The Qbead

BSc Graduation Thesis: Hardware Subgroup

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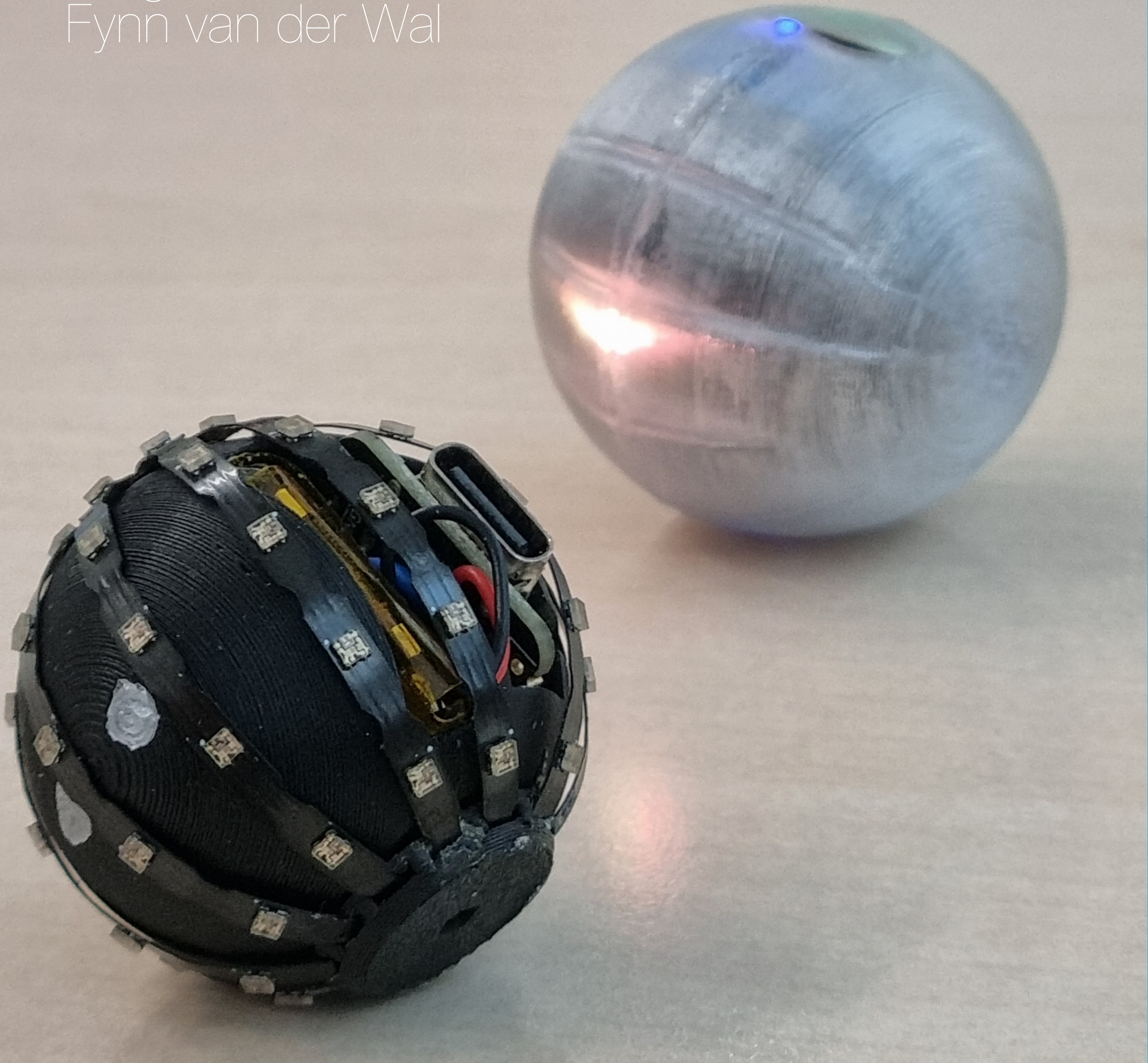

TU Delft

The Qbead

BSc Graduation Thesis: Hardware Subgroup

by

Henk Bakker
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to obtain the degree of Bachelor of Science
at the Delft University of Technology,
to be defended publicly on Tuesday June 24, 2025 at 9:00.

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Project duration:	April 22, 2025 – June 27, 2025	
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TU Delft

Abstract

This thesis presents the hardware development of the Qbead, an educational tool designed to make knowledge about quantum computing more accessible through a tangible representation of a qubit using a spherical LED display. The Qbead simulates the Bloch sphere, enabling users to visualize quantum states and gate operations in an interactive, physical format. The project focused on redesigning the Qbead's hardware to address limitations in the previous version, including insufficient LED density, fragile PCB structure, and complex assembly. Key improvements include a newly designed flexible PCB with 107 LEDs arranged for more homogeneous coverage, a custom microcontroller shield integrating a 9-axis IMU and reducing soldering complexity, and an upgraded 3D-printed casing that improves structural integrity and simplifies assembly. These enhancements were validated through prototyping and testing, showing improved usability.

Preface

This report documents the bachelor graduation project as part of the Electrical Engineering program at the TU Delft. The thesis ”The Qbead” will discuss the progress made to the Qbead project during the bachelor graduation project. This project was proposed by C. Errando Herranz with the goal of continuing development on the Qbead project. This report will specifically discuss the hardware improvements to the project, while the other report will dive into software.
This project introduced us to the world of quantum computing, which was an exciting experience. We hope that our contributions to the Qbead will help to achieve the goal of educating more excited students about quantum computing. We would like to thank our supervisor, C. Errando Herranz, for providing us with this project and for the guidance throughout the project.
And last but not least, we would also like to thank our teammates from the software subgroup, Ard Geuze, Mack Chen and Victor Hoogendijk, for their helpful collaboration in the past three months.

Henk Bakker
Rutger Gosselink
Fynn van der Wal
Delft, June 2025

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1 Introduction

1.1. The world of quantum computing

Quantum computing is an emerging field of cutting-edge computer science which applies the unique qualities of quantum mechanics to solve problems, which for some applications make quantum computers faster than even the most powerful classical computers [1]. This field is very exciting, with lots of ongoing research and a constant flow of new discoveries being made.
Classical computers use bits, which can be either 0 or 1, to encode information. Quantum computers use qubits, which can be best understood as the quantum equivalent of a classical bit [2]. A quantum computer takes advantage of the four key principles of quantum mechanics [1]:

- Superposition, where the qubit is a combination of all possible configurations.
- Decoherence, the collapse of a qubit into a non-quantum state.
- Entanglement, the ability to correlate their state to other qubits.
- Interference, where the superpositions of multiple qubits get sent out as waves and interfere into new outcomes.

With this, quantum computers can tackle large and complex problems at orders of magnitude faster than current classical computers [1].

1.2. Why the Qbead is important

Quantum computing technology is growing at an incredible rate, especially here in Delft. This emerging field has great applications for the future. For example in finance [3], logistics [4], healthcare [5] and countless more applications. It is of paralleled importance that young potential engineers and scientists are educated and excited about Quantum computing technology. Given the complex and often counter-intuitive nature of quantum mechanics, it is critically important that we begin educating and inspiring the next generation of engineers, physicists, and computer scientists who will shape the future of this technology. This is precisely where the Qbead fits in. Designed as an accessible and engaging educational tool, the Qbead serves as a tangible interface for students and enthusiasts to build a foundational understanding of quantum computing principles.

1.3. How the Qbead works

The Qbead, which is currently in development, has the goal to deliver a ”qubit” (a quantum bit) into everyone’s hands. It is of course not a real qubit, but a representation of a qubit. It does this by imagining the Bloch sphere. The Bloch sphere is an intuitive approximation of the state of a single qubit, by picturing a unit vector inside a sphere [6]. The Qbead visualises the Bloch sphere through a sphere with LEDs placed on the outside of the sphere, which is about the size of a golf ball. This is a helpful way to help students build understanding about the Bloch sphere [7]. The state is represented by illuminating the LED on the sphere that is closest to where the unit vector touches the sphere. The Qbead changes a theoretical model into a physical object, as currently, only online qubit simulators are easily accessible. One of the many available online Bloch sphere simulators is shown in Figure 1.1. Here, quantum gates can be applied to the qubit, and the outcome of the gate will be shown.

