Plastic Identification Anywhere

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Plastic Identification Anywhere

Development of open-source tools to simplify plastic sorting

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Summary

Plastic pollution is a well-known problem worldwide, and is still growing. It negatively affects humans and wildlife through animal death, groundwater pollution and incorporation of micro plastics in our digestive system.
There are many initiatives focusing on reducing the negative effects of plastic pollution, but the amount of plastic consumed and the subsequent pollution is still increasing every year. Additionally, in the current COVID-19 pandemic the dependency on single-use plastics has increased exponentially.

That is why it is important to keep improving recycling infrastructure, especially in low and middle-income countries. Their plastic waste management is often informal, and tools are insufficient for the correct management of plastic waste, resulting in plastic pollution.The research conducted in this thesis showed that especially the sorting stage of the plastic recycling process is very time consuming and labor-intensive. This discovery led to the central research question: *which resources can be developed to accelerate the process of plastic sorting for informal recyclers?*

Discrete near-infrared spectroscopy makes it possible to identify over 75% of all plastic used in everyday life. Therefore, it became my mission to make this technology accessible to recyclers in low and middle-income countries.

By applying principles of context variation, local manufacturing and open development in the design process, tools that accelerate the sorting of plastic waste were created. This brings Plastic Identification Anywhere another step closer, with the end goal of fighting plastic pollution, together, today.

The project described in this paper resulted in a complete ecosystem of open-source resources (figure 1) that can be used to implement near-infrared spectroscopy in any plastic waste management setting, especially in low and middle-income countries. This ecosystem consists of:

-A **breakout board** that combines all components to emit and sense infrared light on a small printed circuit board with standard communication protocols.

-A **handheld scanner** that integrates the breakout board into real-world applications. It enables local machine-learning processing of the sample, all in a compact form factor.

-A **kit** that delivers all the components for the breakout board in a small package with clear instructions on how to assemble a breakout board, making board building more accessible.

-A **website** that informs (and inspires) all potential users about the Plastic Scanner, connecting those who want a Plastic Scanner to those who can build a Plastic Scanner.

-**Documentation** that is published online in its entirety, to enable cooperative working and transparency. This also makes it possible to modify a Plastic Scanner to personal preference.

-**Software** that communicates with the hardware and implements machine learning for optimal and quick prediction of plastic types.

> **“An open-source ecosystem to accelerate plastic sorting.“**

Figure 1: Overview of open-source ecosystem, from left to right: documentation, breakout board, kit, handheld scanner, and website.

Preface

For this project, I found myself in a unique situation, where I was allowed to work on a self-initiated project. This enabled me to pursue my dream of open hardware development for a better world. I would like to thank Jan Carel Diehl and Jo van Engelen for their support, and their confidence in me taking on this project. However, working on a self-initiated project could also be challenging at times, especially when I had to be the client and contractor at the same time.

The project was further challenged by the ever-changing situation regarding the Corona pandemic, and all the more so by having contracted Corona myself.

Developing a device that accelerates the process of plastic recycling in situations with limited resources, and is meant to function on the other side of the world, all in 100 days, is ambitious and unrealistic.

By sharing this work open-source online it is possible to involve more people in the project, have experts verify and improve the working principle, and create the foundation for a long term project that hopefully extends well beyond my moment of graduation. The method of open source working also leads me to thank Armin Straller, the person who initiated the ReReMeter project and who inspired the start of this project. His willingness to help and his contributions to the software of the project were vital for the successful completion of this project.

Another vital contribution to the project came from Student4Sustainability and FastFund in the form of financial support. This enabled me to develop multiple prototypes and rapidly come to tangible results.

A picture says more than 1.000 words, this report says more than 12.469, thank you for taking an interest in my thesis.

Jerry de Vos

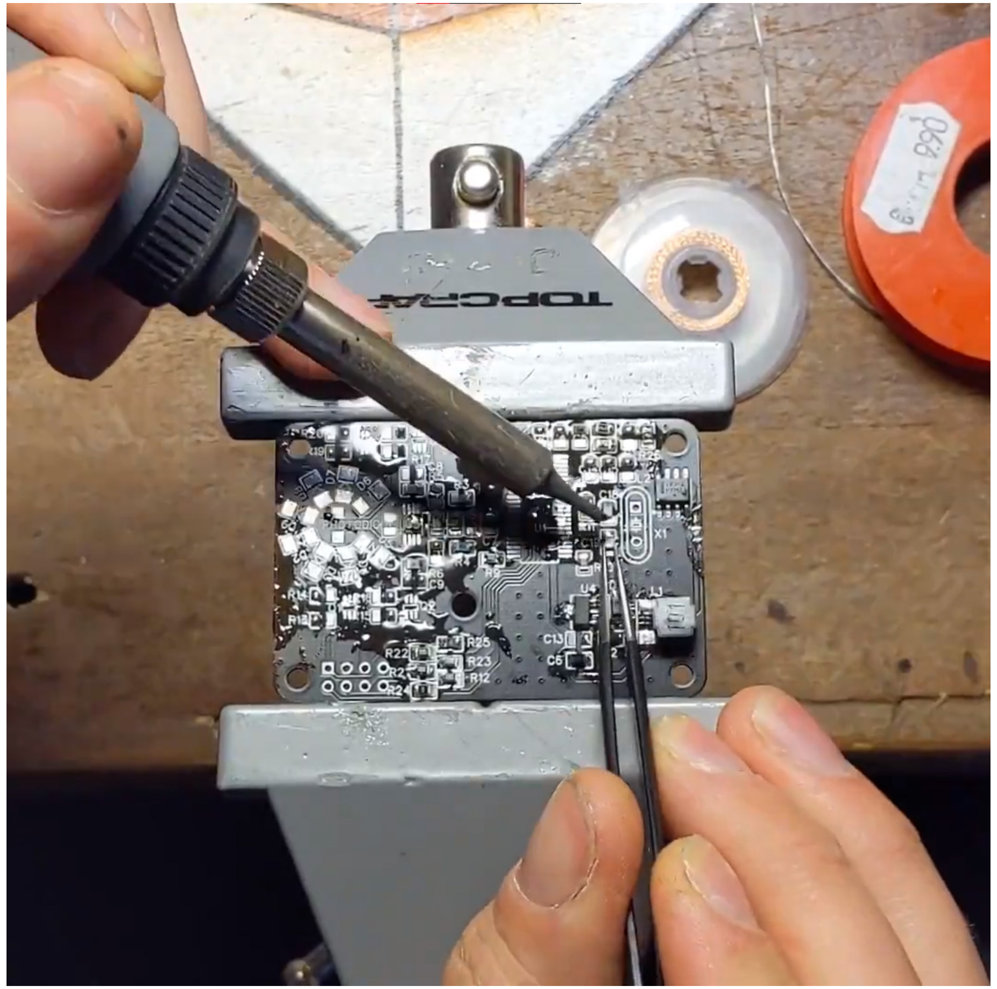
First prototype of plastic scanner.

Glossary

General
DIY - Do It Yourself
LMIC - Low- & Middle-Income Countries
MVP - Minimum Viable Product

Technical
ADC - Analog to Digital Converter
API - Application Programming Interface
IDC - Insulation-Displacement Connector
I2C - Inter-Integrated Circuit
LED - Light Emitting Diode
MEMS - MicroElectroMechanical Systems
NIR - Near InfraRed
PCB - Printed Circuit Board
SMD - Surface Mount Device
SPI - Serial Peripheral Interface
THM - Through-Hole Mounting

Plastics
HDPE - High Density PolyEthylene
LDPE - Low Density PolyEthylene
PET - PolyEthylene Terephthalate
PP - PolyPropylene
PS - PolyStyrene
PVC - PolyVinyl Chloride



Soldering of breakout board.

Contents

Photo by Stijn Dijkstra from Pexels

Start

This chapter provides an overview of the project. It highlights the reason the project was started and the importance of a solution for the problem discussed. Lastly, it explains the methods used in this project.

In this chapter:

1.1 Introduction

Every second the volume of a truckload worth of plastic enters the ocean (Jamback, 2015). Recent research has shown that this has devastating effects on nature and animals(Law, 2017, p. 209). Many initiatives try to reduce the impact of plastic pollution on our planet. They do this by for example retrieving plastic from the ocean (The Ocean Cleanup) or by providing people with the knowledge and tools to build their own recycling machines (Precious Plastic). Lastly, governmental action is taken as well by, for instance, banning plastic bags. Yet the amount of plastic in the world is still growing (Geyer et al., 2017). This can be seen in figure 1.1.

If the goal is to reduce the negative effects of plastic, we first need to better understand plastic itself. Plastic has some great positive aspects, for example: making cars more fuel-efficient and making food last longer. But most of the negative aspects of plastic in our environment result from its end-of-life phase -the phase where plastic is discarded and, if mismanaged, becomes plastic pollution. These negative aspects are, for example, animal death (Gall & Thompson, 2015, p. 175), groundwater pollution(Chae & An, 2018, p. 391), and incorporation in our food chain (Wilcox, Sebille & Hardesty, 2015).

Since its introduction in 1907, the world has been producing more plastic each year than the year before. Because of its relatively short “in-use” period, plastic quickly becomes waste. If this waste is not managed correctly the result is plastic pollution. Research from Jambeck et al. (2015, p. 770) shows that most of this mismanaged plastic waste is concentrated in countries that are defined as Low- and Middle-Income Countries (LMIC), such as India, Nigeria, or Bolivia. This can be seen in figure 1.2.

This leads to the initial research question:

“Is it possible to develop resources to reduce the quantity of plastic pollution originating from LMIC? “

This research question will be answered by an analysis of the waste management contexts in LMIC, an exploration of current recycling techniques and the development of resources based on the double diamond method (see chapter 1.2).

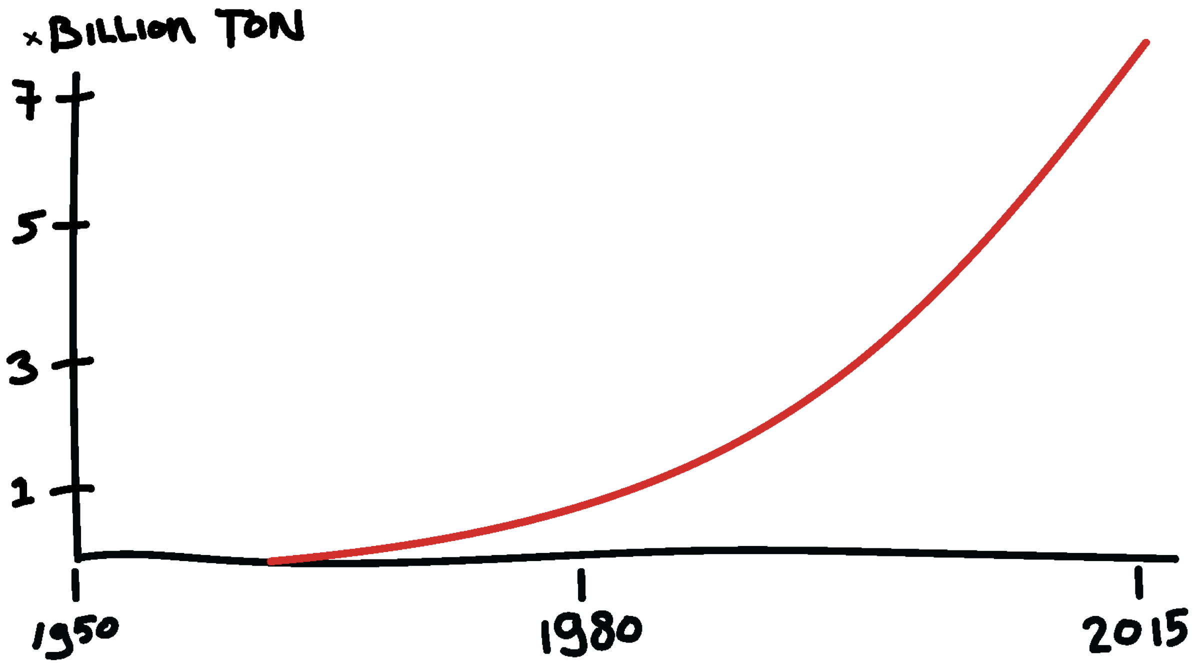


Figure 1.1: Cumulative global plastic production between 1950 and 2015. (Geyer et al.)

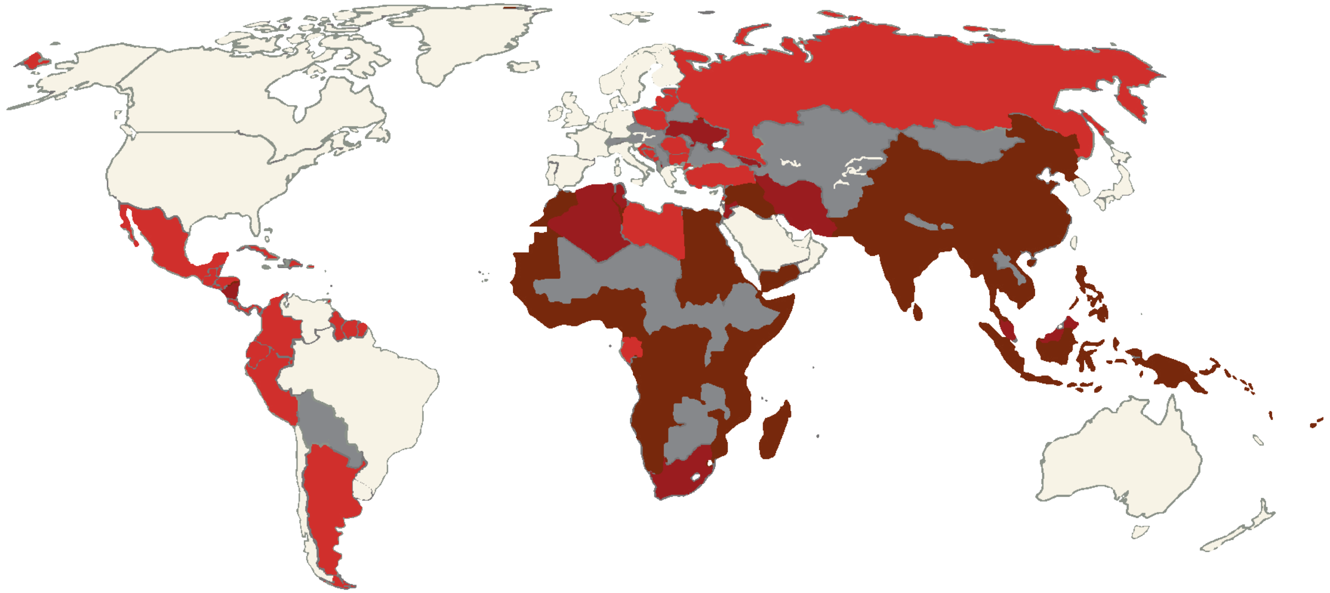


Figure 1.2: Share of plastic waste that is inadequately managed, 2010. (Jamback et al.)

1.2 Approach

The organization of this project is based on the Double-Diamond method (figure 1.3) (Design Council, 2007). This breaks the project up into four phases: Discover, Define, Develop, and Deliver. This method makes it possible to work towards an evident result in 100 days. Within these 100 days, the aim is to tackle the biggest risks and assumptions first and only then continue more in-depth.

In the introduction above, the current situation was described. The Discover (chapter 2) phase includes multiple analyses that delve deeper into the current situation, revealing the actual problem that needs to be solved. It also specifies the research question, after which a hypothesis is set. The Define (chapter 3) phase describes methods by which the hypothesis is answered, and their main design challenges. The Develop (chapter 4) phase solves these design challenges and that way creates the final product, which is presented in the Deliver (chapter 5) phase.
Lastly, this report concludes with a conclusion of the project, an answer to the research question and recommendations for future development.

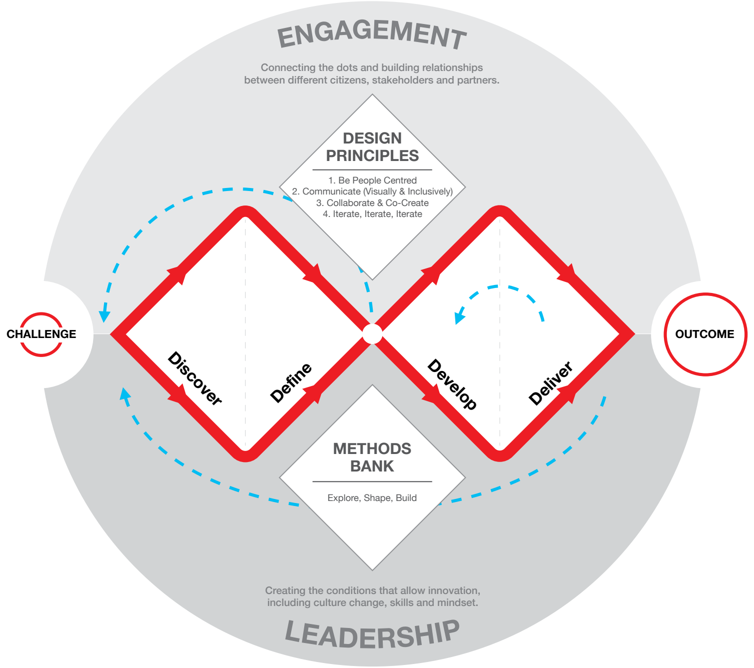


Figure 1.3: Visualization of the double diamond method. (Design Council)

Screenshot from bi-weekly reflection video.

