SSL certificate validation requires a minimum of 60kB of available memory, dangerously close to the device's operational limit. The lack of descriptive error messages compounds this issue, necessitating extensive investigation to decipher the underlying problem. Anecdotal evidence suggests that errors may occur when available memory dips below 42kB [9], though during testing, errors consistently manifested when nearing the 60kB threshold. This discrepancy may be attributed to various factors, including CircuitPython version and memory fragmentation.

To mitigate memory constraints, a strategy was devised to import libraries only when needed. For instance, if the device operates in WiFi mode, code related to the SIM7020E module remains dormant. Additionally, the garbage collector is called upon constantly to minimize memory fragmentation and ensure sufficient space for SSL certificates.

During testing, the following errors were encountered:

- When available memory is insufficient by a big margin:

```
x509-crt-bundle:PK verify failed with error FFFFBD70
x509-crt-bundle:Failed to verify certificate
Exception:  <class 'RuntimeError'> Error connecting socket:
 (-12288, 'MBEDTLS_ERR_X509_FATAL_ERROR')
```

- When available memory is nearly adequate but still falls short a regular `MemoryError`.

In testing, it was challenging to ascertain the precise threshold between encountering the two errors. However, observations indicated that the first error surfaced at approximately 50kB or below, while a MemoryError occurred within the range of 50kB to 60kB.

Addressing this challenge proves daunting, as memory optimization can only achieve so much, and the alternative—removing code to reduce functionality—is undesirable.

4.5.3. NFC Reader Unresponsiveness

As detailed in Chapter 2 (see Chapter 2), during the later stages of testing, a significant issue emerged with the NFC reader. It would abruptly cease responding to requests until power was disconnected and reconnected. The only visible indication of this malfunction was the erratic flickering of the red LED on the board.

In software, the NFC reader would not trigger any error when polled solely for the presence of a keycard nearby. Therefore, continuous polling of the PN532 for its firmware version was used to ascertain its operational status. If it failed to respond, a reset was initiated with the assistance of a transistor.

4.5.4. Storage

The problem

Due to the necessity of retaining all clockings until their transmission to the server and even after system resets, the data had to be stored in the internal memory of the Raspberry Pi Pico. Despite its ample 2-megabyte capacity, sufficient to accommodate tens of thousands of clockings, the implementation was far from straightforward.

Initially, the process seemed straightforward. However, CircuitPython imposes limitations on writing to internal storage unless configured in the `boot.py` file, utilizing the `storage.disable_usb_drive()` function. Unfortunately, activating this function disables the Pi Pico's appearance as a drive on connected computers, thereby negating one of CircuitPython's key advantages for rapid debugging against MicroPython. Consequently, file transfers were relegated solely to the COM Port.

Once this hurdle was overcome, clockings could be stored in the internal storage. However, a critical scenario emerged: if the device experienced prolonged connectivity loss and accumulated 1 megabyte of clockings in internal storage, each clocking sent to the server necessitated removal from internal storage. Given that stored clockings should be sent in order of arrival, that is, a queue, the deletion process began with the first entry. Unfortunately, the provided filesystem lacked a "delete" method to selectively remove file content, forcing the entire file's rewriting.

This predicament not only engendered prolonged read and write times, potentially degrading flash memory, but also posed a fundamental memory constraint. With the Pi Pico lacking 1 MB of RAM to retain all data in memory simultaneously for file rewriting, the process proved doubly challenging.

The solution

To address the storage issue, an algorithm was developed to create multiple files, each with a fixed maximum number of clockings. For simplicity, let's assume each file holds up to 50 clockings, amounting to approximately 5kB per file.

As clockings accumulate, new files are created, each containing 50 clockings. These files are sequentially named starting from `file0` (e.g., `file0`, `file1`, `file2`, ..., `fileN`). When connectivity is restored, the clockings are removed from `file0` onward, maintaining a queue structure where the oldest entries are processed first. After removing many of the oldest clockings, the file structure may be, for instance: `file5`,..., `fileN`, which has to be accounted for in the algorithm.

This approach ensures that when a clocking is added or removed, the maximum amount of data handled in memory at any given time is limited to 5kB. This data is then quickly rewritten to storage, significantly reducing the risk of memory overload and enhancing system performance.

4.5.5. Connecting to the Google Cloud Platform

During initial testing with an API hosted on a local computer, connectivity issues were not encountered. However, after deploying the API on the Google Cloud Platform (GCP), the SIM7020E module began experiencing intermittent problems establishing the HTTP connection. Specifically, the CHTTPCON command would occasionally error out, causing significant delays in sending POST requests.