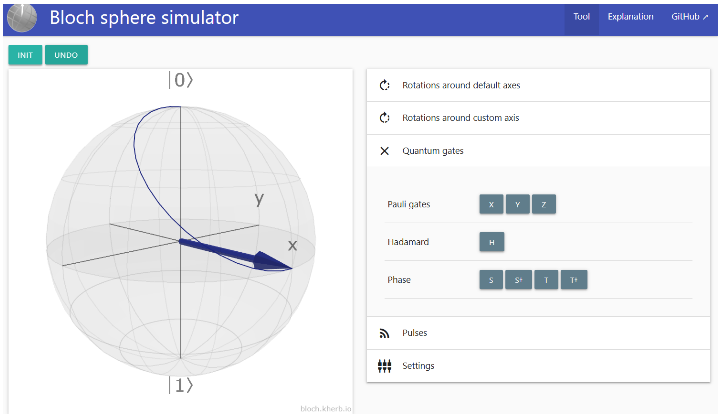
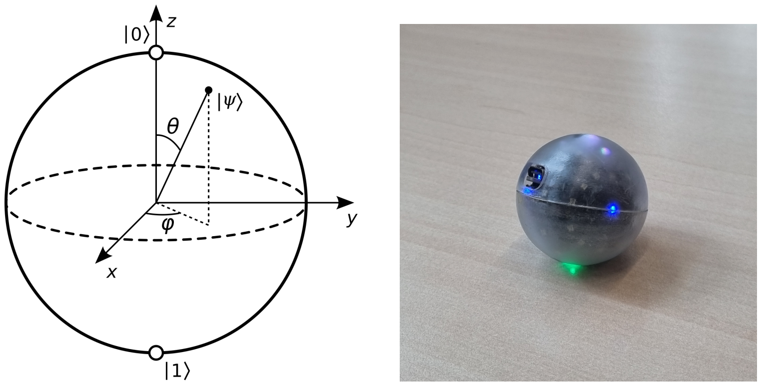


Figure 1.1: Interactive Bloch sphere simulator



(a) The Bloch sphere [8]

(b) Qbead in idle state

Figure 1.2: The Bloch sphere and a Qbead

The Qbead, which is shown in Figure 1.2b, can perform gate operations, such as the Pauli X-, Y-, Z- and Hadamard gates, and rotational operations. Because of that, the Qbead can be used as a helpful learning tool for building intuition about quantum bits. Qubits and the Bloch sphere can be seen as abstract subjects at first, and using an intuitive tool like the Qbead can help the student understand the subject.

1.4. The structure of the report

The report is structured in such a way that the reader is guided through the research and design process of the hardware subgroup during the bachelor graduation project. Firstly, in Chapter 2, the state of the project prior to the involvement of the subgroup is presented through the existing Qbead design, along with an overview of the associated issues that were discovered. In Chapter 3, the programme of requirements is set up according to the problems that are illustrated in Chapter 2. In Chapter 4, the design process is presented, with relevant information found during the research phase. The final design is also shown in this chapter. And finally, in Chapter 5 and Chapter 6, conclusions will be drawn from the project, and the final result will be discussed.

2

The previous Qbead design

2.1. Introduction

The Qbead hardware consists of a microcontroller, a battery, a flexible printed circuit board (flex-PCB) connected to the LEDs, an inertial measurement unit (IMU), which measures the acceleration and rotation exerted on the Qbead. All these electronics are fitted in and around a 3D printed core and are encased by a 3D printed shell for improved robustness.

2.2. Microcontroller

The microcontroller that is currently used by the Qbead is the Seeed XIAO nRF52840 Sense [9], which is equipped with a Nordic nRF52840 MCU and integrates Bluetooth 5.0. The specifications of this microcontroller are [10]:

- 64 MHz clock frequency
- 21x17.5 mm area
- Single-sided surface-mountable design
- 11 digital I/O pins used for PWM
- 6 analog I/O pins used for ADC
- Supports I2C, UART and SPI
- 256KB RAM, 1MB flash onboard and 2MB programmable flash storage.
- Supports Python, Arduino and other programming languages.
- Power consumption of 10.38 mA and low power mode below 5 μA.

Figure 2.1: XIAO nRF52840 Sense

2.3. Flexible PCB

To form a PCB into the shape of a sphere, the current design uses a flexible PCB. The flexible PCB is currently being produced by PCBWay where they use the flexible characteristics of polyimide and polyester films to create the flexible properties of the circuit [11]. These flexible PCBs are also very thin and lightweight, which saves space and reduces the weight of the Qbead. The current PCB design features 12 arms, each with five pre-soldered LEDs, totalling 60 LEDs. Including one LED at the top and one at the bottom brings the total to 62 LEDs used in a single Qbead. The current design of the flexible PCB is shown in Figure 2.2.

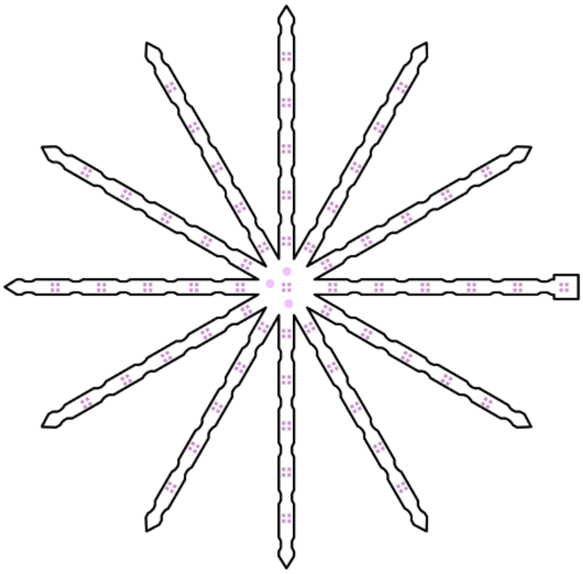
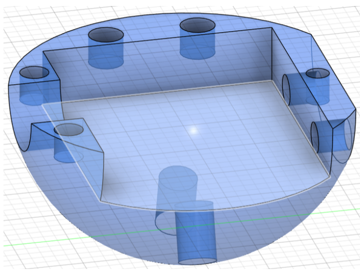


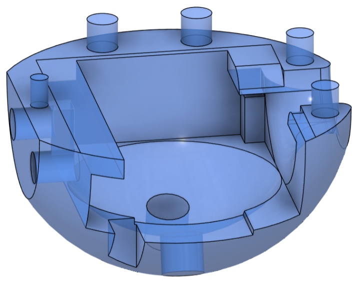
Figure 2.2: Current flex-PCB design

2.4. 3D printed casing

The casing for the Qbead is produced locally with a 3D printer. The design consists of two inner half-spheres that can be connected together via pins, these inner spheres can be seen in Figure 2.3. The design also has an opening in the centre of the sphere, where there is space for the microcontroller and battery. And, two outer half-spheres fit around the PCB to make the design more robust, the spheres leave a hole at the USB-C port of the microcontroller so that the Qbead can be charged and newly developed code can be uploaded. The material used for the casing is a plastic polymer, which is frequently used for small DIY 3D printer projects [12].



(a) Top half of the inner shell



(b) Bottom half of the inner shell

Figure 2.3: Inner shell of the current Qbead design

2.5. Product assembly and production cost

During the assembly process, the flex-PCB is removed from the flexible paper and folded into a spherical shape around the inner sphere, after being soldered to the microcontroller. After that, the Qbead is placed in the 3D printed protective casing, and then the Qbead is completed. This assembly process requires the user to have some experience in soldering and takes around 45-75 minutes, depending on the level of the user. Currently, the Qbeads cost around €30 to assemble. The goal for the next generation of Qbeads is not to greatly increase this cost price. Reflecting on the assembly process raised a few ideas, like making a Qbead that doesn't require soldering so anyone can build it at home or to speed up the assembly.

2.6. Problems with the current Qbead design

2.6.1. Previous experiences

To investigate the issues with the previous Qbead design, a meeting was held with one of the producers of the earlier Qbead version, who also has experience in its assembly. Several significant flaws were identified:

1. **The LED distribution is not optimised and lacks homogeneity.**

The program that runs on the Qbead has a pixel travel over the surface of the sphere. As the pixel travels across the sphere's surface, the non-homogeneous spacing between LEDs results in unpredictable and imprecise jumps.

2. **The PCB is difficult to detach from the sheet.**

Due to the fragile nature of the PCB, detaching it from the sheet requires extreme care. This process is time-consuming and still sometimes results in damage.

3. **The PCB is prone to breaking during assembly.**

During assembly, the flexible PCB must be wrapped around a core while already having wires attached. Then the arms are fitted into the crown. Additional bending occurs, which sometimes causes the PCB circuitry to break.

4. **The 3D-printed core requires post-processing to ensure the connection fits properly.**

The tolerances of the 3D printer are not sufficiently compensated for in the design. This requires manually adjusting the size of the sockets to fit the pins.

5. **The soldering pads on the flex PCB are challenging to work with.**

In an earlier version, these SMD pads were through-hole pads. That turned out to be easier to solder. The current SMD pads make it challenging to securely connect wires.

6. **A substantial amount of time is required to solder wires.**

Connecting the battery to the microcontroller requires two wires, and three more are needed to connect the flexible PCB. In total, eight solder joints are required, which adds significant time to the assembly process.