Plastic capture system. (The Ocean Cleanup)

DIY plastic recycling machines. (Precious Plastic)

Plastic pollution. (Sheila)

Photo by Mumtahina Tanni from Pexels

Discover

This chapter aims to create an understanding of the current challenges around plastic pollution. Through a combination of literature research, interviews, and personal experiences, a common understanding is created, from which the main research question can be formulated and the hypothesis is derived.

In this chapter:

- 2.1 Waste management analysis
- 2.2 Plastic Sorting analysis
- 2.3 Infrared sorting technique
- 2.4 Potential usage scenarios
- 2.5 Proposed solution

2.1 Waste management analysis

Since most of the mismanaged plastic waste is concentrated in Low- and Middle-Income Countries (LMIC) (Jambeck et al. 2015, p. 770). It is vital to get a better understanding of their local waste management. To do so, a broad literature study was conducted. This research was supplemented with four semi-structured interviews with people working at informal recycling facilities in LMIC. These people were:

- Tita, Indonesia, running a recycling business in Surabaya.
- Manduku, Kenya, head of Precious Plastic workspace Kisii.
- Prad, India, former Precious Plastic engineer from Delhi.
- Debrah and Mitchell, Curacao, initiating plastic recycling in Willemstad.

Qualitative insights from past field trips to waste management in the Maldives and Mauritius completed the research and provided a holistic overview. The above combination of literature study, interviews and field trips led to the following insights:

Although plastic waste management in LMIC differs from country to country, there are some big differences between LMIC and countries where mismanaged waste is low. The key difference is the governmental role in waste management being much smaller or non-existent in LMIC (Sida, 2004). Countries either have a formal recycling infrastructure or an informal recycling infrastructure. In places where informal waste management infrastructure is dominant, there is a higher chance of mismanaged plastic waste (Jambeck et al. 2015, p. 770). In an informal setting, waste management is not monitored by any form of government, individuals start recycling by themselves and often do not pay taxes (Sida, 2004). As an example, an informal plastic recycling plant is shown in figure 2.1.

Figure 2.1: Informal recycling in Dhaka, Bangladesh. (Precious Plastic)

Research by Nandy et al.(2015, p. 177) concluded that the recycling industry in India is informal and quite mature, all actors having their own defined role and specific waste stream they cover. Waste items pass through the hands of many individuals that each pick out a specific material. This was confirmed by interviewee Prad (personal communication, September 18, 2020), and interviewee Tita (personal communication, September 18, 2020). Research from Mutha et al.(2006, p. 238) highlights that most recycling units in India have a small budget, and can be described as informal recycling. Their analysis of plastic concluded that 83% of the plastic products used in India consist of PE, PP, PVC, or PS and that PVC will slowly be replaced by PE or PP.

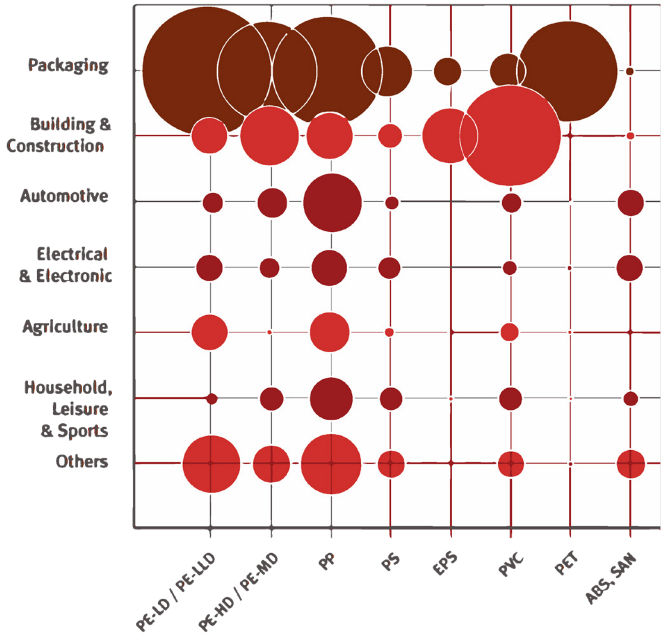


Figure 2.2: Plastic consumption in the EU in 2018, broken down by type and application. (Plastics Europe)

More recent facts on plastic usage in the European Union confirm a similar usage pattern, where 73% of the plastic used in the European Union is made from PE, PP, PVC, PET, and PS (Plastics Europe, 2019). An overview can be found in figure 2.2. Except for PVC, a similar usage pattern was found in Trinidad and Tobago by Millette et al. (2019).

Research in Kenya by Oyake-Ombis et al. (2015, p. 192) found that economical aspects are the main drivers to start recycling within the informal sector. This was partly confirmed by interviewee Manduku (personal communication, September 17, 2020) who owns a Precious Plastic recycling workspace in Kisii(-Kenya) (figure 2.3), but also highlighted the sustainability aspect of his recycling workspace.

There is a high demand for this kind of workspaces and each week a new workspace is set up by different people around the world.

Figure 2.3: Manduku at his recycling workspace, Kisii. (Precious Plastic)

The interviews and field research gave an overview of the recycling infrastructure in the informal sector, which consists of the following stages:

Collecting - cleaning - sorting - shredding - producing.

The interviewees acknowledged the difficulty in sorting and identifying plastics. Often this is done by hand, where the person needs to find the resin identification code on the product and place it in the appropriate bin. This can be seen in figures 2.4 and 2.5. The workspaces of the people interviewed were very interested in improving their sorting and identification process. More information about the context can be found in appendix III (Anywhere)

The above problems encountered by the recycling spaces specify the research question: which resources can be developed to accelerate the sorting process for plastic waste management in the informal sector?

Figure 2.4: Handsorting bottlecaps. (Krizjohn Rosales)

Figure 2.5: Handsorting plastic in Indonesia. (Madina)

Manduku collecting plastic.

2.2 Plastic sorting analysis

To create valuable, high-quality products from recycled plastic, sorting based on plastic-type is essential (Ruj et al., 2015). Different types of plastic have different melting temperatures and not sorting plastic would result in unknown and mixed material properties and partially burned or degraded plastic. This can be compared to metal recycling where stainless steel, copper and normal steel are each sorted accordingly. Current sorting methods for plastic recycling can range from very basic to very complex. A breakdown of the different sorting methods is displayed in figure 2.6 (Wisse, 2018).

Most sorting methods separate their inflow in a binary manner. Plastic falls either in group A or in group B . For example, separating plastics that float from plastics that sink. This is a workable method if the inflow of types of plastic is known, or if there is a continuous inflow of plastic. In informal recycling there is no foresight about the types of plastics that are entering and fluctuations in the inflow make binary sorting methods difficult and slow. For these situations, optical sorting methods are more suitable, since they make it possible to distinguish multiple materials at once (Ruj et al., 2015). Within optical sorting, infrared sorting is the most suitable method. It has the advantage that a machine interprets the plastic type instead of a human, making the sorting more objective and eliminating the requirement of training and previous knowledge about plastic recognition. More information about plastic and its sorting techniques can be found in appendix II (Plastic).

Size

-Ballistic
-Drum

Optical

-Hand sorting
-Burn testing
-Near infrared

Density

-Sink-float
-Air classification

Electro Magnism

-Static
-Magnetic density

Figure 2.6: An overview of different sorting methods for plastic recycling.

This specifies the research question to:

“Is it possible to develop an infrared sorting device to accelerate the process of sorting plastic in the informal waste management sector? “

Birdnest from plastic. (Woodhouse)

2.3 Infrared sorting technique

Infrared sorting works by shining IR light on a plastic object and measuring the reflection of the different wavelengths. Absorption within the visible spectrum gives information about the color of a product, and absorption in the infrared spectrum gives information about the chemical bonds associated with the atoms of a functional group.

Different chemical bonds (like O–H, C–H, and N–H) vary in strength and therefore the amount of energy required for the bond-vibration varies as well. This variation in energy can be expressed on a spectrum as a series of absorptions at different wavelengths. This can be seen in figure 2.7 (Davies, 2005). An example: white light shines on an object, only the wavelength of the object is reflected, this reflection enters your eyes, making you aware that the object is, for example, blue. This can also be done with IR light; the reflection gives us details about the molecular structure of a product, making it possible to identify the type of plastic.

Near-infrared spectrometry can be used to identify different types of plastic, since different types of plastic have different absorbance peaks. PVC, for example has an absorbance peak at 1660nm and PET has an absorbance peak of 1716nm. Based on this principle, Scott(1995) was able to successfully separate PET from PVC. In 2012 Masoumi and Safavi repeated this experiment and were able to identify five different types of plastic using just the ratio between 1656nm and 1724nm (Masoumi et al., 2012). A visualization of these absorption curves is shown in the figure 2.8, where the vertical axis represents the absorption in percentages and the horizontal axis represents the wavelength in nanometers.

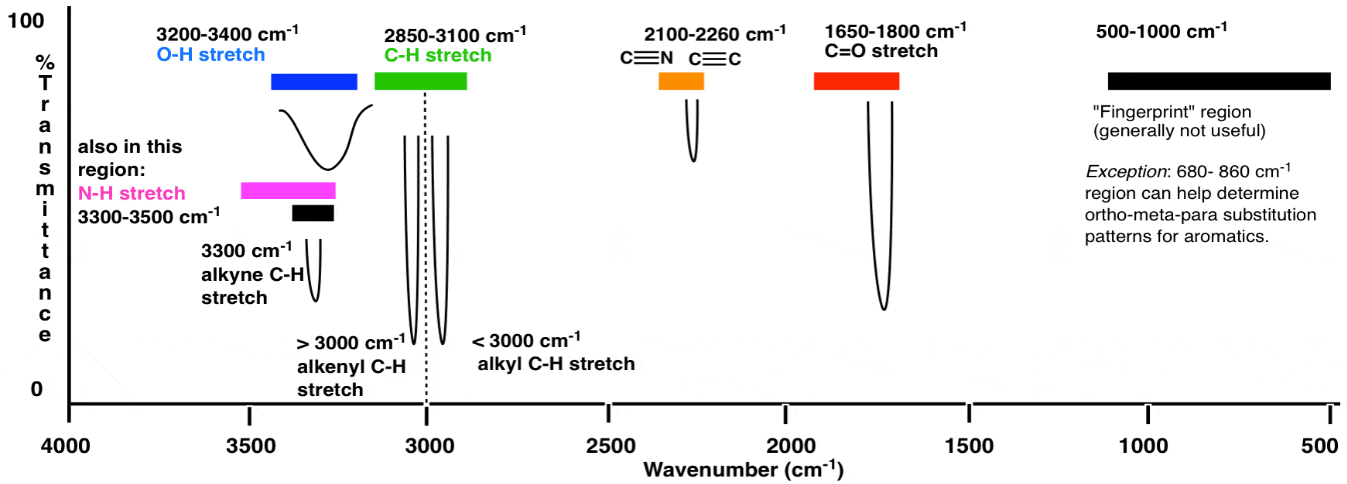


Figure 2.7: Absorption values for different typypical chemical bonds. (Master Organic Chemistry)

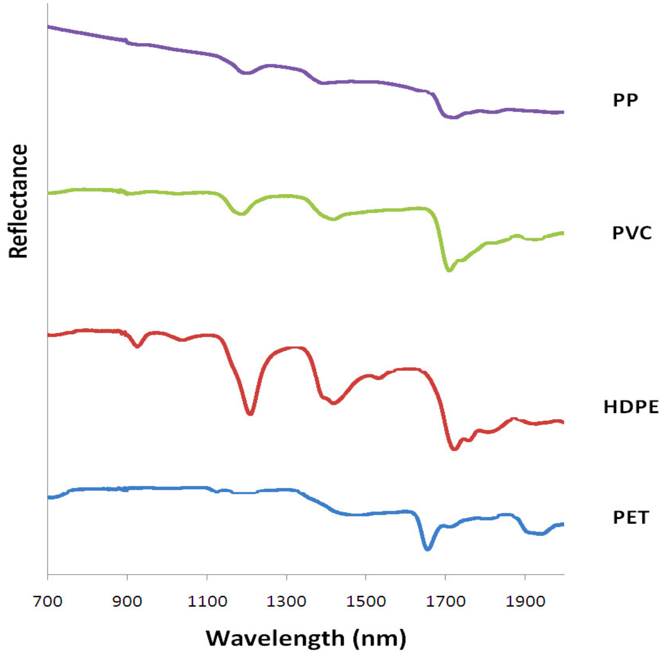


Figure 2.8: Spectral reflection analysis of common plastics. (Masoumi et al., 2012)

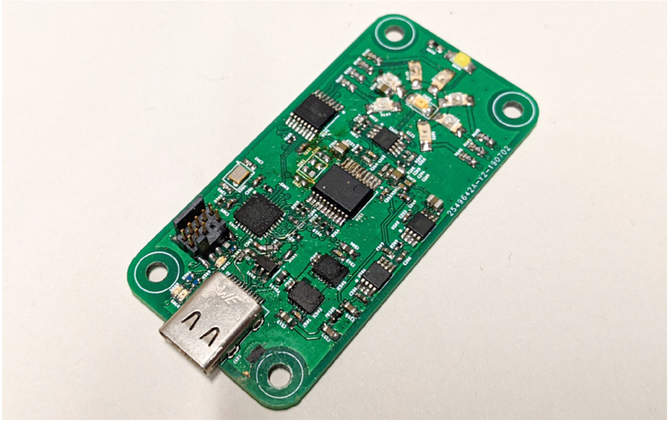


Figure 2.9: ReReMeter.

Current infrared sorting techniques are divided into two categories: Conveyor belt style or handheld scanner .

With the conveyor belt method, a sensor is placed above the conveyor belt, and based on the reading of the infrared sensor the object is sorted (often with compressed air). With handheld scanning, a user scans a plastic object whereafter the scanner tells what type of plastic it is. Users in LMIC benefit most from a handheld scanner since their inflow is often not continuous and there are no conveyor belts in place on which to mount infrared sensors.

Market research in the field of handheld scanners, or more precisely infrared spectrometers showed that based on the technology used to sense the reflection there are three categories: Micro Electrical Mechanical spectroscopy Systems (MEMS), Optical spectroscopy systems and discrete spectroscopy systems. The category that is most suitable for LMIC is discrete spectroscopy. MEMS spectroscopy is complex to manufacture, while Optical spectroscopy is expensive. Discrete spectroscopy is less accurate but research by Straller and Gessler (2019) suggests that it can still identify the plastics mentioned earlier. Straller's research led to the development of the open-source ReReMeter (figure 2.9). This plastic identification tool is used as a starting point for the development of this project. Since open-source knowledge is used in this project, it is therefore also expected to share the project in an open-source manner.
More information about infrared identification can be found in appendix IV (identification)

This narrows down the research question: is it possible to develop an open-source handheld **discrete** infrared sorting device that accelerates the sorting process for plastic waste management in the informal sector?

2.4 Potential use cases

As stated in chapter 2.1, informal recycling differs from country to country. To get a better understanding of the usage context, four typical example contexts where infrared spectroscopy could be useful were envisioned, based on the insights from the previous chapters. These four contexts are derived from vastly different places, so that a general, abstract image of informal recycling can be formed As the overlaps and differences will become apparent, they can subsequently be integrated into potential designs. All this is done to ensure that infrared spectroscopy fits all different use cases, now and in the future. The contexts are sorted based on feasibility over time , this makes it possible to directly incorporate in use case one, and over time in the other more use cases.

The Ocean Cleanup

The Ocean Cleanup wants to identify and separate ghost nets, but is currently struggling to do so. Ghost nets are fishing nets that have got lost at sea during fishing. These ghost nets are taken out of the ocean and moved to a recycling facility. Often, these ghost nets are very entangled with each other and require manual identification and separation, as can be seen in figure 2.10 (E. Sneijder, personal communication, September 25, 2020).
The Ocean Cleanup wants to separate different types of ghost nets. These nets float on the surface of the ocean and thus are polyolefins (PP, HDPE, LDPE). Separation is currently done with a 30.000 Euros Thermo Scientific PhazIR PC (see figure 2.11), This is expensive and cannot be used offshore (E. Sneijder, personal communication, September 25, 2020).