Attempts to establish the connection varied widely, sometimes requiring anywhere from 1 to 40 attempts to successfully execute the CHTTPCON command. This inconsistent behavior severely slowed down the data transmission process, necessitating an urgent resolution.

After extensive testing over several months, it was determined that this issue was unique to the GCP, particularly when using Google Cloud Functions. This discovery prompted a thorough investigation into all potential causes, following every lead possible.

Initially, a source suggested that the problem might be related to the lack of support for Server Name Indication (SNI) by the SIM7020E module [17]. However, this theory was initially dismissed since the issue was intermittent, which is not typical of a fundamental incompatibility like SNI support.

Complicating the investigation further, in some locations, the device could not connect to the GCP at all, despite having internet access and being able to synchronize time with Google's time servers. Meanwhile, other locations could establish connections after only a few attempts, indicating a potential environmental or network-related factor.

Signal quality and strength were also considered as possible culprits, but even with excellent signal conditions, the connectivity issues persisted. Additionally, swapping SIM cards between different operators appeared to affect the frequency of the problem. For instance, using Movistar SIM cards resulted in more frequent failures, whereas a multi-operator provider, Diferenza, showed fewer issues.

Seeking a definitive answer, the team contacted SIMCOM, the manufacturer of the SIM7020E module. SIMCOM's response was that Google had discontinued their IoT Cloud services, and they recommended switching to Azure or AWS. They also mentioned that the SIM7020E module was discontinued, with the SIM7022 as its successor, which after investigating this new variant, it turns out it supports SNI.

Despite these insights, a clear resolution remains elusive. The most plausible speculation is that the issue might indeed be related to SNI. The variability in GCP's internal server behavior could mean that some instances of their servers require SNI, while others do not. This inconsistency might explain the intermittent

nature of the problem and its location-dependent variability.

The next steps involve considering alternative hardware solutions. The SIM7022 module, which supports SNI, could potentially resolve the issue, but it would require board-level modifications beyond the team's current capabilities. Alternatively, the Waveshare module with the SIM7080G, which also supports SNI, offers a more accessible but costlier solution.

Chapter 5

API Development

After developing a basic working device, the next major milestone was enabling it to send data over the internet. Achieving this milestone was crucial for demonstrating the project's progress to executives, proving that the project is on track for success. Such progress not only instills confidence in the project's viability but also helps secure additional financing for further development. This financing is essential for acquiring necessary resources, such as a 3D printer, which will be discussed in the next chapter.

Developing an *Application Programming Interface* (API) was a fundamental step in this process. The API acts as an intermediary, facilitating communication between the device and a database where clockings are stored. It ensures that data from the device is accurately and efficiently transmitted to the database. This capability is vital for the real-time tracking and management of employee clockings, which forms the core functionality of the device.

This approach adds an extra layer of security. The alternative—directly inserting clockings into the database—would pose a significant security risk. If someone were to open the device and access its code, they could potentially see the database credentials. Given that the database contains personal data, maintaining its security is paramount. By using an API, the devices are restricted to only sending data, without the ability to read any data. This ensures that even if the device is compromised, the database credentials remain protected and the integrity of the personal data is maintained.

5.1. Requirements and Design Decisions

This time, the requirements are straightforward. The API needs to receive a JSON payload via a POST request, verify an API key, and process the data format to make it compatible with the database. For instance, it adapts the time format sent by the RTC clock of the Pi Pico into the format recognized by the database. This is more efficiently handled in an environment with extensive library support, rather than on a microcontroller running CircuitPython. After processing the data,

the API must send it to the database and respond with an *HTTP 200 status* if the operation was successful.

Given the team's prior experience with Java and the *Spring Framework*, it was decided to use Spring to quickly deploy the API. Spring is a comprehensive framework for enterprise Java development, providing tools and features to build robust, scalable, and maintainable applications. It offers extensive support for web development, including RESTful services, through its Spring MVC module [16]. By leveraging Spring, the team could efficiently create a secure and reliable API.

The code for the API was intentionally kept very simple to ensure ease of development and maintenance. The first step involved creating the "Clocking" entity, which served as a model for the data structure representing each clocking event. This entity allowed Spring to seamlessly connect to the database, providing a straightforward way to store and retrieve clocking data.

Spring Security was then configured to require an API key for authenticating requests. This setup added an essential layer of security, ensuring that only authorized devices could send data to the API. By using API keys, the system could verify the source of the requests, preventing unauthorized access and potential data breaches.