2.6.2. Author's experiences

Following this meeting, the authors of this paper assembled several Qbeads themselves. In addition to the previously mentioned issues, they identified the following additional problems:

7. **The overall assembly process is highly time-consuming.**

The total time it takes for the Qbead to be assembled takes between 45 and 75 minutes, depending on the experience of the assembler. All imperfections mentioned above add up to a lot of time that should be saved.

8. **The 3D-printed shell does not fit perfectly and has issues with the connecting pins breaking off.**

The pins connecting the shell with the core are placed at an angle to grab the core and hold it in place. The brittle nature of both resin and PLA is not suitable for this type of connection.
Based on these findings, a programme of requirements has been formulated, which is presented in Chapter 3.

3

Programme of Requirements

After the issues with the current Qbead design have been assessed in Chapter 2, a programme of requirements was set up. This programme of requirements is split up into four different parts, one for the PCB, one for the microcontroller, one for the 3D printed shells and one for requirements that do not fit in these three categories. Each category is further split into two levels: “must-haves” and “should-haves.” The “must-haves” are essential for a successful final product, while the “should-haves” are desirable improvements that enhance the product but are not critical.

3.1. PCB

As the current PCB design did not maximize LED density nor provide homogeneous coverage, the improved design must meet the following requirements:

(A) The PCB should cover more area of the sphere to accommodate room for extra LEDs, compared to the current design.

(B) The new design must have at least 50 percent more LEDs than the current design of 62 LEDs (i.e. a minimum of 93 LEDs).

(C) The PCB must leave a space for the USB-C connector to pass through.

(D) The LED distribution should be more homogeneous than the current design.

3.2. Microcontroller

The current microcontroller functions adequately, but the physical connection and integration can be improved. Therefore, the following requirements apply:

(E) The microcontroller must have a USB-C connector.

(F) The microcontroller should have a 9-axis IMU (Inertial Measurement Unit).

(G) The microcontroller-to-PCB connection should have fewer solder joints than the current design.

3.3. 3D Print

Improving the 3D printed shells is not the primary focus of the project, but changes are necessary to facilitate easier assembly and adapt to the new internal hardware:

(H) The hardware must be able to fit inside the inner shell.

(I) The hardware must be firmly secured inside the inner shell.

(J) The two halves of the inner shell must be easily connectable and remain connected, it must not require additional post-processing.

(K) The outer shells must be easily connectable to the inner shells, it must not require additional post processing.

(L) The design should not require a resin printer.

(M) The crown should make space for LEDs and the legs of the PCB.

3.4. Other Requirements

A few requirements do not fall into the categories above, such as those involving time and cost:

(N) The assembly time should be reduced by 25 percent.

(O) The production cost should not rise by more than €10.

4 Design

The goal of this project is to build a physical representation of a Bloch sphere. The current Qbead design does this by arranging LEDs in a spherical pattern using a flexible PCB, as described in Chapter 2. With the knowledge about the current Qbead design, the problems that were found, and inspiration from other projects, the design process could start. This process was split up into three different parts: PCB design, the microcontroller and the 3D print. In this chapter, inspirations and useful information gathered during the research phase will be presented, and after that the reader will be taken through the design process for each part. Finally, the improved design of the new Qbead will be shown.

4.1. PCB design

There are many ways of making a three-dimensional PCB. The manufacturing of PCBs is a very mature technology. Many online services allow anyone to order cheap, industrial-grade PCBs. This is why a lot of research focuses on utilising PCBs in novel ways. In particular, researchers explore ways to move beyond the flat nature of PCBs and design 3-dimensional circuits. After gathering a lot of interesting ways to design PCBs and flex-PCBs to form the shape of a sphere, these inspirations were listed together to discuss the pros and cons of each idea.

4.1.1. Solutions from the DIY space

Since the Qbead is closely related to the DIY space, some research was done on existing LED sphere designs. Multiple DIY designs were found and are presented below together with a visualisation of the designs in Figure 4.1.

Carl Bugeja [13] [14] This design uses flexible PCBs much like the Qbead. In the first design the author uses an approach with flexible arms. The second design divides the sphere into triangles that can be folded over a 3D support.

Jiri Praus [15] This LED sphere design is created as a free-form circuit. No PCB was used. The LEDs are soldered to brass wires in a 3D printed mould to hold them in place. Then the mould is removed. This design requires many hours of soldering to create.

Hari Wiguna [16] This design uses LEDs that are soldered orthogonally to the PCBs.

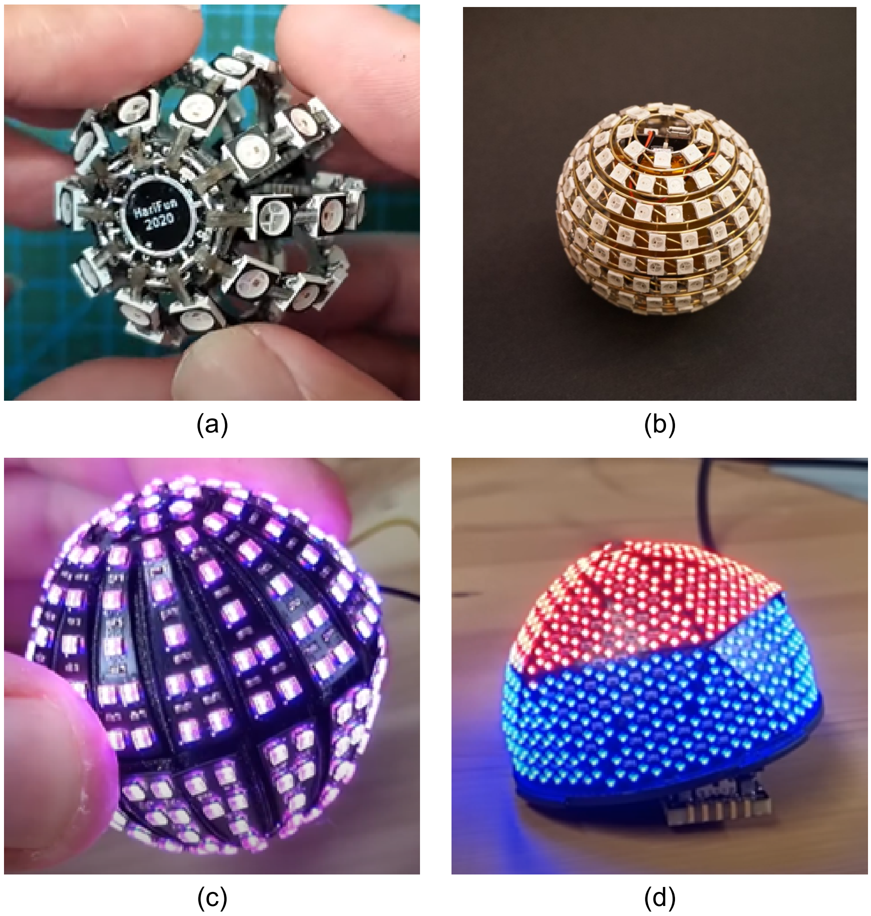


Figure 4.1: (a) Design by Hari Wiguna with leds orthogonal to the PCB [16], (b) Design by Jiri Praus that relies on very precise soldering [15], (c) Design by Carl Bugeja that uses a flexible PCB [13], (d) Design by Carl Bugeja that uses a flexible PCB divided into triangles [14]