Timeline: 2020-2025

Requirements:
- Separate PP from PE plastics
- Able to identify fishing nets
- A handheld device for mobile identification
- Scanning in under five seconds
- Can be used offshore
- ~ 1000 Euros resell price
- Product needed as soon as possible


Figure 2.10: Ghost nets being sorted. (The Ocean Cleanup)


Figure 2.11: PhazIR being used to identify ghost nets. (The Ocean Cleanup)

Middle-sized recyclers in LMIC

Middle-sized recyclers in low- to middle-income countries (figure 2.12) can handle tons of plastic per week but are not capable of investing large sums of money for big recycling infrastructure. The goal is to give them the possibility to go from fully hand-sorting, (figure 2.13), to mixed human-machine working.
Currently, in many places, hand-sorting is viable since labor cost is low. However it is expected that the demand for more automation will slowly increase. Hand sorters will still be able to quickly pick out a few recognizable plastics, but plastics that need to be assessed will require too much time, making them unviable. In this case an automated sensor can help.

Timeline: 2020-2030

Requirements:
- Sort plastic that is unknown to hand sorters
- Daisy chain multiple sensors
- Have sensors move actuators
- Stability of sensor readings
- Scalability of number of scanners


Figure 2.12: Plastic shredded in India. (Shailendra Yashwant)


Figure 2.13: Plastic collection in Hanoi. (Nhac Nguyen)

Hyperlocal western recycling

In recent years there has been a growing trend towards local sustainability and community-based living. These communities try to be self-sufficient and limit the amount of plastic they use. An important part is the reuse of materials, with all raw materials needing to be put back into their own circular economy (figure 2.14).
These places often recycle their own plastic with the help of DIY (do-it-yourself) recycling machines. Just as in any other recycling process the raw material needs to be separated according to chemical type (figure 2.15). As plastic recycling is often not the main job of the people living in these communities, they lack the knowledge to recognize different types of plastics. A simplified method of sorting plastic would benefit this target audience and allow them to make new, valuable items on the spot.

Timeline: 2025-2030

Requirements:
- Can handle a broad range of plastics
- Historical statistics on weight of plastic collected
- Implementation of a reward system or reward points
- A DIY product that can be self-made

Figure 2.14: Plastic collection. (Precious Plastic)

Figure 2.15: Plastic sorting. (Precious Plastic)

Rag pickers in LMIC

In India, rag pickers are a common sight. These are people whose job it is to collect recyclable materials. Each rag picker focuses on their own specialized material. One collects cardboard, the other collects glass, and yet another one collects PET bottles. Each rag picker makes similar rounds in the same area (figure 2.17) and at semi-regular intervals visits a buyer to weigh their collected material and be paid for it (figure 2.16). In the future, it will be more viable for rag pickers to combine efforts and collect all materials in a single round. This means that products will need to be sorted afterwards.
Mixed plastic waste streams need to be sorted to get the most value from the collected material. With the help of a simple NIR sensor, this process can be streamlined.

Timeline: 2030 and beyond

Requirements:
- Long battery life to enable on-location identification
- Proof of purity of scanned items
- Historical statistics of scanned items
- Robust build quality

Figure 2.16: Rag picker collecting plastic. (Anas Jawed)

Figure 2.17: Rag pickers on landfill. (Tom Fisk)

Conclusion

All envisioned use cases will benefit from easy and reliable identification of plastic. All of the use cases collect common types of plastic and the people involved told me that they strive for high purity collection since this makes recycling more economically viable.

This means that the quality of the scan and the interpretation of plastic samples should l be equal for all use cases. What will vary, based on their needs and budget, is the processing time, visualization, and performance will vary based on their needs and budget.

2.5 Proposed solution

The discovery phase can be summarized as follows: Plastic pollution is harmful to our environment. All countries contribute to it, but most of the plastic that ends up in nature does so in LMIC. The recycling infrastructure in LMIC can be described as informal, and is currently lacking the tools to correctly manage plastic waste.
Especially sorting plastic is a highly manual process that is time-consuming and labor-intensive, as the inflow of plastic often fluctuates and the plastic types that needs to be sorted varies. Handheld infrared sorting is the most viable sorting method for informal recycling, as it does not require big workspace infrastructure like conveyor belts and can distinguish between multiple types of plastic at once.

The main research question arising from the above factors was: How can resources be developed that accelerate the process of plastic sorting for informal waste management?

Hypothesis: This can be done by developing an open-source ecosystem that allows anyone to implement discrete infrared spectroscopy at their plastic recycling facility.

In theory this makes it possible to perform Plastic Identification Anywhere, and it will result in improved waste management, a reduction in plastic pollution, and a better living environment for people and animals on land and in the sea.
An additional benefit beyond the scope of this project is the social impact: since plastic recycling will be accelerated and thus simplified, it will make starting a recycling business more viable and might create more jobs and sustainable communities.

Main research question:

“How can resources be developed that accelerate the process of plastic sorting for informal waste management?“

Hypothesis:

“This can be done by developing an open-source ecosystem that allows anyone to implement discrete infrared spectroscopy at their plastic recycling facility.“

Plastic sorting. (Precious Plastic)

Plastic collection Manduku.

Waste management Thilafushi, Maldives.

Online interviews due to Covid-19.

Photo by Dayee on Unsplash

Define

This chapter defines the design space in which the research question needs to be answered. Boundaries are set through values, requirements, and challenges. These form the starting points for the physical development of a Plastic Scanner.

In this chapter:

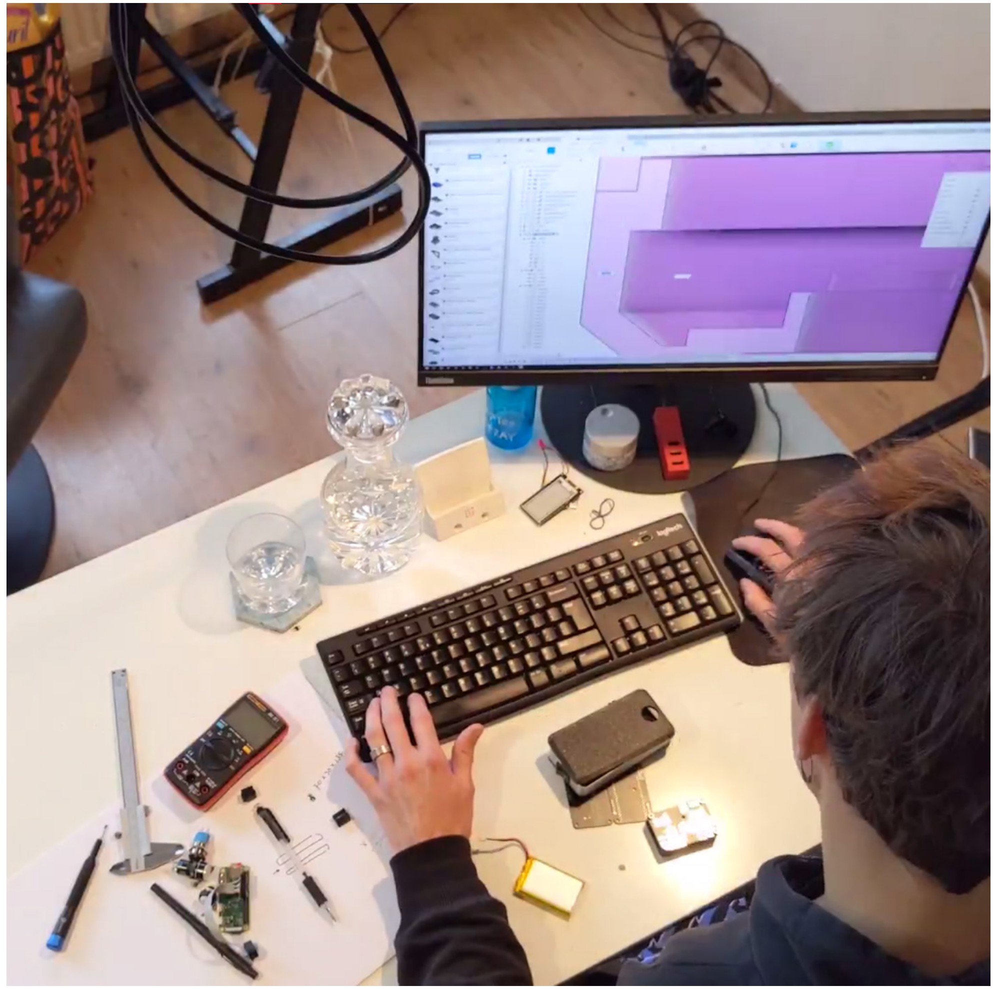
3.1 Approach

To develop the open-source ecosystem mentioned in chapter 2.5, several design challenges needed to be overcome first. These challenges are bound by the wishes and requirements gained from the insights of the Discover phase, and are hereafter called: design values and design requirements.

The *Design Values* form the vision throughout the design process, they are key attributes that help make decisions in the design process. For example, ‘designed for ease of use’ or ‘designed for context variation’.

The *Design Requirements* are the measurable and physical demands the product has to meet for it to be successful. For example, dimensions, scanning range, or accuracy.

The *Design Challenges* are challenges that require further tests or prototypes to solve. They are based on the insights collected during the Discovery phase of the project. For example, the effect of protective glass on the sensor readings.



3D modelling of the enclosure.

3.2 Design Values

Often in design projects, there isn't a single correct answer to the initial design question. Multiple solutions can solve the same problem, just in different ways. To be able to prioritize the various solutions, different design values are selected to clarify the vision for the final deliverable.

Design for context variation

Design for context variation (Kersten, 2020) is a method to strengthen the base artifact of your product and to improve the chances of success in various contexts around the world. By envisioning potential usage scenarios, like in chapter 2.4, and reviewing what is similar and what is different, a base artifact can be derived which combines similarities and separates peripherals that can be added to fit the exact context. For example, modularity can help to make the product adjustable, while as an added benefit resilience is built in to enable future upgrades.

The implication of *design for context variation* on the development of the product:
Modularity often has a negative impact on performance and cost (Salvador et al., 2002, p. 552), Nevertheless, it allows for a broader product family, satisfying more contexts. This design value can be realized by separating the processing and the sensing components of an infrared spectroscope. The processing and sensing components should be connected through standard connectors and communication should happen via standardized communication protocols to ensure that the adjustability to various contexts is not compromised. Using a high-level programming language makes the software easy to understand and allows users to adapt the software to their context.

Design for local manufacturing

Design for local manufacturing (Kostakis et al., 2015, p. 127) is a method in which the manufacturing process is included in the development process. The product is developed in such a way that people in the desired contexts are able to produce it locally, using the resources available to them. This allows for local employment and leads to a lower dependency on single production locations while reducing shipping cost and energy.

The implication of *design for local manufacturing* on the product:
To ensure that local manufacturing can be implemented, a distributed network of workspaces capable of manufacturing a discrete infrared spectroscope needs to be found. Fablabs and Makerspaces are community workspaces that can form such a distributed network. They can be found all around the world and have a standard inventory of tools. These tools often include 3D printers, laser cutters, soldering stations, and basic hand tools. This design value can be realized by using Makerspaces and Fablabs as a benchmark during the development phase to assure local manufacturing.

Design for open development

Design for open development (Arndt et al., 2020) is a method that incorporates the basic principles of open source working within the design process. By sharing information about the project openly this method makes it possible to accelerate innovation cycles, and allows for experts to contribute to the project. Additionally, open publication online allows for transparency regarding the technical functioning and product quality. Lastly, it allows for personalization by the user who builds the project. By publishing a broader, more general project it is possible to build a purpose driven community that is more likely to contribute to the project. In contrast, publishing a finished project results in a narrow solution without opportunity for contributions.

The implication of *design for open development* on the product:
Making the project open for development has certain benefits, but also means additional requirements. Users need to be able to study, modify, make, and distribute the information. This value can be realized by publicly sharing the source files of the project, using file formats that are easy to modify and providing a platform to allow for contributions.

3.3 Design Requirements

Based on the research done for this project, both in the literature as well as derived from real life examples and interviews, the final design must meet the following main requirements stated in table 3.1.

Requirement	**Origin**
Identify the following types of plastics: PE, PET, PP, PS, and PVC	These are the 5 most common plastics and account for more than 75% of consumer waste plastic.
Create a plastic scanner that costs less than 500 Euros to manufacture	Current handheld scanners range from 5.000 Euros to 50.000 Euros. They are not accessible to small informal recyclers.
Consist of a plastic scanner that can be used in the field	The product should be able to withstand normal operations, similar to the robustness of a smartphone.
The output of the scanner needs to be configurable	The different contexts require the flexibility of a plastic scanner. Some users might want to have a screen that tells them what type of plastic it is, while others may wish to actuate a motor based on the output of their scanners.
Use of multiple scanners	The number of scanners at a facility might differ. Some measure only plastics that cannot be sorted by hand, while others want to be able to scan all types of plastic. This requires the ability to connect multiple sensors to one central processing unit.
Scanning history	Once an item is scanned the user might want to review the measured data at a later time. The product should store these values and make it possible to review them at later on.
Scanning time	The measurements then need to be as short as possible to ensure the movement of the sample does not influence the sensor reading. The time needed for interpretation needs to be comparable to a human identifying plastic.

Table 3.1: Overview of the main requirements.

3.4 Design Challenges

The design challenges connect the discovery phase to the development phase. Certain insights gathered during the discovery phase required further development, in the shape of experiments, prototypes or micro research. The discovery phase resulted in the following design challenges stated in table 3.2.

Challenge	**Experiment question**
Sensor	What exact sensor setup is the best?
Light	How can issues related to external light and noise be solved?
Printed Circuit Board (PCB)	What options are there for printed circuit boards and which of them makes the most sense?
Enclosure	What tools are available for enclosures, what elements should be provided ?
User Interface (UI)	What is the interaction with the user, does this affect the components?
Software	Which tasks does the software need to execute, and based on which libraries?
Manufacturing method	How can the product be manufactured, what are viable options?

Table 3.2: Overview of the design challenges.


Photo by Krizjohn Rosales from Pexels

Develop

This chapter aims to solve the current uncertainties and design challenges, through practical research and development. This can be done through experiments, prototypes, or research into common practices. Each of the sub-chapters solves a specific problem. The combination of these solutions will form the basis of the next chapter.

In this chapter:

4.1 Exploded overview

Before the rest of this chapter delves deeper into the different design challenges, it's useful to have a general overview of all components (figure 4.1). This shows all the different components required for discrete infrared spectroscopy to work. The combination of all these components will from now on be called "Plastic Scanner ".

In its most abstract form, a Plastic Scanner has the following components:

- **Light**, the component responsible for shining IR light on the plastic object.
- **Sensor**, the component responsible for measuring the IR reflection from the plastic object.
- **PCB**, a board that connects all electrical components physically and electrically.
- **Processing**, a processing unit that converts measurement data to a prediction.
- **UI Output**, a screen to display predicted plastic type.
- **UI Input**, a button to start the scanning procedure.
- **Enclosure**, a housing that connects all parts and protects them.
- **Battery** (optional), to make the device handheld.
- **Charge IC** (optional), to supply the correct voltage to the PCB and to charge the battery.

Steps required in the process of infrared spectroscopy.

1. A user presses the input button to notify the scanner that they want to take a measurement.
2. IR lights shines on the plastic object and the reflection is measured with the sensor.
3. The measured reflection values are transferred to the processing stage.
4. The processors feed the measurement values into a machine learning algorithm.
5. The UI output(screen) displays the predicted plastic-type and confidence level.