In more detail, the process involved defining the "Clocking" entity with appropriate fields such as employee ID, timestamp, and any other relevant information. This entity was annotated with *JPA* (Java Persistence API) annotations to map it to the corresponding database table, allowing Spring Data JPA to handle the *CRUD* (Create, Read, Update, Delete) operations automatically.

For the security configuration, Spring Security was set up to intercept incoming HTTP requests and validate the presence and correctness of the API key. This was achieved by defining a security filter that checked the API key in the request headers and compared it against a predefined valid key. If the key was missing or incorrect, the request was rejected with an appropriate HTTP error code.

5.2. Containerizing the Java application with Docker

Containerizing is a method of packaging an application and its dependencies into a standardized unit, called a container, which can run consistently across different computing environments. This approach isolates the application from its environment, ensuring that it performs the same regardless of where it is deployed. For this API, *Docker* will be used to achieve containerization.

Docker is a platform that allows developers to automate the deployment of applications inside lightweight, portable containers. A Docker container includes everything needed to run the application: the code, runtime, libraries, and system tools.

Advantages of Containerizing with Docker

- **Consistency Across Environments**: Containers ensure that the application runs consistently across various environments—development, testing, and production. This eliminates the common "it works on my machine" problem, as the container encapsulates all the dependencies and configurations.
- **Simplified Deployment**: Docker containers can be easily deployed and managed. With Docker, new instances of the application can be spun up, scaled across multiple servers, and be updated with minimal downtime.
- **Resource Efficiency**: Containers are lightweight and use system resources more efficiently than traditional virtual machines. Multiple containers can run on a single host without the overhead of a full-blown hypervisor, leading to better utilization of server resources.
- **Isolation and Security**: Docker containers provide process and filesystem isolation, which enhances security. Applications running in separate containers are isolated from each other and from the host system, reducing the risk of conflicts and vulnerabilities.
- **Portability**: Docker containers can run on any system that supports Docker, whether it's a developer's laptop, an on-premise server, or a cloud-based virtual machine. This portability simplifies moving applications between different environments.

These advantages significantly outweigh the minimal time required to configure and deploy the container [3] [4].

In fact, the only setup needed in particular for this project, was just creating its *Dockerfile*, which is used to create the *image*, from which containers can be created.

```
FROM eclipse-temurin:17-jdk-jammy
ARG JAR_FILE
COPY build/libs/*.jar app.jar
ENTRYPOINT ["java","-jar","/app.jar"]
```

After the Dockerfile is created, the `docker build` command can be called to create the image [6].

```
docker build -t fichador-api .
```

Then, a container can be created from that image, starting an instance of it:

```
docker run -d -p 8080:8080
    -v fichadorLogs:/logs -env-file ./.env
    -rm -name api fichador-api
```

With the `docker build` command, an image was created with the name "fichador-api", then, with the `docker run` command, a container was started on the port 8080, storing the logs in the `/logs` file, and using a `.env` file to initialize variables, such as the database username and password. The container's name is "api".

5.3. Adaptation to Google Cloud Functions

Hosting an entire Docker container in the cloud can be quite expensive, especially if it needs to run continuously. Given the simplicity of the API and its low resource requirements, this approach is not cost-effective. Consequently, alternative hosting methods were explored. Since the company already utilizes Google Cloud services, Google Cloud Functions was recommended as a suitable solution.

Google Cloud Functions is a serverless execution environment that enables the execution of code in response to specific events without the need to manage or provision servers. It automatically scales based on the load, ensuring that only the compute resources used during the execution of the functions are paid for. This service is ideal for lightweight, event-driven applications, offering a cost-effective and efficient solution for deploying small-scale APIs and microservices. By using Google Cloud Functions, developers can concentrate on writing code while Google manages the infrastructure, scaling, and availability [10].

Fortunately, Spring provides support for Google Cloud Functions. However, adapting the code was not straightforward, and due to the lack of comprehensive documentation and code examples, it took nearly a week to accomplish.The first challenge encountered was the scarcity of examples using Gradle as a dependency manager for building a project on Cloud Functions. Consequently, the project had to be migrated to Maven.Additionally, conventional Spring Controllers could no longer be used and had to be transformed into a function format specified by Spring's documentation. This format expects a specific input and output data type. In this case, the function received a Clocking object and could output various response types, such as a simple string response like "OK".

A working prototype was successfully developed, but it is currently pending approval for use. Executives have decided to use an existing API and make minor adaptations to fit the current use case, rather than introducing entirely new code.

Chapter 6

Designing and Fabricating the Enclosure: 3D Modeling and Printing

Chapter 7

Cost Analysis and Competitive Comparison

Chapter 8

Conclusions and Future Work

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Appendix A

Recycling High Density Polyethylene for 3D Printing