4.1.2. PCBend

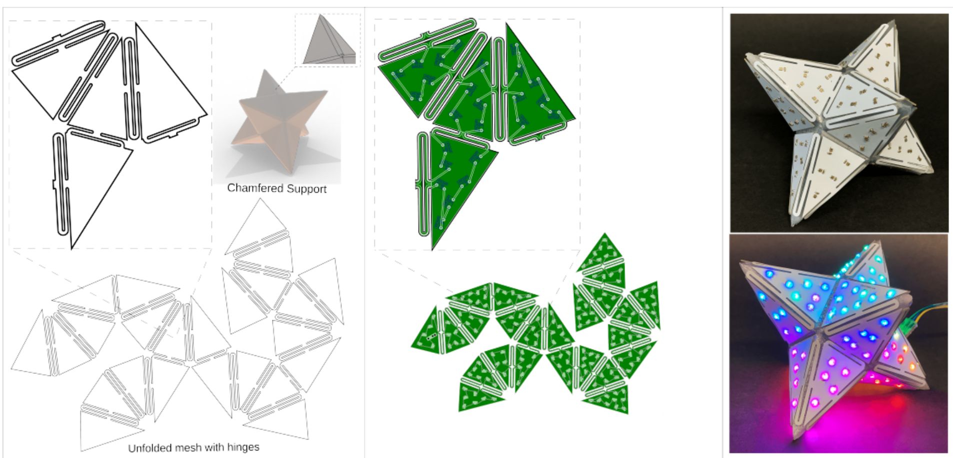


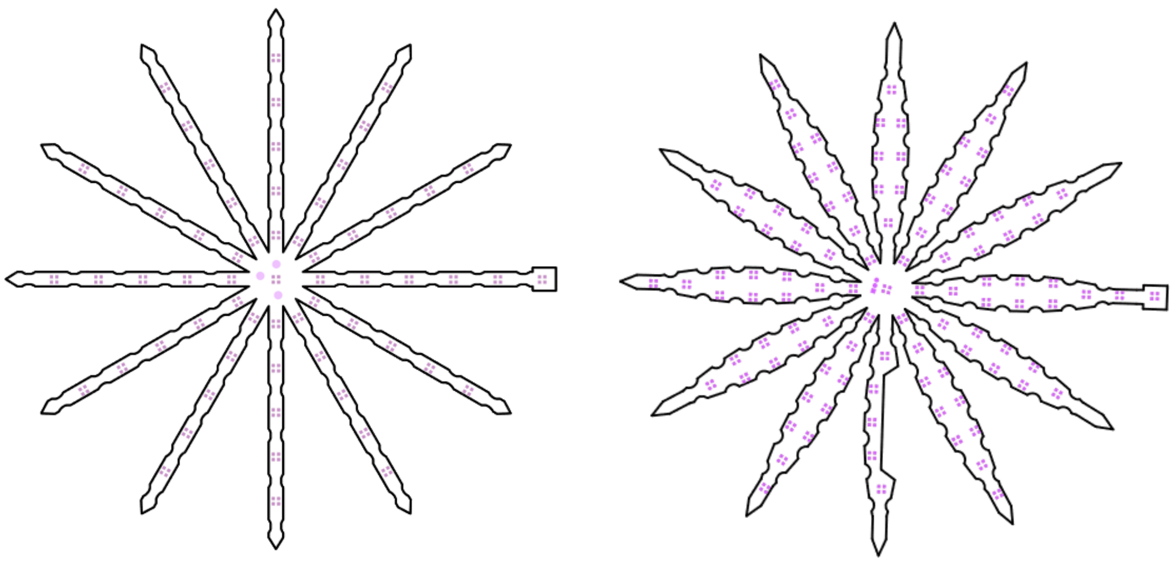
Figure 4.2: 3D circuits by bending rigid PCBs [17]

The PCBend project [17], seen in Figure 4.2, is an interesting out-of-the-box idea that could be used to develop the new generation of Qbeads. This design greatly increased the number of LEDs and also seemed more robust than the current flex-PCB design. However, when working out this idea, some problems arose. The main issue was with the algorithm that was developed during the PCBend project. During the setup of the algorithm, some errors occurred that couldn't easily be fixed. In a desperate measure to fix this issue, the head researcher of the PCBend project was contacted, but due to time constraints, the PCBend idea was put on hold, and other options were investigated.

4.1.3. Flex-PCB

One of the other options was developing a flex-PCB, like the current Qbead also uses. With the design of the current Qbead and together with inspiration from DIY projects such as the LED sphere made by Carl Bugeja [13], a new and improved flex-PCB was designed.

This design can be seen in Figure 4.3. The new design has increased the number of LEDs from 62 to 107. The new LEDs have been spaced around the sphere, locating them to make the grid more homogeneous, to meet Requirements (A) and (D). This has been achieved by widening the legs of the PCB, which gave space to place two LEDs next to each other on one leg around the equator. An online calculation tool [18] was used to calculate the width of the legs to approximate the area of a sphere. A 1 mm gap was left between each leg when wrapped around the core to prevent overlap and provide space for connecting the outer shell to the inner core. These regions did not require PCB coverage, as the spacing between LEDs on a single arm exceeded 1 mm anyway. As a result, LEDs on adjacent legs can be spaced just as closely as those on the same leg, despite the 1 mm gap between folded legs.



(a) The current flex-PCB design (b) The improved flex-PCB design

Figure 4.3: Comparison between the current and new PCB design

The LED density has also been improved along the leg. The current design has large unused spaces between the legs of the PCB, while this new design almost forms a complete sphere, this again helps with Requirement (D). Because of this, one leg of the PCB had to be changed to have a space for the USB-C connector to go through, with which the design meets Requirement (C). This space can be seen on the bottom leg in Figure 4.3b. The three rows that are closest to the equator now have double the LED density. The maximum spacing between LEDs along the latitude is 3.9 mm, while the maximum spacing along the longitude is 5.9 mm, this can be seen in Figure 4.4. For the inner latitude rings near the poles, the spacing between LEDs would be 2.8 mm if every arm included one. When only half of the arms contain LEDs, the spacing increases to 5.5 mm leaving the distance still below 5.9 mm. The latter configuration is more cost-effective and reduces potential points of failure, without compromising uniformity. The previous version of the PCB had pads to solder wires on, to connect it to another PCB. The pad was difficult to solder wires to, so they are now replaced with through-hole connections.

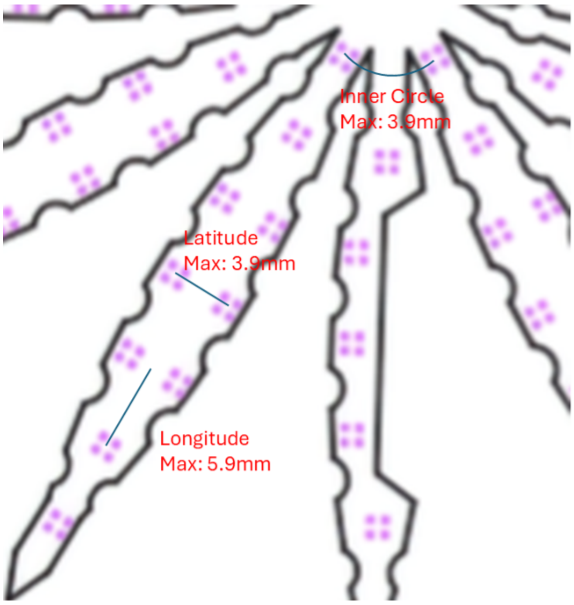


Figure 4.4: PCB dimentions

One common issue with flex PCBs is component detachment caused by bending. In the previous design, this was addressed by adding indents between components. These indents helped concentrate mechanical stress in specific areas, reducing bending directly beneath the components. At first, ridges of equal width were considered as shown in Figure 4.5. This would allow for uniform bending of the arm. This idea was eventually discarded for three reasons. First, with wider arms, the deep indents would make the PCB under the outlying LEDs too flimsy. Second, uniform bending is not necessary since the PCB wraps around a spherical core. Thirdly, using a wider connection with smaller indents also improves resilience during installation, making the internal traces less likely to break accidentally.

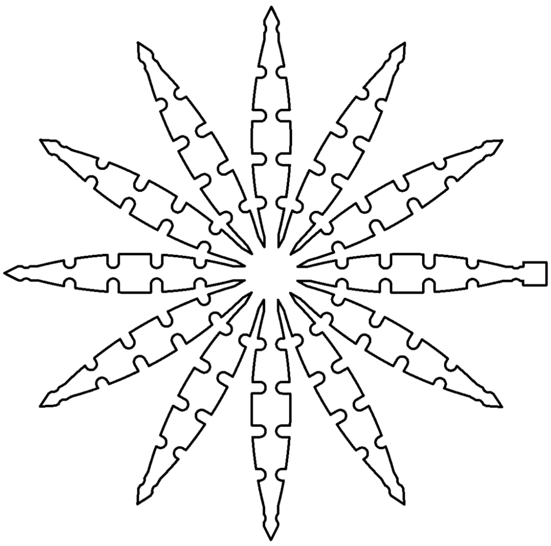


Figure 4.5: A considered PCB outline

The PCB was printed on paper to confirm the shape of the PCB and the location of the components. Figure 4.6 shows the paper prototype wrapped around a core.
Reflecting on the Programme of Requirements in Chapter 3, Requirements (A), (B), (C), and (D) have all been satisfied, as the design meets all specified criteria.

Figure 4.6: PCB printed on paper

4.2. Microcontroller

A requirement for the updated Qbead design is fewer solder joints for reduced assembly time (Requirements (G) and (N)). Also, a 9-axis IMU should be added to the microcontroller (Requirement (F)).

If a connector could be added to the XIAO, this would reduce the amount of soldering connections. Which would also greatly reduce the assembly time, since the XIAO is hard to solder. Since the current microcontroller that is used (the XIAO Seeed nRF52870) is open source, one idea that was considered is making a custom version that has a connector for the flex-PCB and a 9-axis IMU. However, the XIAO has a very complicated PCB design with tight tolerances and a lot of components, which is hard to manufacture. Also, the open-source files that are available online are not entirely complete. After careful consideration, this idea was dropped. Instead, it was decided that a custom *shield* for the XIAO would be developed since this requires far less work and the chances of the PCB working in the first revision round are far higher.