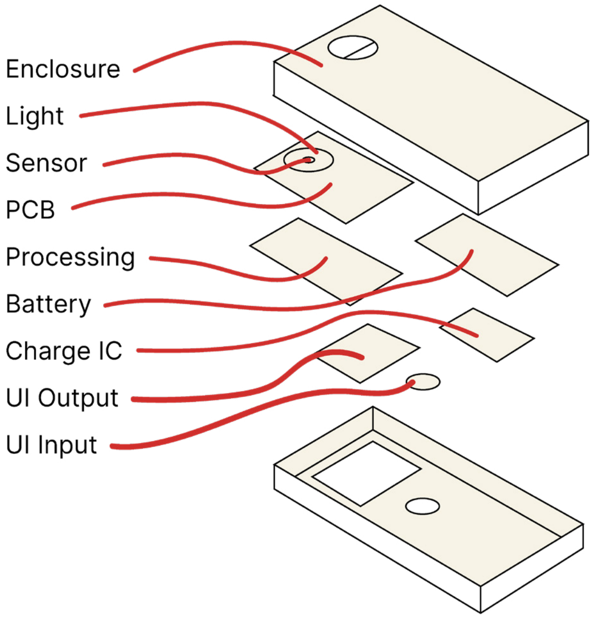
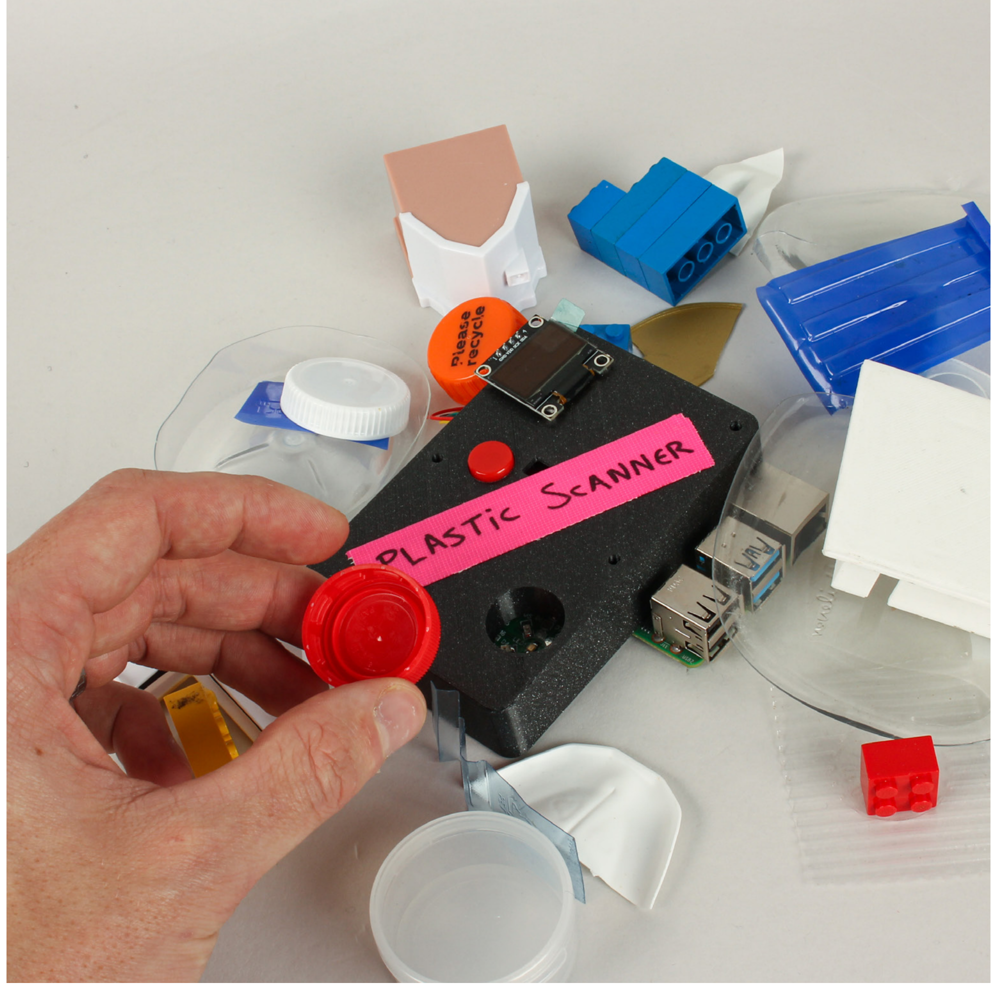


Figure 4.1: Schematic representation of components in a Plastic Scanner.



Minimal Viable Product testing.

4.2 Sensor

The most important component in near-infrared spectrometry is the sensor. The sensor needs to be able to measure different wavelengths of IR light. This is commonly done with an InGaAs sensor. The analysis in chapter 2.3 described the three main methods for handheld scanning: Discrete, MEMS, and optical. Discrete was chosen since it is the easiest to implement and it is relatively cheap. Only one expectation was found to this conclusion, the Hamamatsu C14273 (figure 4.2). This is a MEMS sensor module with a relatively low price point for full spectrum measurements. A comparison is made in table 4.1 Conclusion: To make an infrared scanner that is simple to build and accessible to people in LMIC the discrete LED technology was chosen. It is easy to implement and can still identify the five most common plastics (Straller & Gessler, 2019). To incorporate resilience and modularity, a possible future upgrade to a MEMS sensor is anticipated by adding extra mounting holes and a ten pin Molex connector.

	Discrete LEDs	Hamamatsu C14273
Cost per unit	100 Euros	300 Euros
Measurement points	8 points	50+ points
Wavelength	950nm-1650nm	1550nm-1850nm
Required expertise	Low	High
Signal quality	Low	High
Disadvantage	LEDs difficult to source	Requires difficult driving mechanism
Advantage	Quality is adjustable by soldering more LEDs	Full spectrum can give more information

Table 4.1: Comparison between Discrete IR LEDs and Hamamatsu MEMS sensor.

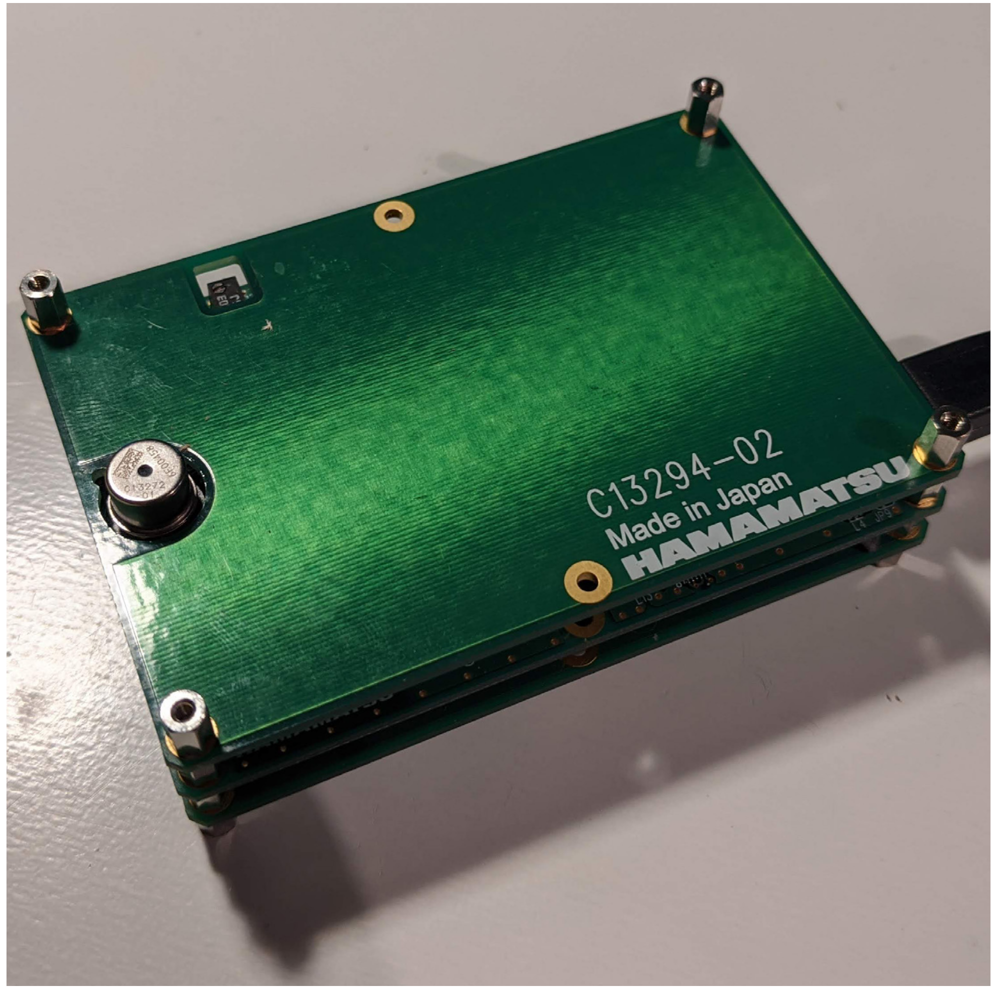


Figure 4.2: Hamamatsu C14273 sensor on development board.

4.3 Light

Ideally, the light shone on an object has a precisely controlled wavelength. In these cases, light with a wavelength of 1656nm and 1724nm would be sufficient for identifying PET, PVC, PE, PP, PS, as the research by Masoumi et al. (2012, p. 219) suggests. Currently, LEDs with these specific wavelengths are not available. The only IR LEDs on the market have a peak wavelength of 850,950,1050,1200,1300,1450,1550 and1650nm. Instead of using two highly specific wavelength LEDs, eight more generic LEDs were chosen for interpretation of the plastic types. At a later point in time, the possibility of reducing the number of LEDs without compromising quality can be investigated.

LEDs with the before mentioned peak wavelengths are not often used, resulting in a limited number of suppliers, namely: Marktech, OSA-Opto and OSI-Optoelectronics. The available LEDs result in the IR emittance chart displayed in figure 4.3.

In an ideal setup, all the IR light is either absorbed by the plastic or reflected onto the sensor. In real-world usage this is not the case: Some of the IR light “leaks” to the outside and external IR light enters the sensor, both situations negatively impacting the quality of the measurement. To reduce this effect, three methods are implemented (figure 4.4):

1. **Strategically placing the sensor.** Placing the sensor facing downward prevents external light from entering the sensor, since most light sources are placed overhead, facing down.
2. **Adding foam.** Adding soft material mitigates the gap between the sensor and the object to identify. This can be done by placing a ring-shaped piece of foam between the scanner and the object
3. **Addition of a high pass filter.** This filters out light with a frequency not equal to the frequency of the emitted light.

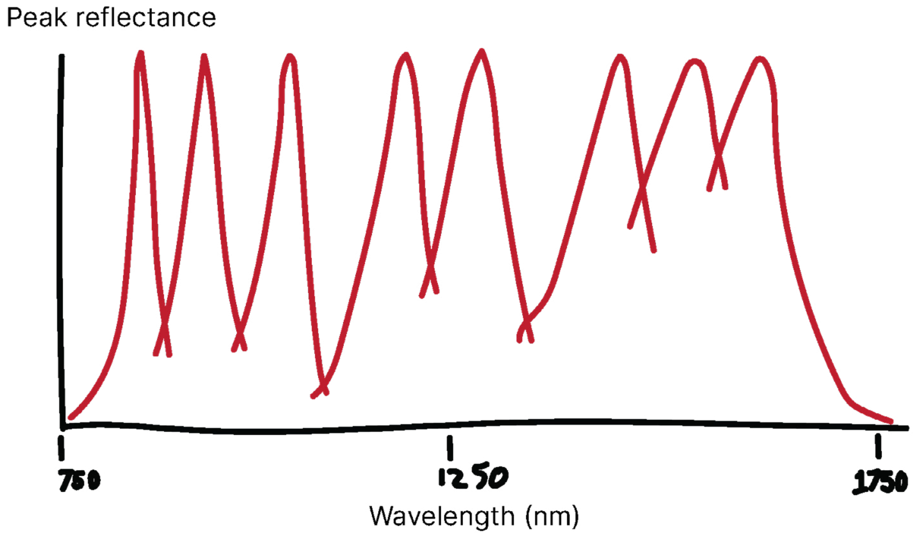


Figure 4.3: Emittance chart of all eight IR LEDs.

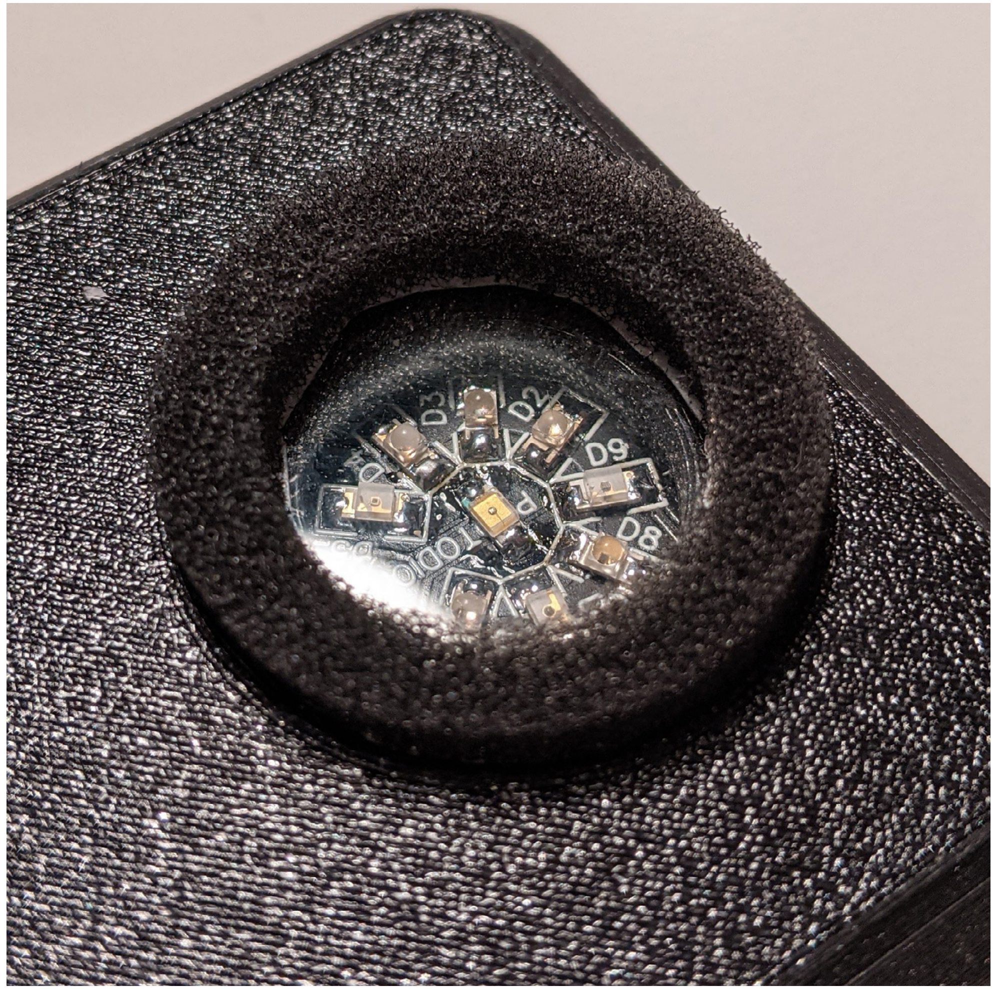


Figure 4.4: Underside of a handheld scanner.

4.4 Printed circuit board

A printed circuit board (PCB) is designed to connect all components in the most viable and feasible manner, both physically and electrically. Within PCB design there are a few different design considerations. They are:

The production method. The most common methods of PCB manufacturing are milling, etching, and silk-screening. The last method has increased in popularity last years due to the rise of online PCB manufacturers. PCBs can be ordered online and are manufactured and delivered within days. This greatly simplifies the production method and does not require any specialized tools.

The style of the components. For electrical components there are two types, Surface Mount Components (SMT) or Through-Hole Mounting (THM). While THM components are easier to solder, they take up more space, and automating the assembly process is also more complex with THM components. Within SMD components there are various sizes. Everyone should be able to hand solder 0805 components or bigger, and with some practice people can also solder 0603 components. 0402 components or smaller are usually not soldered by hand, but by machine. To ensure manufacturability, 0805 SMD components were selected. These also enable automation of the PCB assembly process, something which is often offered by PCB manufacturers as well for users who do not feel comfortable soldering the components by hand.

The placement and layers of the components. The price of PCBs depends mainly on the quantity and complexity. Complexity can be reduced by using just two layers (front and back). This option is available from all PCB manufacturers. Another method to improve manufacturability is placing all components on one side. This makes soldering easier and allows for automatization.

Conclusion: Using of 0805 size components, placed on one side, SMD allows for automation in the future, as well as being hand soldered. This can be seen in figure 4.5.