4.2.1. Shield

A shield is a common way of expanding a microcontroller's capabilities by connecting an extra PCB on the top or bottom to the GPIO pins. To connect the two boards together, the most common way is to use header pins [19]. But for our design, these pins are way too big. So, header pins were not an option.

It was then considered to use SMD board-to-board soldering for the connection, since this is also supported by most XIAO boards. An example of connecting a XIAO to another PCB in this way can be seen in Figure 4.7. This design requires far less space. However, the number of solder connections would increase significantly. One can argue that these types of SMD solder connections are far quicker to make than wire-to-board connections, but it still takes more time than not having to solder at all.

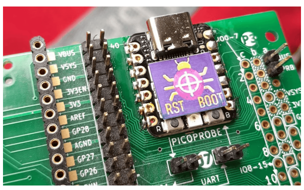


Figure 4.7: A SEEED XIAO connected via SMD board-to-board soldering

Now the aforementioned considerations resulted in a final design. It was discovered that Seeed offers a version of the XIAO with an integrated *board-to-board connector*: the **XIAO ESP32S3 Plus**. Normally, this connector is used to connect an expansion module containing a camera and SD-card reader. But the connector pins can be repurposed as GPIO pins. By making a custom shield that fits onto this connector, all the following design requirements could be achieved:

- (F) A 9-axis IMU can be added to the shield.
- (G) The microcontroller to PCB connection should have less solder joints than the current design

The final design of the PCB can be seen in Figure 4.8. Also, a rendered version of the shield connected to the XIAO ESP32S3 can be seen in Figure 4.9 and 4.10.

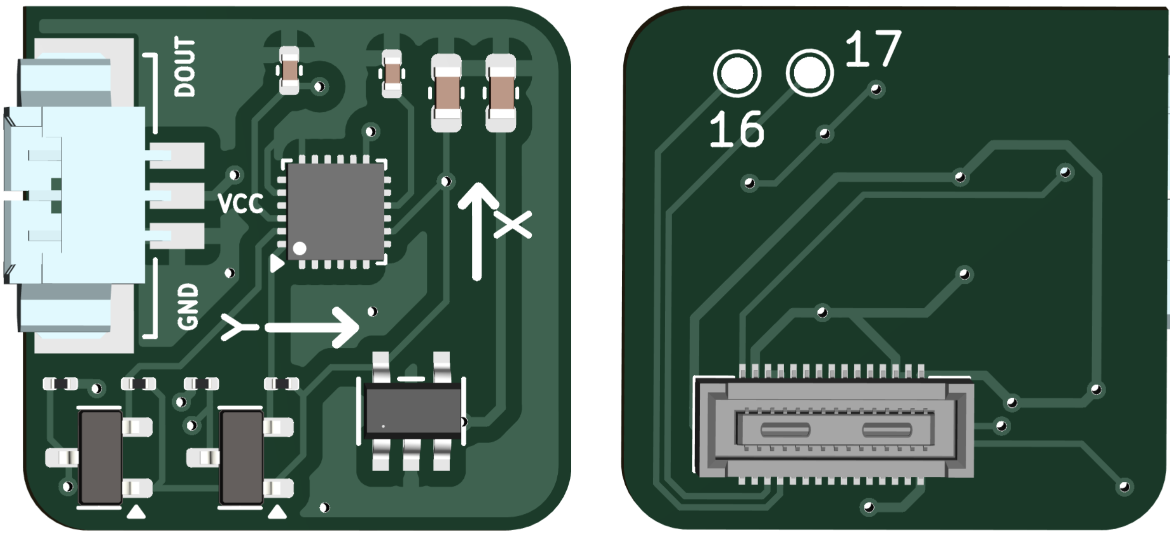


Figure 4.8: The shield PCB design

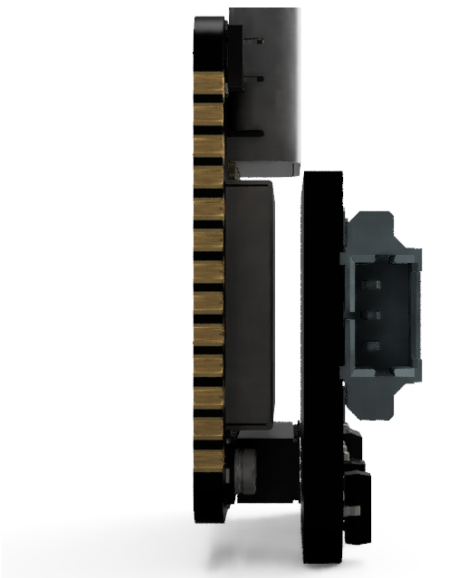


Figure 4.9: Shield connected to the XIAO ESP32

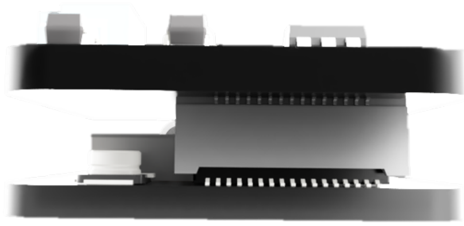


Figure 4.10: Board to Board connector of the shield

4.2.2. Shield schematic

The schematic in full can be viewed in Appendix A. The IMU that was chosen for the shield is the ICM-20948 IMU [20]. This choice will be further elaborated upon in Section 4.2.4. Because the *9 axis IMU* operates via I2C on a logic voltage level of 1.8V as opposed to the XIAO, which requires 3.3V. Two logic level shifters had to be implemented on the shield. Also, a 1.8V voltage regulator was needed. This piece of the schematic can be seen in Figure 4.11.

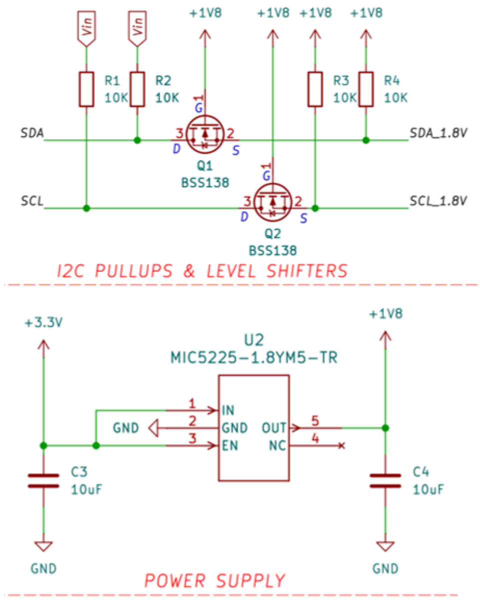


Figure 4.11: schematic of the I2C pull-ups, level shifters and the 1.8V regulator implemented on the PCB

The function of a level shifter is to facilitate communication between a high voltage device and a low voltage device. It is usually implemented with two MOSFETs and two 10kΩ pull-up resistors as can be seen in the figure above (4.11). For the MOSFETs in our configuration, it is important that the threshold voltage is below 2.3V. This is because if a LOW is initiated from the high voltage side, the MOSFET works like a diode and the source becomes 0.7V (see Figure 4.12), then the Gate-to-Source voltage is $3.3 - 0.7 = 2.3V$. If the threshold voltage V_{GS_T} of the selected MOSFET is lower than 2.3V, the MOSFET will never turn on and the LOW will not be pushed to the low voltage side. Figure 4.12 below was sourced from a Digikey article. Digikey uses and recommends the BS170 N-channel MOSFET for level shifting applications. For application in the shield however, this is a bad choice since it has a threshold voltage V_{GS_T} ranging from 0.8V to 3.0V worst case. The BS170 would only partially turn on in the worst case. Luckily, another MOSFET was found: *the BSS138*. This MOSFET is designed with level shifting in mind as a potential application and has a V_{GS_T} ranging from 0.8V to 1.5V, as can be seen in the datasheet [21].

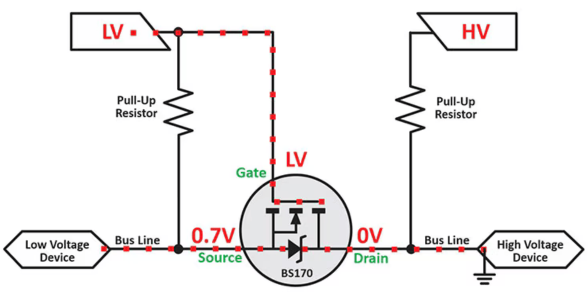


Figure 4.12: Near logical LOW voltage translation initiated by a high voltage device.[22]

4.2.3. ESP32S3 board

To connect the shield to the microcontroller via the described board-to-board connector, the microcontroller was changed to the XIAO Seeed ESP32S3 [23]. This microcontroller is not very different from the current XIAO Seeed nRF52870 Sense in technical characteristics, the ESP32S3 can operate at a higher frequency of 160 MHz and has more storage (4 MB flash), but it has a slightly different I/O pin configuration compared to the nRF52870 Sense [10]. The ESP32S3 board does not have an IMU directly connected on the chip. However, this is not seen as a downside for us, as the goal was to integrate a 9-axis IMU into the system. This 9-axis IMU could be connected to the shield, for which the characteristics will be described in the next section.