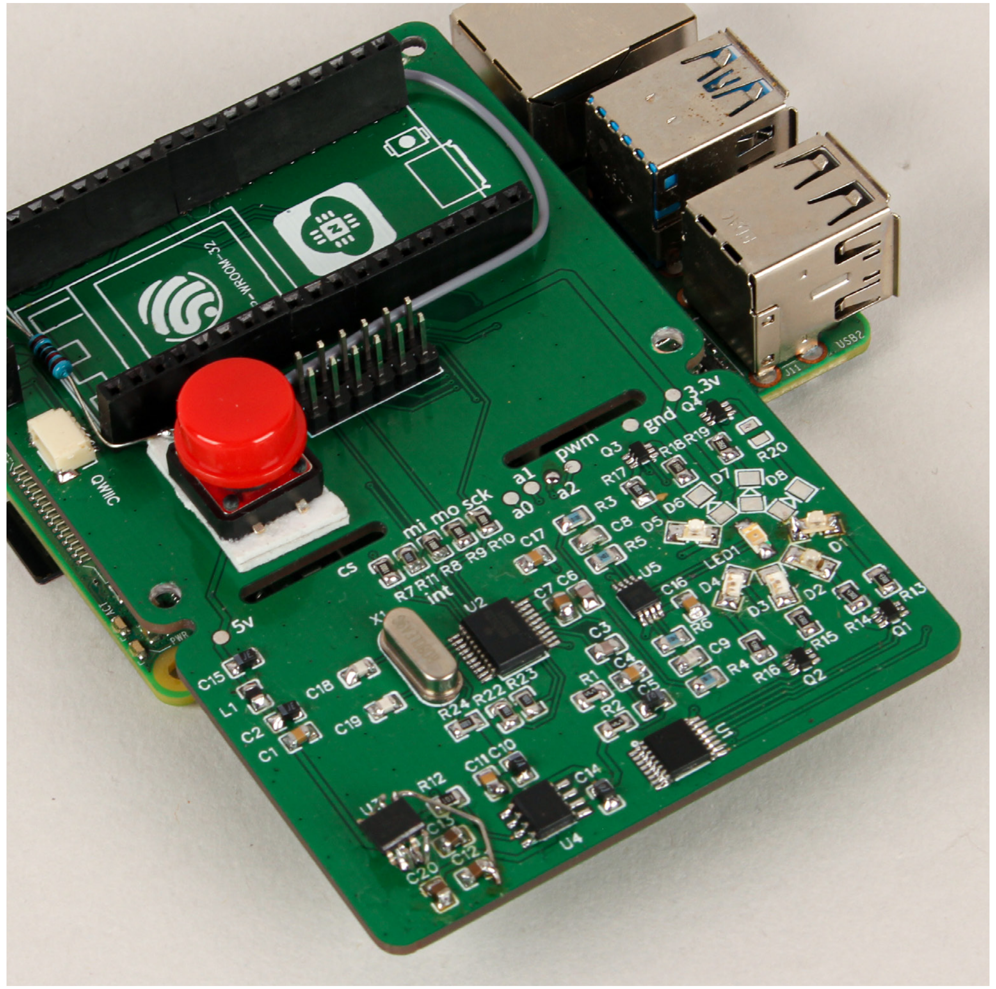


Figure 4.5: PCB ordered online with 0805 SMD components on a single side.

4.5 Enclosure

The enclosure of a Plastic Scanner holds all the components together, protects the user from the electrical components on the inside and protects the electrical components from influences from the outside. Based on the design value of local manufacturing, we want Makerspaces and FabLabs around the world to be able to build the Plastic Scanner. This means we are limited to the tools available at Makerspaces: 3D printers, laser cutters, and basic hand tools.

As an example, a 3D printed enclosure was developed (figure 4.6). It consists of three parts, a bottom, a middle, and a top. This makes it possible to easily adjust its components and only reprint one part of the enclosure. Apart from the 3D print, the enclosure consists of a glass screen and a foam ring. The glass screen is added to protect the LEDs and sensor from dirty plastic. The foam is added to reduce the risk of external light entering the sensor. The enclosure is held together with two screws.

Conclusion: The enclosure needs to be able to be built at a Makerspace or FabLab, i.e., by 3D printing, laser cutting, or with basic tools. As an example for those wishing to build one, a 3D printed enclosure will be provided, as well as the mechanical drawings that are needed to be able to make custom cases.

Figure 4.6: 3D printed enclosure with PCB mounted inside.

4.6 User interaction

Based on the sensor readings from the different wavelengths, the Plastic Scanner needs to make a prediction of the type of plastic. Since this is a prediction, the quality of the prediction is also a valuable piece of information. This means more complex information that needs to be communicated to the user. A binary response like a single LED or a buzzer is not sufficient. A graphical screen displays the rich information that contains the measurement as well as status information like connectivity or battery status. Whether the screen is on the device or on a smartphone can be decided by the end-user.

Conclusion: the above results in the need for a graphical display or an external display (i.e. a smartphone). For a handheld scanner, an OLED screen as shown in figure 4.7 is ideal as it can be easily implemented as a module and can convey complex information.

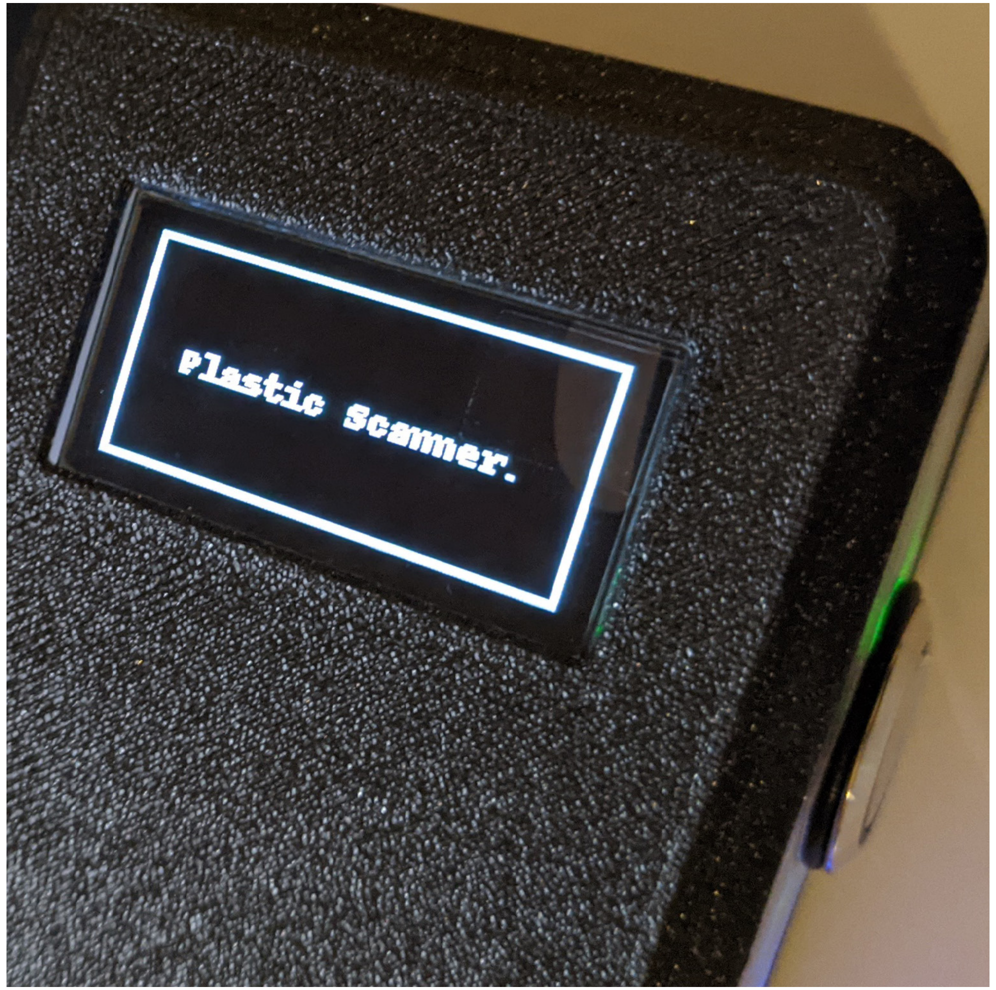


Figure 4.7: Image of a 1.3-inch OLED graphical screen.

4.7 Software

Interpreting the IR reflection measurements is vital for the functioning of a Plastic Scanner. Software makes it possible to control the hardware and processes the measurement through a machine learning algorithm. The software consists of three parts: Hardware interaction, prediction algorithm and training algorithm.

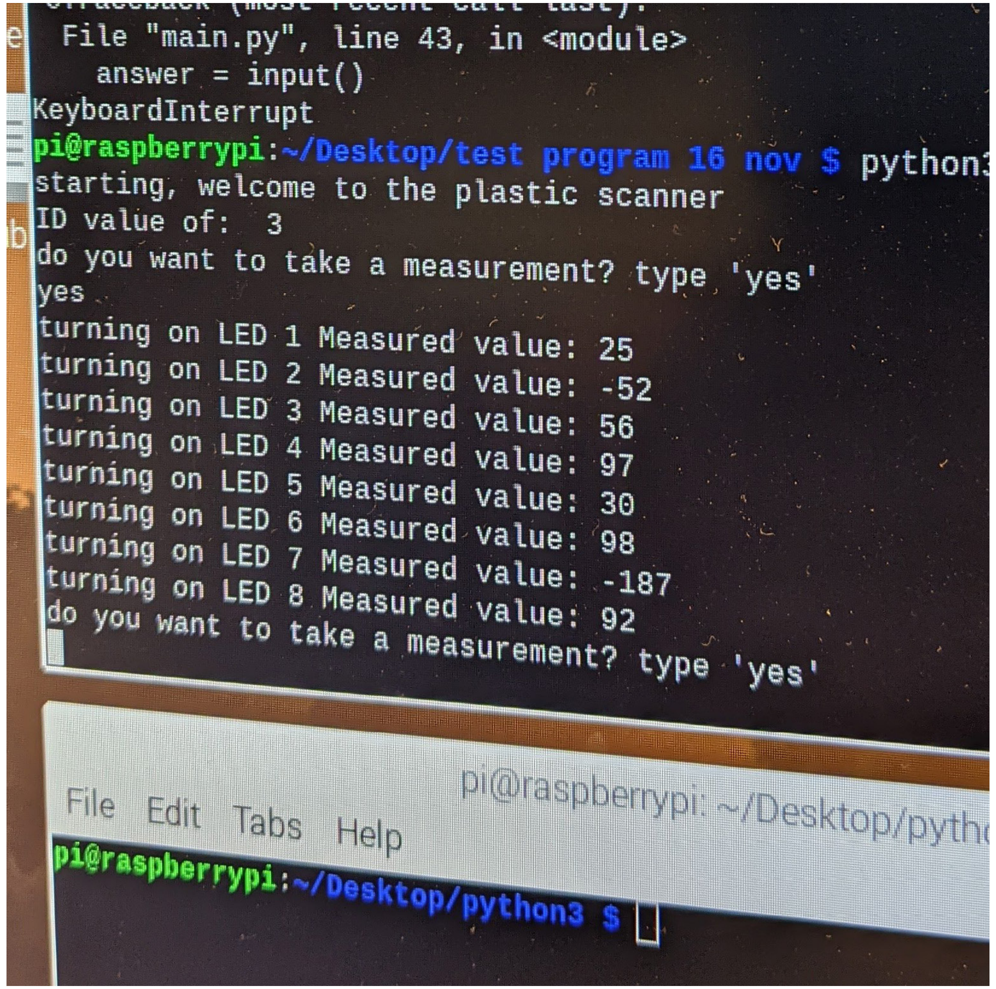
Hardware interaction: this piece of software communicates with all the connected hardware of the Plastic Scanner. It checks whether buttons are pressed, displays the information on the screen and takes measurements from the sensor.

Prediction algorithm: this piece of software feeds the readings from the sensor into an algorithm that predicts which of the five types of plastic it is, responding with the type and the certainty of the prediction.

Training algorithm: this piece of software only needs to be run at the beginning, with sensor readings taken from known samples (samples that have a resin identification code on the product). This way the algorithm can learn to differentiate the different clusters of plastic and make accurate predictions. The more samples the algorithm has trained with, the more accurate it will be.

Python is a high-level programming language capable of providing the required scripts mentioned above. A high-level programming language means that there is a strong abstraction from the details of the computer and that it is easier to read by the user. With the help of MicroPython it can be implemented in many different processing units. TensorFlow was chosen as the machine learning integration, since it is an open-source project with a broad community of support.

The Raspberry Pi Zero W can be used to run the required software. It is a low cost single board computer which can easily be embedded. The Zero W module was is chosen specifically, as it has a compact formfactor but is still capable of running TensorFlow. The built-in wireless capabilities allow for easy implementation into various contexts.



```
  File "main.py", line 43, in <module>
    answer = input()
KeyboardInterrupt
pi@raspberrypi:~/Desktop/test program 16 nov $ python
starting, welcome to the plastic scanner
ID value of:  3
do you want to take a measurement? type 'yes'
yes
turning on LED 1 Measured value: 25
turning on LED 2 Measured value: -52
turning on LED 3 Measured value: 56
turning on LED 4 Measured value: 97
turning on LED 5 Measured value: 30
turning on LED 6 Measured value: 98
turning on LED 7 Measured value: -187
turning on LED 8 Measured value: 92
do you want to take a measurement? type 'yes'
```

```
pi@raspberrypi:~/Desktop/python3 $
```

First data capture.

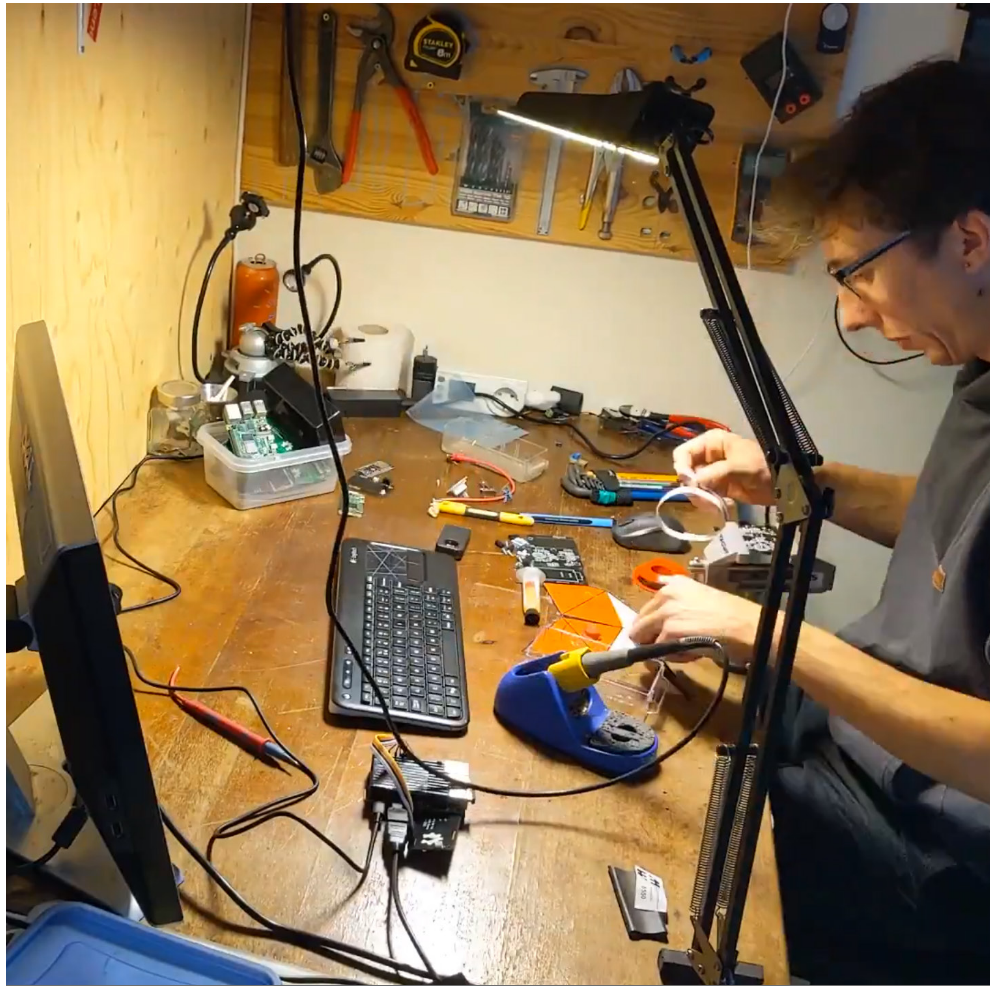
4.8 Manufacturing method

Products like a Plastic Scanner can be provided in many forms (table 4.2). Only providing the user with an instruction manual on how to build one results in low cost but high need for resources(time), whereas providing a service for the user in the form of pre-fabricating certain elements of the Scanner results in high cost but low need for resources(time), Different options were stated below to find the most suitable option for the project.

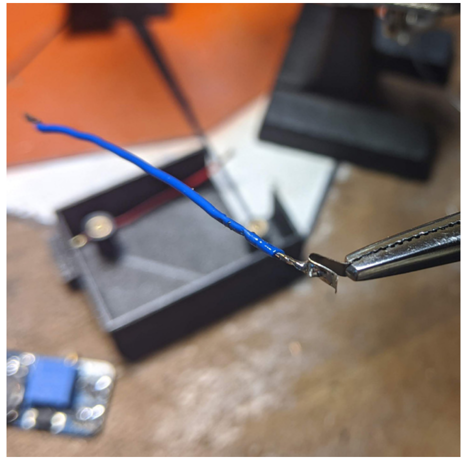
Conclusion: It is best to make only providing a manual the default option, as this enables open development. A good reason to sometimes also opt for the kit version, is that selling them provides a business model for the continuation of the project. More advanced versions can be made upon request.

	Download	**Kit**	**Basic**	**Advanced**	**Service**
Cost	free	€250	€350	€450	€50 p/m
Manual	✓	✓	✓	✓	✓
PCB		✓	✓	✓	✓
Case			✓	✓	✓
Calibration				✓	✓
Maintenance					✓

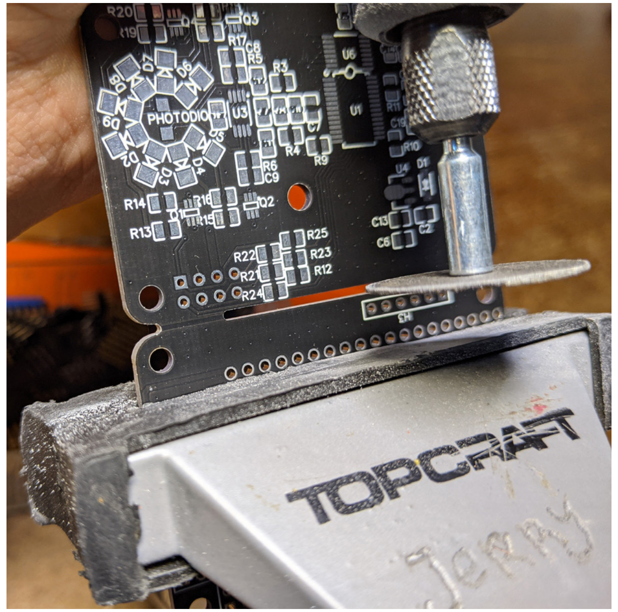
Table 4.2: Comparison between different manufacturing options.



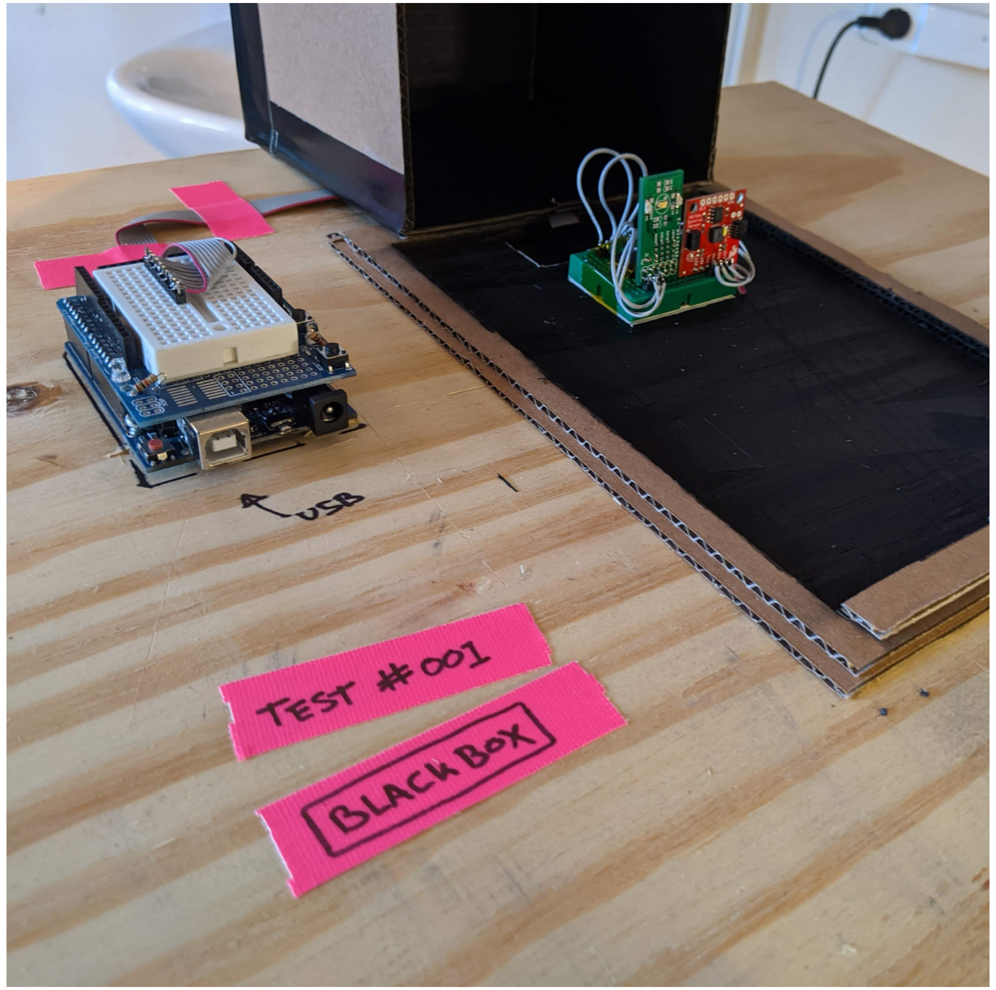
Manufacturing of breakout board with simple tools.



Wire for prototype.



Modification of PCB



Initial test setup.

Photo by Daria Shevtsova from Pexels

Deliver

This chapter presents the final design outcome of the master thesis project. It is a complete ecosystem that creates the foundation for Plastic Identification Anywhere.

In this chapter:

5.1 The ecosystem

The final design proposal to enable Plastic Identification Anywhere is a combination of multiple tangible and intangible components (figure 5.1). As stated in the hypothesis in chapter 2.5, the project should lead to an ecosystem around discrete infrared spectroscopy instead of just a single piece of hardware. The result is a broad ecosystem framework consisting of the following components:

-A breakout board that combines all components to emit and sense infrared light on a small printed circuit board with standard communication protocols.

-A handheld scanner that integrates the breakout board into real-world applications. It enables local machine-learning processing of the sample, all in a compact form factor.

-A kit that delivers all the components for the breakout board in a small package with clear instructions on how to assemble a breakout board, making board building more accessible.

-A website that informs (and inspires) all potential users about the Plastic Scanner, connecting those who want a Plastic Scanner to those who can build a Plastic Scanner.

-Documentation that is published online in its entirety, to enable cooperative working and transparency. This also makes it possible to modify a Plastic Scanner to personal preference.

-Software that communicates with the hardware and implements machine learning for optimal and quick prediction of plastic types.

The result is a combination of the solutions found for the design challenges. The ecosystem contains different components which are developed to serve their primary goal. Over time, each component can be easily improved upon once the ecosystem is launched. The following chapters get into more detail about the features of each component in the ecosystem.

Figure 5.1: The ecosystem, left to right : Documentation, breakout board, kit, handheld scanner and website.

5.2 The breakout board

The breakout board (figure 5.2) is the heart of the ecosystem. It shines sequential infrared light on a plastic object, measuring the reflectance at multiple wavelengths. The measurements are communicated over the SPI protocol to an external processor.

Description of the breakout board
The breakout board houses all the components required to perform discrete infrared spectroscopy. With a size of just 60x40mm, it is a tiny board that allows people to identify the five most common plastics with ease. The breakout board shines 8 individual LEDs with a wavelength of 850, 950, 1050, 1200, 1300, 1450, 1550 and1650nm. The LEDs have a narrow bandwidth with a full-width half max of 20nm and tolerance of just 3nm. The reflection from these LED lights can be measured by the sensitive and precise analog- to -digital converter, the ADS1256. This communicates to a processor with a standard SPI interface, making plastic identification as straightforward as possible. An overview of the way the breakout board works is presented in figure 5.3.

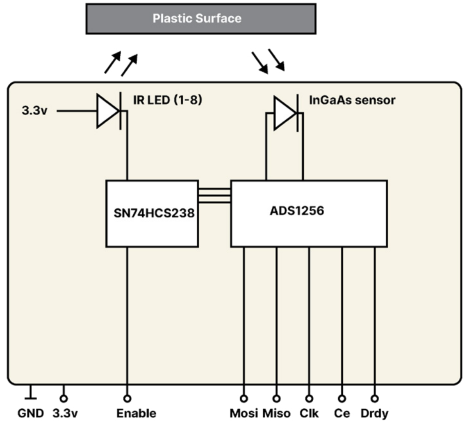


Figure 5.3: Block diagram breakout board.

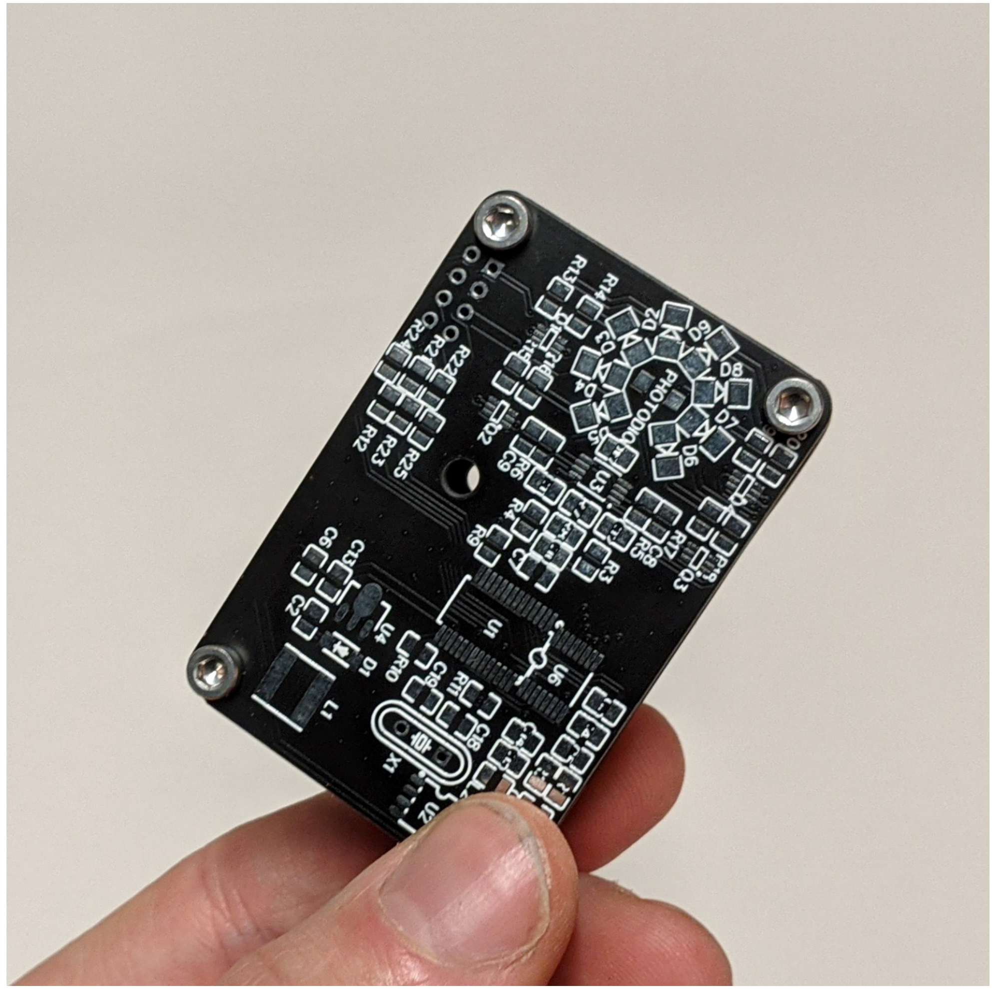


Figure 5.2: Unpopulated breakout board.

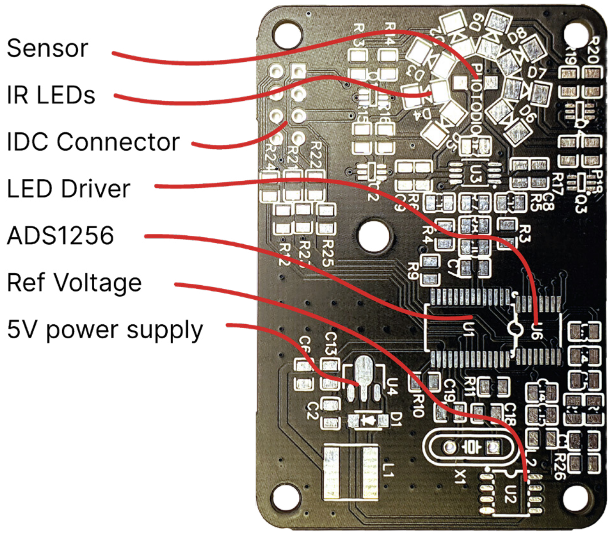


Figure 5.4: Components of breakout board PCB.

PCB	1.6mm PCB, 60x40mm. All components are 0805 SMD and are placed on a single side. 3mm mounting holes plus an extra mounting hole for possible future upgrades.
IR LEDs	Discrete wavelength IR LEDs to illuminate the plastic object are placed in a circular shape around the InGaAs sensor. The IR LEDs range from 850 to 1650nm.
InGaAs sensor	This Photodiode measures the amount of light reflected from the plastic object.
ADS1256	This analog-to-digital converter (ADC) translates the sensitive and precise voltage from the InGaAs sensor to a human-readable output over an SPI interface. The converter also controls the LED driver with SPI commands.
LED driver	The LED driver makes it possible to turn the IR LEDs on and off sequentially. It also allows for pattern flashing to reduce measurement noise.
5V	The 3.3 volts input voltage is boosted up to 5 volts required for the analog front end of the ADC.
2.5 reference voltage	Supplies the ADC with a 2.5 volts reference voltage to ensure high-quality measurements.
IDC connector	The eight pin IDC connector is the main interface of the breakout board, with the indicator slot preventing reverse connection.

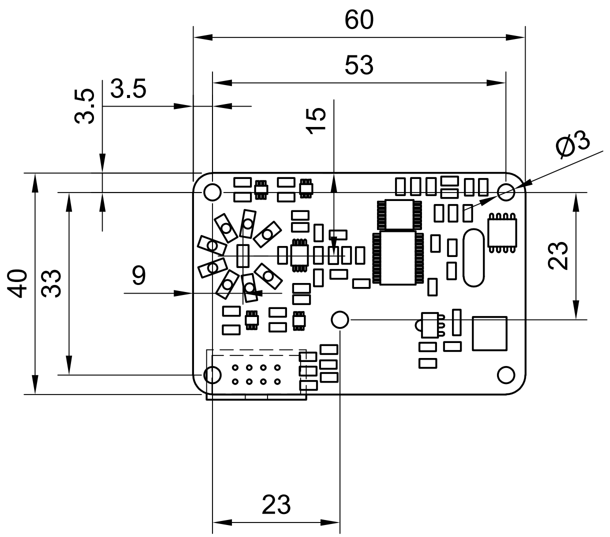
Table 5.1: Components of the breakout board and their function

Functioning of the breakout board

The breakout board is connected to an external processor through an eight PIN IDC connector, a connector with an indicator slot that prevents reverse connection of the breakout board. The connector houses a 3.3v line, a ground line, a strobe line for the LEDs, and the SPI lines. The SPI lines connect the external processor to the ADS1256. The ADS1256 is a 24-bit analog-to-digital converter i.e., a very precise voltage meter. The ADS1256 controls the SN74HCS238, a demultiplexer which, based on four signal pins, can have eight output pins. Each of the eight output pins controls a MOSFET, which turns the desired LED on or off. Once a LED is on, the ADS1256 measures its input voltage and turns the LED back off. This is done for each LED. The voltage the ADS1256 measures is the voltage generated by the sensor, amplified with an op-amp. This makes the ADS1256 a very sensitive, precise, voltage meter. The 5-volt power supply and the reference voltage are required for the ADS1256 to function correctly (table 5.1 & figure 5.4).

The result is a breakout board that is built in a modular manner, with manufacturers able to choose a desired processing type, which makes is possible to incorporate the breakout board across a wide range of recycling contexts. The breakout board is built with components which are readily available online and can be soldered by hand, making it ideal to be built by local Makerspaces or Fablabs close to the desired context. No proprietary tools or software are required to replicate this breakout board, and the source files are shared in an open and accessible manner.