The IMU that is added to the shield is an ICM-20948 IMU [24]. with some logic level to convert the 3.3V down to 1.71 V, which the IMU has as the voltage input [25], and two connectors, one for the microcontroller and one for the flex-PCB. The design of this shield can be seen in Figure 4.8. These connectors reduce the number of solder connections in the system.

4.2.4. 9-Axis IMU

The XIAO Seeed nRF52870 Sense already has a 6-axis IMU, the LSM6DS3, integrated into the system. In our new design with the ESP32S3 board and the shield, we integrated a 9-axis IMU into the system (Requirement (F)), the ICM-20948. With this, a magnetometer is added to the already present gyroscope and accelerometer. This would remove the drift from the system as the magnetometer adds a reference point to the system [26], this gives more possibility for software to use yaw in the experiments. The communication interface (I2C or SPI) has an I2C fast mode of 400 kHz and an SPI fast mode of 7 MHz, both with a sensor resolution (16 bits) the LSM6DS3 and the ESP32S3 [27], [25]. The accelerometer and the gyroscope also retain the same properties, with the added magnetometer having a range of +/- 4900 μT [25]. However, this added magnetometer increases the power consumption of the IMU to 3.1 mA, compared to 1.25 mA for the 6-axis IMU. The ICM-20948 also increases the number of pins to 24, where the current IMU has 14 (the pin layout can be found in Appendix B). For this project, 10 IMUs were ordered for €5.85 a piece, but this price will be closer to €5 for higher quantities [20].

4.3. 3D print

Polymers are the most frequently used materials in 3D printing due to their versatility, affordability and ease of use [12]. They are composed of materials that can be heated and then reshaped. Polymers are mostly used in combination with the Fused Deposition Modelling (FDM) printing technique. FDM is a procedure where thermoplastic filament is brought to its melting point to be accurately printed and connected to the layer of polymer underneath [28].

4.3.1. Core

For the core, small changes to the design had to be made to accommodate for the changes made to the current Qbead electronics. Since there is now a different microcontroller board with an additional shield, there needs to be more space inside the core to pass Requirement (H). This new core is shown in Figure 4.13. The inside of the core is now more divided into different departments, securing the electronics better in place (Requirement (I)). The core now opens along a different axis, rotated 90 degrees. This design allows the electronics to be installed inside before the two halves of the core are closed. It also ensures a better fit for the crown, as the crown is now attached to just one half, reducing issues caused by alignment imperfections. The pins that connect two inner shells together have been replaced by bigger ridges to make the connection more solid, with this Requirement (J) is passed. Similarly, the pins, as can be seen in Figure 4.14, used to attach the outer shell to the inner core, have also been replaced with ridges, as shown in Figure 4.17. This makes the connection between the inner and outer shells more stable than the current Qbead, and is less prone to breaking during assembly. With this improvement, Requirement (K) is also passed.

4.3.2. Crown

The crown has undergone several modifications, which can be seen in Figure 4.15. Its diameter has been reduced to accommodate the additional rows in latitude. The tips of the flex PCB are too wide to allow for holes in the same configuration as the previous design. Mathematically, the decrease in width

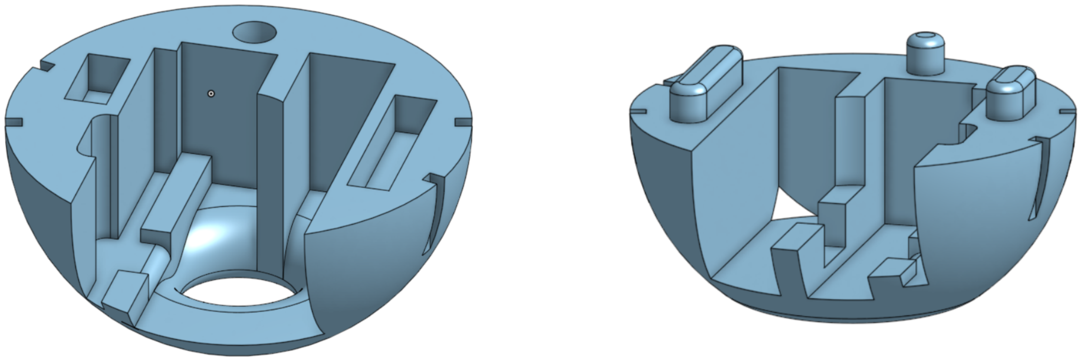


Figure 4.13: Two halves of the new core

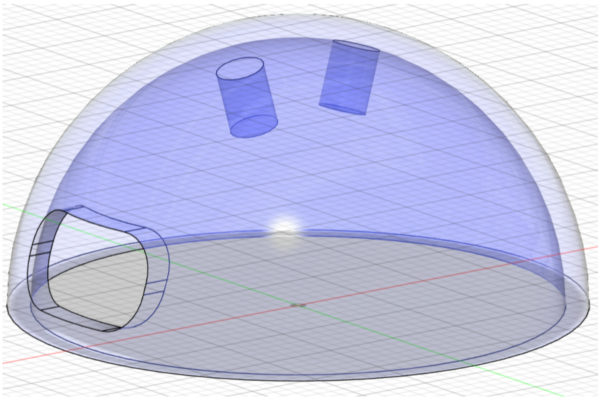


Figure 4.14: Previous design outer shell

of the tips should be more aggressive, but this would compromise structural integrity. To support the thicker arms, a multilayer crown was selected. Additionally, the pins connecting the crown to the core have been replaced with two asymmetrical rivets. This ensures proper placement during the installation of the crown and, therefore the flex PCB on the core.

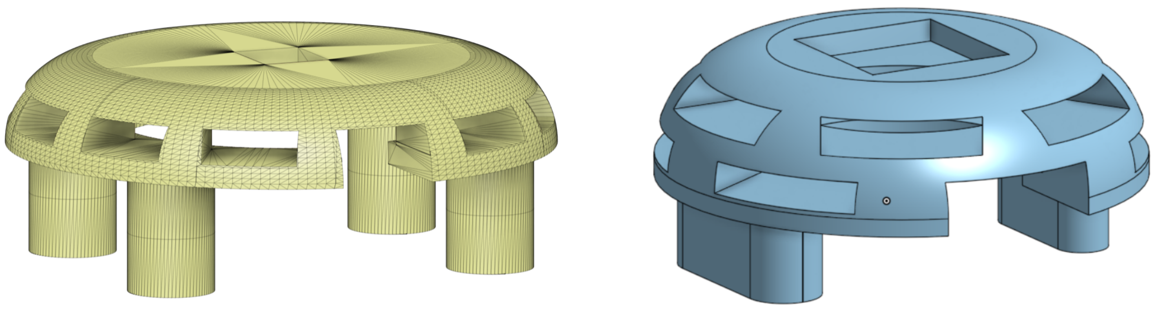


Figure 4.15: The old crown on the left and the new one on the right

4.3.3. Materials

During assembly of the old Qbead, a noticeable difference in print quality emerged between resin and polymer printers. The polymer printed parts were less precise, particularly around the pins connecting the two halves of the core, requiring the use of a resin printer for proper fit. The new design of the core compensates for the inaccuracies of polymer printers and no longer needs resin printing. This change helps reduce assembly costs and passes Requirement (L).

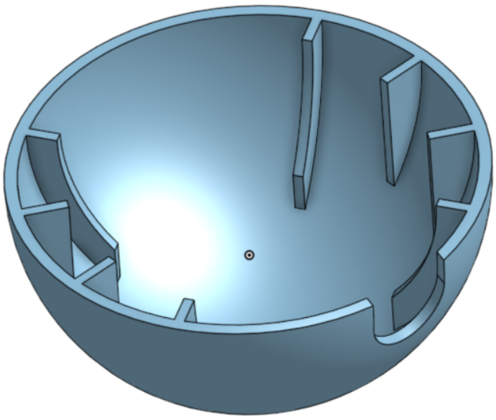


Figure 4.16: Design of the 3D printed sphere

PETG was chosen for the shell due to its favourable properties. It is available in a transparent form and exhibits minimal shrinkage during printing, eliminating the need for an enclosed printer. This also simplifies the design process by making tolerances more predictable. Additionally, PETG has a lower melting temperature compared to some less common and more expensive materials. When subjected to repeated loads or potential fractures, PETG offers greater strength and stability than ABS or PLA (two very common 3D printing materials) [29].