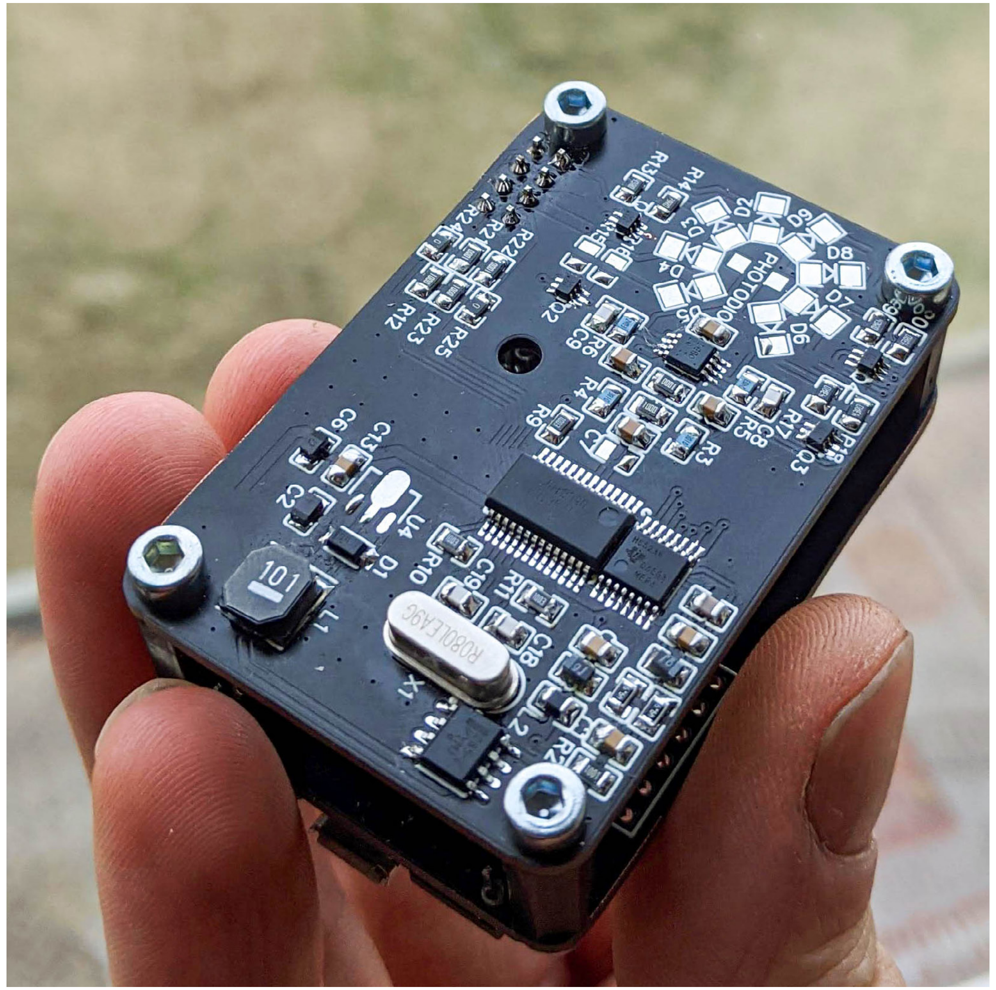
Render breakout board.



Mechanical drawing breakout board.

	Part number	**Part Description**	**Identifier**	**Quantity**	**Cost**
PCB	1.00	printed circuit board	n.a.	1	€1.00
ADC	1.01	ADS1256	U1	1	€15.30
Volt ref	1.02	2.5ref volage	U2	1	€0.85
Opamp	1.03	Opamp 237	U3	1	€3.08
Demultiplexer	1.04	Demux	U6	1	€0.35
5V PSU	1.05	5v power	U4	1	€0.17
Photodiode	1.06	InGaAs sensor	Photodiode	1	€13.80
Inductor	1.07	inductor	L1	1	€1.50
Diode	1.08	diode	D1	1	€1.40
Crystal	1.09	crystal	X1	1	€0.75
Connector	1.1	8 pin header	H1	1	€0.96
Transistor	1.11	Transistor	Q1,Q2,Q3,Q4	4	€0.55
Ferrite bead	1.12	ferrite bead	L2	1	€0.09
LEDs	1.13.1	1650nm	D2- D9	8	€131.71
Resistors	1.14.1	240k	R1-R26	29	€0.40
Capacitors	1.15.1	47n	C1-C19	19	€2.21
				Total cost Breakout board	€176.97

Table 5.2: Materials required to build a breakout board.



Breakout board with components.

5.3 The handheld scanner

The handheld scanner (figure 5.5) connects the breakout board to real-world applications. In this case the application is adapted to the Ocean Cleanup case described in chapter 2.4. It features a 3D printed enclosure that holds the breakout board, a Raspberry Pi Zero W, a 1.3-inch OLED display and a button interface. It is powered by a 2.200mAh battery.

Description of the handheld scanner

The handheld scanner puts the breakout board into practice by adding a 1GHz processor with wireless capabilities in the form of a Raspberry Pi Zero W. This minicomputer communicates over SPI with the breakout board and displays the predictions on a 1.3-inch OLED screen. The Raspberry Pi is a popular development board with great community support, making it possible to easily run machine learning models on the handheld scanner itself. It is an all-in-one package, with local machine learning interpretation, simple storage on an SD-card, and easy (wireless) communication with the user. An overview of the way it works can be seen in figure 5.6.

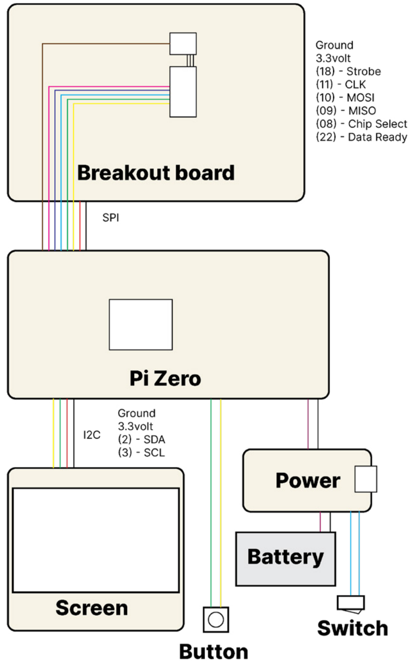


Figure 5.6: Schematic of handheld scanner.

Figure 5.5: Handheld Scanner.

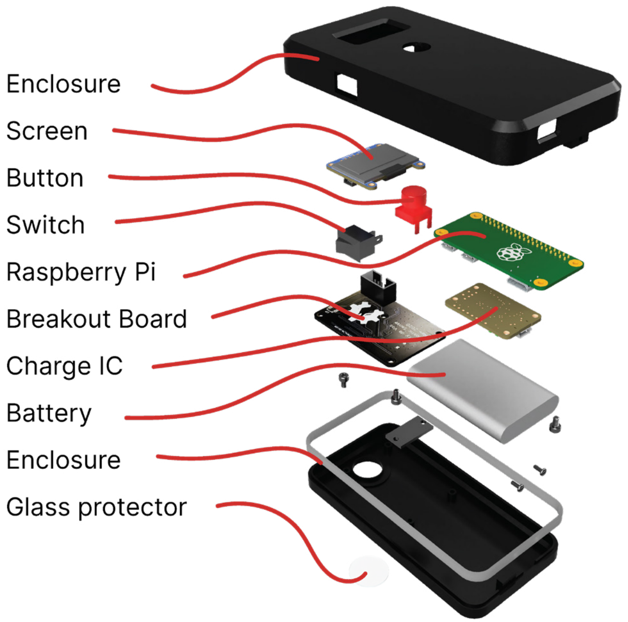


Figure 5.7: Exploded view of all components that make up the handheld scanner.

3D printed enclosure	Having the enclosure consist of 3 parts makes it easy to print and adjust to the needs of the user. Components are mounted with threaded inserts to ensure reusability.
Breakout board	Features of the breakout board described in chapter 5.2
Raspberry Pi Zero W	The main processor of the scanner. It feeds the measurement data of the breakout board into a machine learning algorithm and controls all input and output.
1.3 inch OLED screen	Graphical output for user, guides user through processing section and displays predicted plastic type, quality of the prediction, and battery indication/levels.
Button	Allows the user to start the scanning procedure.
Battery management chip	Controls the voltage of the battery and enables charging.
Battery	2.200mah battery with 5-hour usage.
Glass protector (optional)	Protects the sensor from debris.
Foam protector	Protects the sensor from external light.
Bolts	M3 5mm screws to fasten the breakout board and the Raspberry Pi.

Table 5.3: Components of the handheld scanner and their function.

Functioning of the handheld scanner

After the user has turned on the handheld scanner, the screen tells them to push the scanning button once a scan is desired. As soon as the Raspberry Pi recognizes that the button is pressed it sends a command to the breakout board, which starts the scanning procedure. Once the scanning is completed it is communicated back to the Raspberry Pi, which subsequently starts the interpretation algorithm to interpret the sample. Once this is completed the result is shown on the screen (table 5.3 & figure 5.7).

The handheld scanner presented in this thesis encases the breakout board adjusted to the context of The Ocean Cleanup, as described in chapter 2.4. Although the design of the handheld scanner focuses on this exact application, parts of this design can also be used in other contexts, for example the enclosure itself and the display method. The components of the scanner are sourced from the same locations as the components of the breakout board, preventing increased complexity in the need for the product to be able to be manufactured locally. A website where everyone can access the source files to 3D print the enclosure, as well as the other assembly instructions, enables open development.

Front view render of handheld scanner.

Back view render of handheld scanner.

Part number	Part Description	Quantity	Cost
1	Breakout board	1	€176.97
2	Raspberry Pi Zero	1	€10.00
3	SD card	1	€10.30
4	Charge IC	1	€19.95
5	1.3 inch oled screen	1	€19.95
6	Switch	1	€0.31
7	Button	1	€2.50
8	Battery	1	€14.95
9	Glass protector	1	€1.20
10	M3 bolt 5mm	8	€0.11
11	IDC cable	1	€2.00
12	Qwicc cable	1	€0.95
13	Heat inserts m3 3mm	4	€0.12
14	3D print Top	1	€0.80
15	3D print Middle	1	€0.10
16	3D print Bottom	1	€0.67
		Total cost Handheld scanner	€261.99

Table 5.4: Materials required to build the handheld scanner.

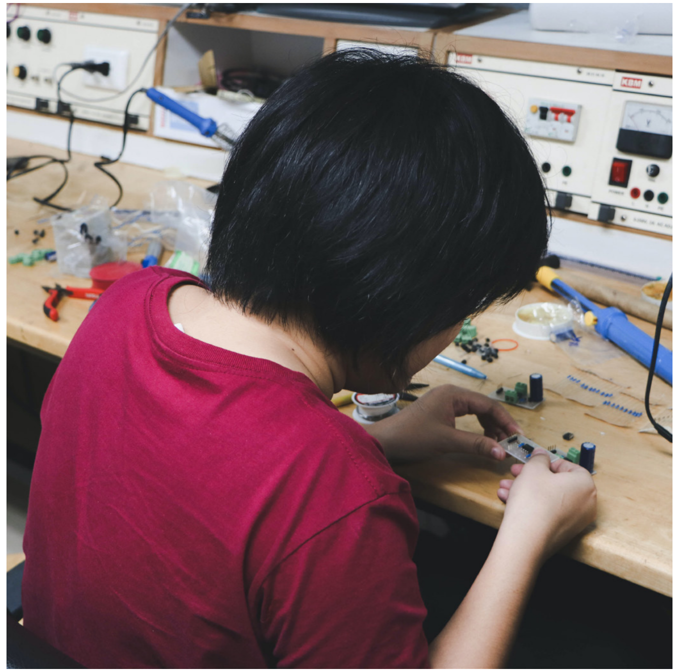
Handheld scanner in context.

5.4 The kit

The kit (figure 5.8) showcases one of the manufacturing methods of the breakout board. A package is ordered by the person who wants to build a Plastic Scanner. All components are included, and neatly presented in a simple guide to soldering your own breakout board.

Description of the kit

For people who do not know whether they can source each component, or want to have ease of assembly, a kit version of the development board is provided. It contains all components needed to build your own plastic scanner breakout board, together with easy instruction to guide you through the process. Providing the breakout board in the form of a kit also adds a business opportunity: selling the kits can provide a modest profit which can be used to sustain the project.



Person soldering a kit. (Pim Chu)

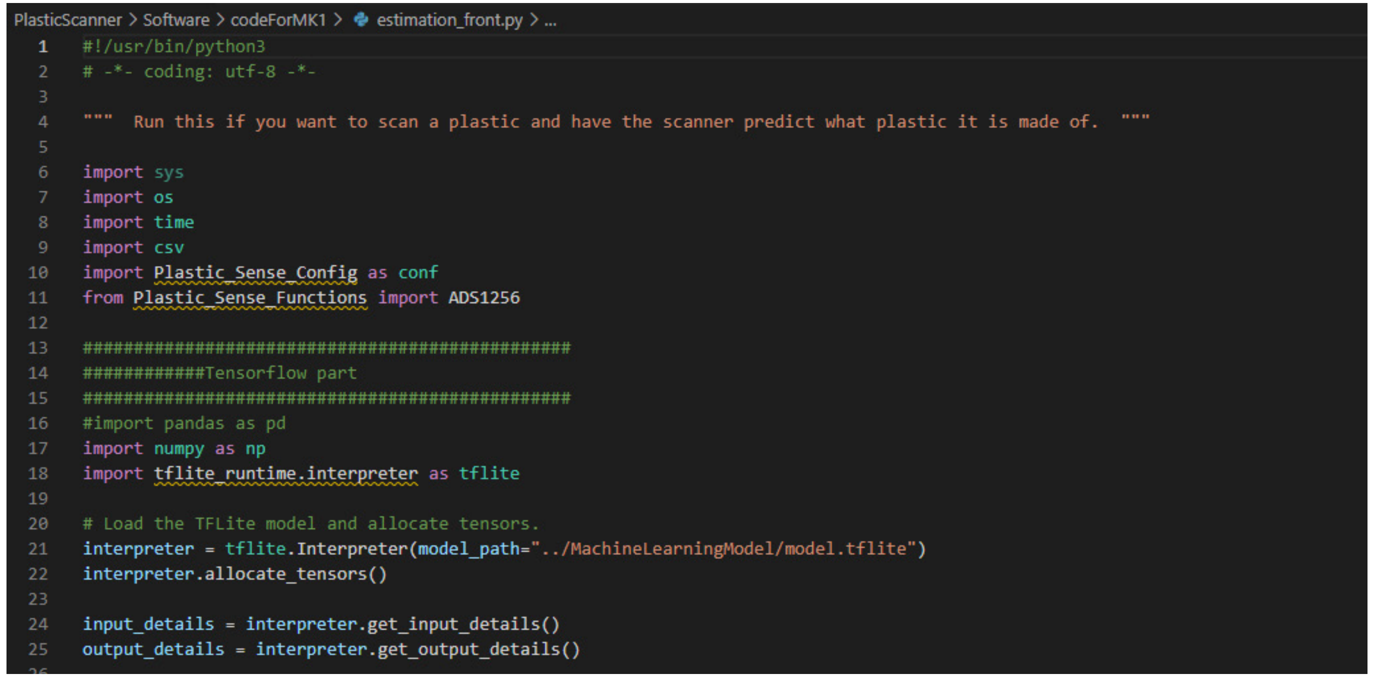
Figure 5.8: Kit version of the breakout board.

5.5 Application programming interface

A plastic scanner requires software to operate, it ensures everything works from the moment you press the button to the moment the scanner makes a prediction. The combination of these pieces of software is called an application programming interface (API)(figure 5.9).

Description of the API

The software consists of two parts: one takes care of the hardware and communicates over SPI to the breakout board, while the other part feeds measurement data into the machine learning algorithm and makes a prediction. After that, the hardware part takes over again and shows the prediction on the display. If the machine learning model needs to be trained or updated, this must be done on an external computer. Usually this is only required once a year. A visualization of the different software components is presented in figure 5.10.



```python
#!/usr/bin/python3
# -*- coding: utf-8 -*-

"""  Run this if you want to scan a plastic and have the scanner predict what plastic it is made of.  """

import sys
import os
import time
import csv
import Plastic_Sense_Config as conf
from Plastic_Sense_Functions import ADS1256

################################################
############Tensorflow part
################################################
#import pandas as pd
import numpy as np
import tflite_runtime.interpreter as tflite

# Load the TFLite model and allocate tensors.
interpreter = tflite.Interpreter(model_path="../MachineLearningModel/model.tflite")
interpreter.allocate_tensors()

input_details = interpreter.get_input_details()
output_details = interpreter.get_output_details()
```

Figure 5.9: Detail of the API.

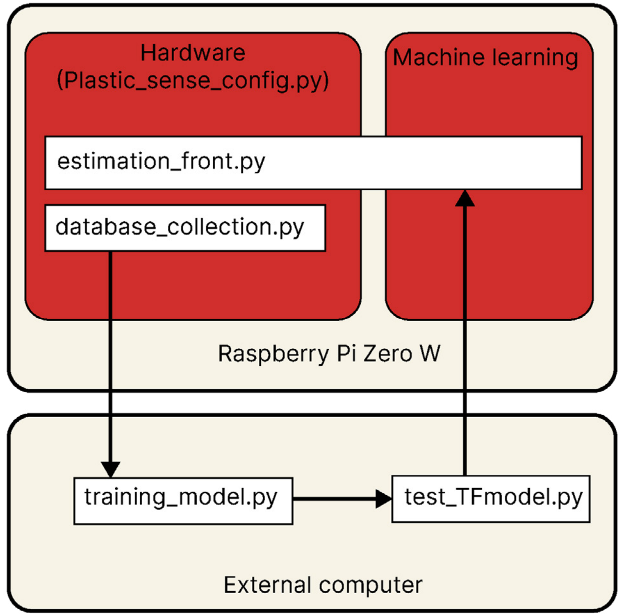


Figure 5.10: Visualization of scripts for handheld scanner and their interaction.