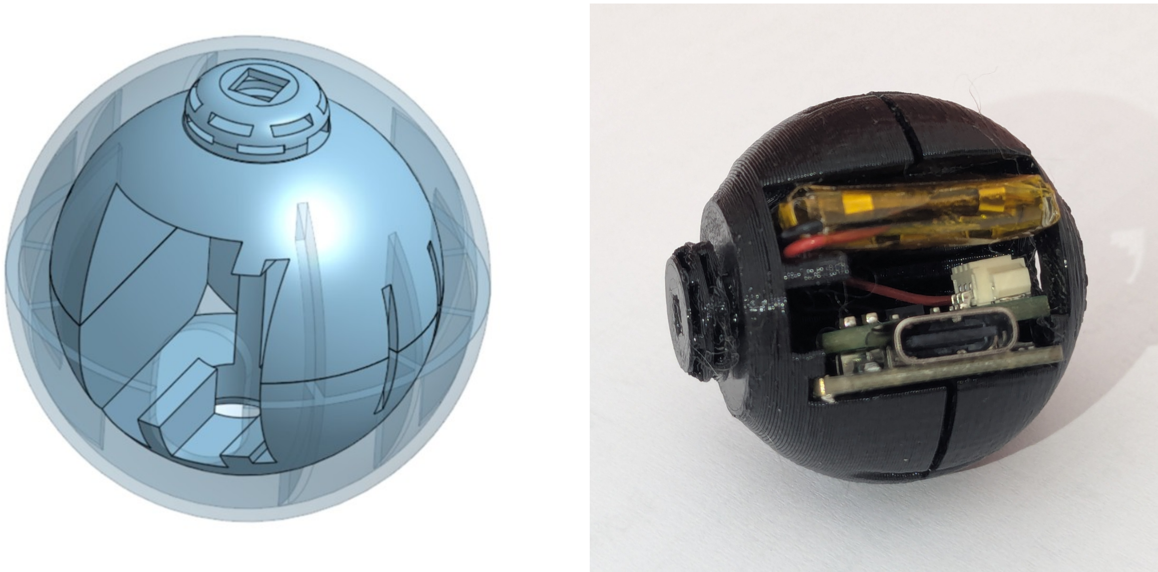


Figure 4.17: Two halves of the new core

4.4. PCB stamp

Removing the flexible PCB from the paper is a slow and delicate process due to the fragility of the PCB. Manual removal takes approximately 15 minutes with a quarter of the PCBs failing. A customised stamp can speed up this process by reducing the process to a single, swift motion. It also prevents the PCB from bending. The stamp design is shown in Figure 4.18.

The stamp's base includes alignment guides that position the PCB accurately over the extraction hole. These same guides also help align the stamp itself. Additionally, the push surface of the stamp has indentations for the LEDs. These further assist in centering the PCB during extraction. Of the 4 PCBs extracted using this stamp, one failed, making the benefits in success rate unclear. Further tweaking of tolerances would make the success rate higher.

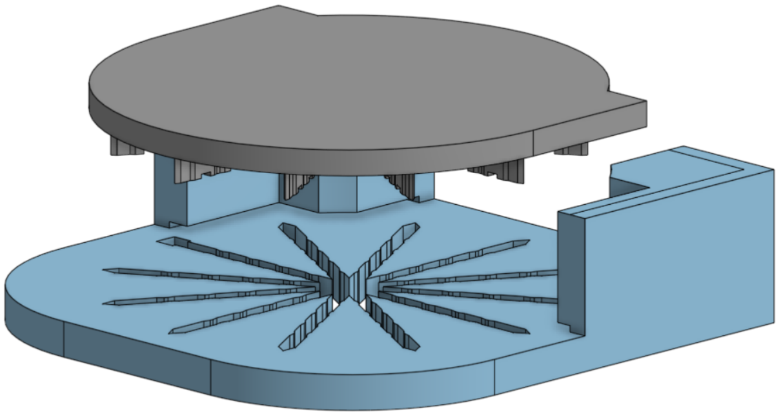


Figure 4.18: Stamp for extracting the flexible PCBs

4.5. Production costs

The new flexible PCB design is not significantly more expensive than the old one. The only added cost is from the added LEDs. These are only a small portion of the total manufacturing cost. The size and number of the 3D printed parts have not been changed in the new design. The new design even tackles inaccuracies of a normal additive 3D printer. Since resin prints are no longer necessary, the cost can be brought down. The shield costs an additional €10 per piece when produced in large quantities. The ESP32S3 board is €10 cheaper [30] than the currently used nRF52840 Sense board [31], so these costs cancel each other out, meaning that the new Qbead is not more than €10 more expensive than the current Qbead, which means that Requirement (O) is met.

4.6. Requirements verification

Table 4.1: Requirement Verification Summary

Category	ID	Requirement	Met?	Evidence / Notes
PCB	(A)	≥ 50% more LEDs than current (min. 93)	Yes	Increased from 62 to 107 LEDs (Section 4.1.4)
	(B)	Space for USB-C connector	Yes	Dedicated cutout included in the PCB design (Figure 4.3b)
	(C)	More homogeneous LED distribution	Yes	Improved layout with tighter, more uniform spacing (Section 4.1.4)
	(D)	Sphere-like shape with improved LED coverage	Yes	Confirmed via paper prototype (Figure 4.6)
Microcontroller	(E)	USB-C connector present	Yes	Included in ESP32S3 board (Section 4.2.3)
	(F)	Integrated or added 9-axis IMU	Yes	ICM-20948 integrated via custom shield (Section 4.2.4)
	(G)	Fewer solder joints than current design	Partial	Connector on shield side implemented, but wires still manually soldered to flex-PCB (Discussion)
3D Print	(H)	Hardware fits inside the inner shell	Yes	Core redesigned for added volume (Section 4.3)
	(I)	Hardware securely mounted	Yes	Compartmentalization and larger ridges implemented (Figure 4.17)
	(J)	Shell halves easily connect and remain stable	Yes	Pin-to-ridge redesign improves stability (Section 4.3)
	(K)	Shell does not require resin printing	Yes	PETG supports improved tolerances and avoids resin printing (Section 4.3)
	(L)	Crown accommodates LEDs and PCB legs	Yes	Multilayer crown design with rivet alignment (Figure 4.15)
Other	(M)	Assembly time reduced by 25%	Partial	Improved through shield and PCB stamp, but manual soldering still needed (Discussion)
	(N)	Production cost increase ≤ €10	Yes	Added cost from shield offset by ESP32S3 savings (Section 4.5)

5 Conclusion

This project aimed to improve the existing Qbead hardware by addressing various requirements related to the PCB, microcontroller, 3D-printed parts, and overall cost. This redesign is a step toward making complex quantum ideas easier to understand using physical tools like the Qbead. With the improvements, the new design is even more useful for teaching quantum concepts.

For the PCB, all requirements have been theoretically met. Although it has not yet been manufactured, a paper prototype confirms that the shape and LED placement fulfill the specified criteria. However, the actual functionality of the circuit cannot be validated until the board is produced and tested.

The microcontroller requirements were addressed by adding a shield and switching to a similar model microcontroller that includes a Board-to-Board connector. This allows the shield to be mounted without the need for soldering. This shield contains the 9-axis IMU and a connector for connecting the microcontroller to the flex PCB.

The 3D-printed components were redesigned to accommodate the updated electronics, with additional improvements made to reduce steps in the assembly process.

All new design parts have been confirmed to work and improve the design. When assembled using a paper prototype of the new PCB, all parts fit well within the Qbead. For electronic testing, a Qbead was assembled using all the new components but with the old PCB. This setup worked well.

Looking ahead, the Qbead has strong potential as an educational tool for young people to learn about the fundamentals of quantum computing. With further iteration and testing, it could become an accessible and engaging new gadget in the quantum learning space with the goal of exciting young students about quantum computing.

6 Discussion

Several potential improvements were considered for the Qbead, but they were too substantial to include in a single update. One major issue that remains only partially resolved is the need to solder wires. While the number of soldered connections has been reduced by three, five wires still require manual soldering.

One proposed solution involved using bent header pins on the shield that would poke through the flex PCB, allowing easy solder joints. However, this would need perfect alignment. Because all the hardware is replaced in the new version, getting this alignment right in the same design iteration is not feasible. As a result, the current iteration settled for a connector on the shield side and loose wires on the other as a temporary workaround.

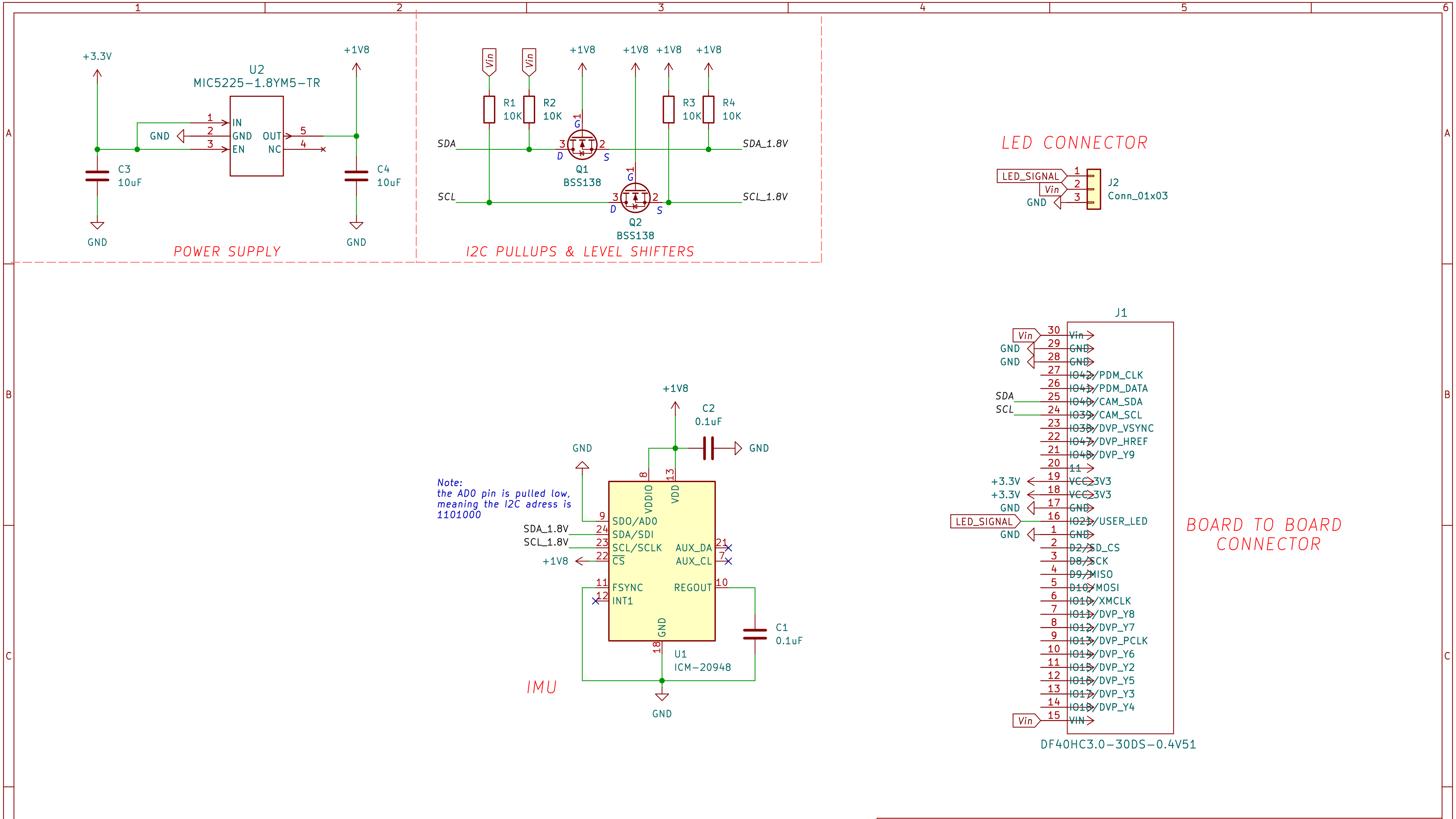
Another improvement could consist of different LEDs. In the current design, if a single LED fails, the entire PCB stops functioning. This unfortunately happens a lot. Switching to a different communication protocol that doesn't rely on a series connection would significantly reduce the impact of a single LED failure.

Similarly, the traces on the flex PCB are prone to breaking during installation, with the same critical consequences as a failed LED. Developing a more robust design for the PCB would greatly improve the Qbead's durability.

The extraction time of the flex PCB from the sheet has been addressed by using a stamp. Another possibility might be to contact the manufacturer of the PCB to discuss different ways to connect the PCB to the sheet. Having a few discrete connection points might make it easier than a continuous line to extract the PCB.

A

Appendix A - Shield Schematic



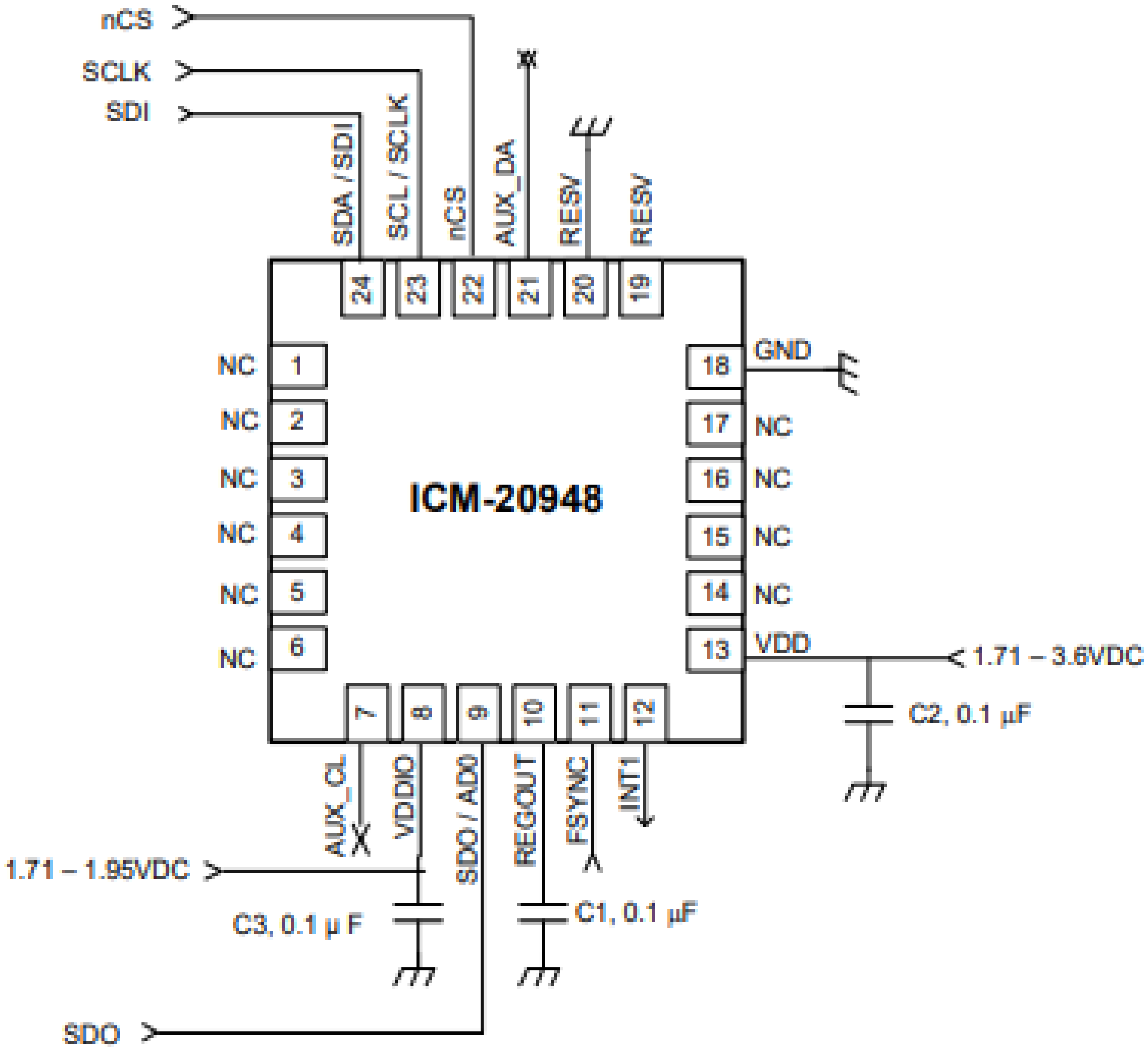
Sheet: /
File: XIAO_Shield.kicad_sch

Title: XIAO shield Qbead

Size: A4 | Date: | **Rev: A**
KiCad E.D.A. 8.0.9 | Id: 1/1

B

Appendix B - IMU Schematic



nCS
SCLK
SDI
SDA / SDI
SCL / SCLK
nCS
AUX_DA
RESV
RESV
24
23
22
21
20
19
NC
1
NC
2
NC
3
NC
4
NC
5
NC
6
ICM-20948
18
GND
17
NC
16
NC
15
NC
14
NC
13
VDD
1.71 – 3.6VDC
C2, 0.1 µF
7
8
9
10
11
12
AUX_CL
VDDIO
SDO / AD0
REGOUT
FSYNC
INT1
1.71 – 1.95VDC
C3, 0.1 µ F
C1, 0.1 µF
SDO

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