The API fulfills two needs. Firstly, it is necessary for the proper functionality of the handheld scanner by doing controlling all hardware components. Secondly, the software provides and insight in the steps required to predict plastic type. This allows for the usage of software outside the context of the handheld scanner allowing users to adjust it to their needs. The code is written in a modular manner and in an accessible language, Python, making it easy to understand and open for development (table 5.5).

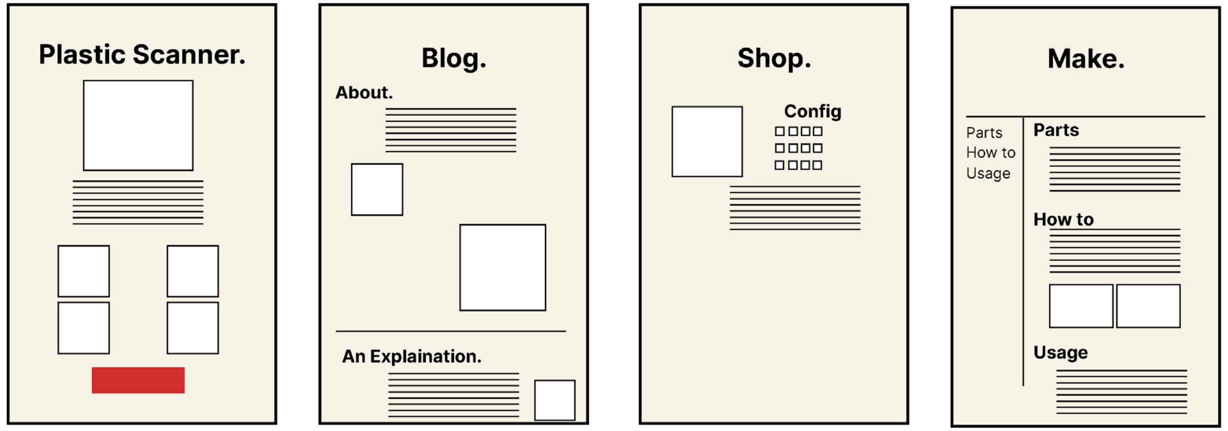
database_collection.py	To measure known plastics to build a calibration database.
estimation_front.py	To scan a plastic and have the scanner predict the specific material it is made of.
plastic_sense_config.py	To configure the way the plastic scanner is connected.
traning_model.py	To train your model with the .csv file made by the database_collection.py file.
test_TFmodel.py	To test the quality of the machine learning model, it takes the first sample from the test_data.csv and runs it through the TF model, then shows whether it is correct.

Table 5.5: Scripts for the functioning of the plastic scanner.

5.6 The website

The website provides a central point for people and groups to connect to the Plastic Scanner project. It serves to promote the project, to provide inspiration for ways to apply the Plastic Scanner, and as a place to research its overall features(figure 5.11). For the exact technical details please consult the documentation provided on WikiFactory .Additionally, the website allows for monitoring the interest in the project and in future can provide a shop where people can buy kits or parts.

The website plays a central role in the initial interaction with the Plastic Scanner, and functions as a medium to form a community around the project. Applications of the plastic scanner in various contexts can be highlighted, inspiring those in need of improved waste management. The main role of the website is to streamline the process of open development, as new ideas can be discussed and methods by which individuals are able to contribute are highlighted (table 5.6).



Landing page

Blog

Shop

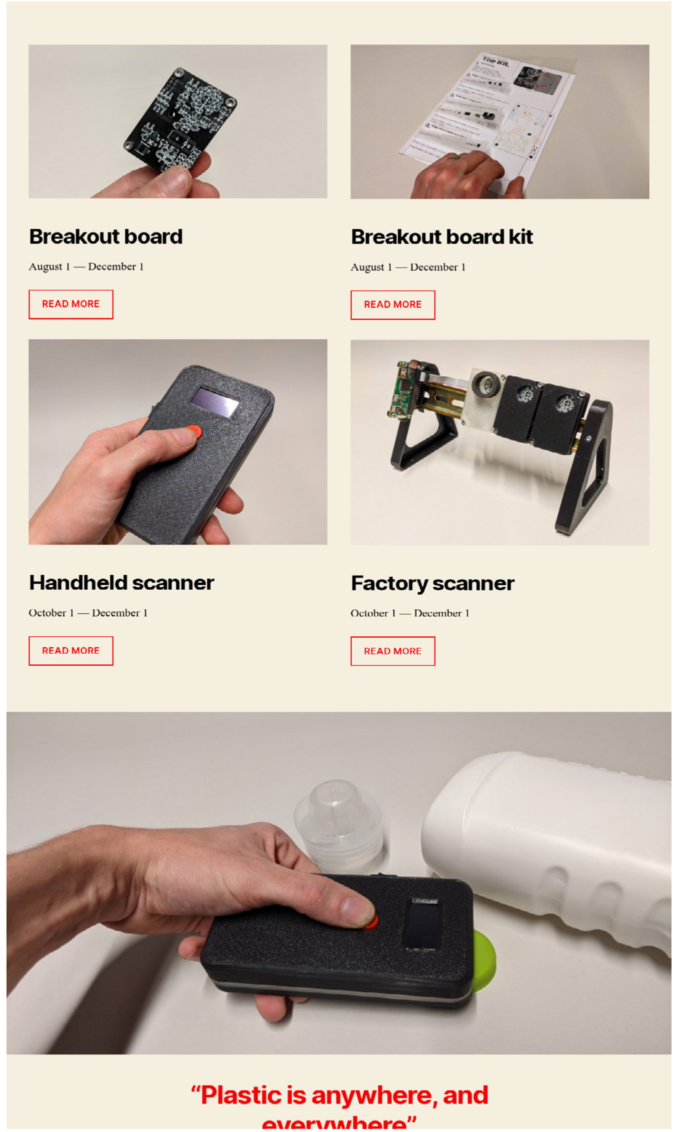
Documentation (wikifactory.com)

Figure 5.11: Schematic representation of sections within the website.

“Visit PlasticScanner.com to find out more!“

Landing page	Introduction to the project, inspiration, creating excitement
Blog	Continuous posts and information about the project.
Shop	Configure your ideal plastic scanner, get a cost estimate, download kit or buy components
Documentation	Documentation on how to build and use a plastic scanner.

Table 5.6: Sections within the website.



“Plastic is anywhere, and everywhere”

Screenshot of website.

5.7 The technical documentation

Once people are certain that a Plastic Scanner is useful in their waste management situation or they want to research the technical workings of the project, they can visit the technical documentation (figure 5.12). All the technical documentation is provided on WikiFactory. It presents the most up to date information on the components and building instructions.

Fundamental to the incorporation of open development into the project is the publication of the technical documentation. This includes the source files to replicate the project, technical drawings, electrical schematics and as documentation on the building and usage phase of the product. This complete package makes it possible to manufacture the product locally and enables users to make the modifications required to fit the exact context (table 5.7).

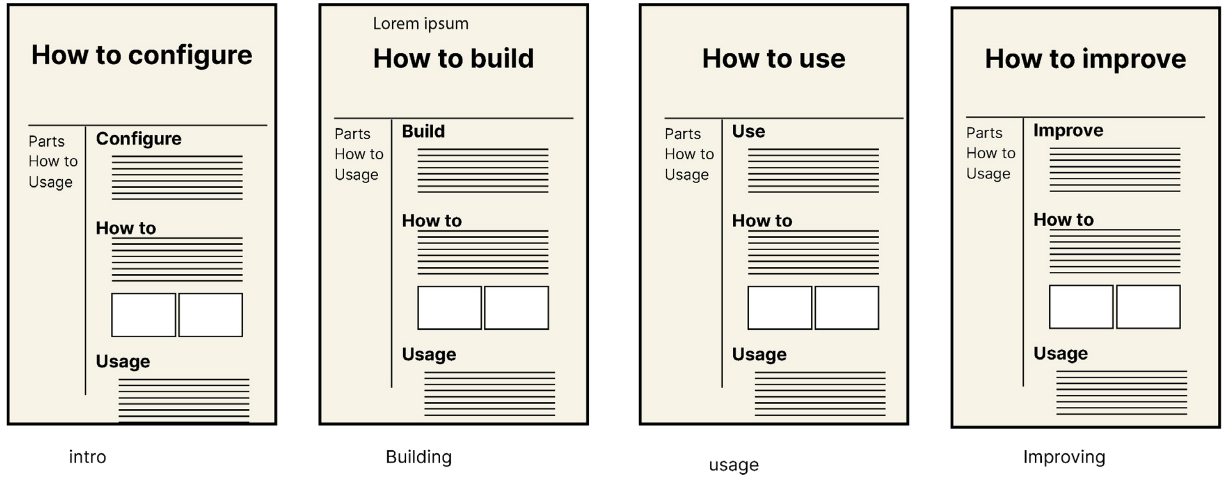
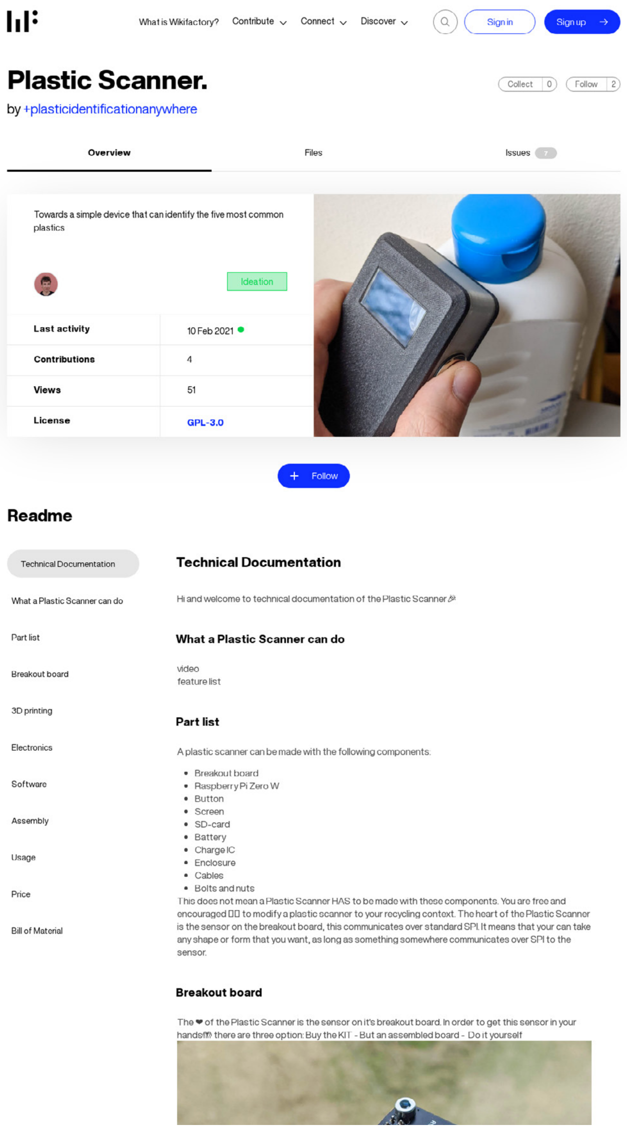


Figure 5.12: Schematic representation of sections within the technical documentation.

“Visit WikiFactory.com/ +PlasticIdentificationAnywhere to find out more!”

Introduction	Information about the features and limitations of the Plastic Scanner, how a Plastic Scanner can be built, and which components are required.
Building instructions	How to build the scanner using technical drawings, electrical schematics, PCB files, and software information.
Usage instructions	Information on how to use the Plastic Scanner.
Potential improvements	Documentation on how to improve the Plastic Scanner itself alongside information about possible ways to contribute to the project.

Table: 5.7: Sections within the technical documentation.



Plastic Scanner.

by +plasticidentificationanywhere

Towards a simple device that can identify the five most common plastics

Last activity	10 Feb 2021
Contributions	4
Views	51
License	GPL-3.0

Readme

Technical Documentation

Hi and welcome to technical documentation of the Plastic Scanner

What a Plastic Scanner can do

video
feature list

Part list

A plastic scanner can be made with the following components:

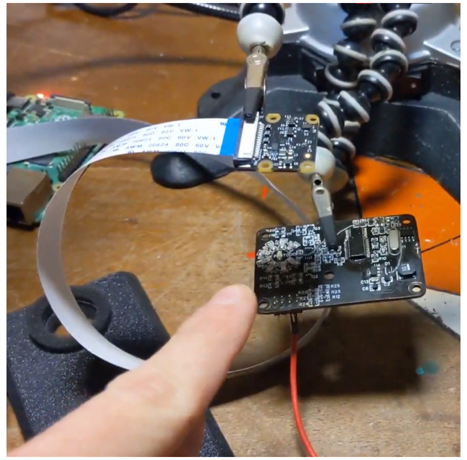
- Breakout board
- Raspberry Pi Zero W
- Button
- Screen
- SD-card
- Battery
- Charge IC
- Enclosure
- Cables
- Bolts and nuts

This does not mean a Plastic Scanner HAS to be made with these components. You are free and encouraged to modify a plastic scanner to your recycling context. The heart of the Plastic Scanner is the sensor on the breakout board, this communicates over standard SPI. It means that your can take any shape or form that you want, as long as something somewhere communicates over SPI to the sensor.

Breakout board

The ❤ of the Plastic Scanner is the sensor on it's breakout board. In order to get this sensor in your hands there are three option: Buy the KIT - But an assembled board - Do it yourself

Screenshor of technical documentation



Glass translucency test.

The Kit.

1. **Cut PCB in half**
Yes that is correct, cut your board in half. It separates the sensor from the processor. Make sure the left side fits in the pocket.

2. **Solder power components on the top**
!Ensure correct polarity of D1 and U2!
Once finishes, measure on spot **1,2,3** it should be 3.3, 5, 2.5v respectivitly

3. **Solder sensor components in the middle**
!Ensure correct polarity of diode, U3 and U1!
Once finished, connect cables to **4** to check SPI communication

4. **Solder LED components on the bottom**
!Ensure correct polarity
Once finished,

Kit folded open.

Handheld scanner in action.

Photo by Shivam Tyagi from Pexels

Conclude

This report concludes with an evaluation of the work done in this thesis, from the fit with the requirements to the potential societal impact. Based on this evaluation, the conclusion is drawn and recommendations for the future are made.

In this chapter:

6.1 Conclusion

This project set out to accelerate the process of sorting for informal plastic waste management. By researching various plastic waste management contexts worldwide and developing open-source tools based on the findings, a possible solution was found: implementing infrared spectroscopy in plastic waste management to make the sorting process quicker and less labor-intensive.

Research of the contexts revealed that most plastic pollution originates from mismanaged plastic in Low or Medium-income countries (LMIC), which led this project to focus on the context of LMIC. As a next step, the optimal sorting method for recycling was established - this was found to be infrared spectroscopy. Adapting this method to the context led to the development of an open-source ecosystem that is able to incorporate discrete infrared spectroscopy in any informal plastic waste management setting.

The quality of the ecosystem was enhanced by incorporating the design principles of context variation, local manufacturing and open development.
The implementation of design for context variation was achieved by adopting a modular component structure with a base artifact that can be complemented with peripherals to ensure an exact fit with the context.
The implementation of design for local manufacturing was achieved by making the design suitable to be built in Makerspaces or FabLabs around the world.
The implementation of design for open development was achieved by making available open-source documentation that will not need proprietary software.

The above shows that it is possible to deliver an open-source ecosystem that allows anyone to implement discrete infrared spectroscopy in their plastic recycling facilities.
Does this solution accelerate the sorting process for informal plastic waste management? This is difficult to answer since the acceptance of this ecosystem needs to be validated through field tests, and research into the expected increase of infrared spectroscopy usage in informal plastic waste management needs to be conducted.

What can be concluded is that the development of these tools contributes to the resources available for plastic recycling and that the implementation of discrete near infrared spectroscopy is now more accessible than ever before, especially in LMIC.

The development of the Plastic Scanner can have a powerful impact, since it allows for the processing of larger volumes of plastic and increases the value of the raw material by making it possible to verify its purity. All of this makes plastic recycling more economically viable, which leads to increased employment in LMIC while reducing the amount of plastic waste ending up in our ecosystem.

Breakout board in DIN rail case.

6.2 Discussion

This project showcases the implementation of three design methods, namely: open development, local manufacturing, and context variation. The following section clarifies how this project relates to these methods.

The method of "design global, manufacture local" by Kostakis et al. (2015, p. 132) describes the process in which design is shared online as a common, and the manufacturing is executed locally. This project fits within this context as both the design is shared as a common and the manufacturing process is developed in such a way that it can be executed locally. The complete coverage of "shared design as a common" or "open-source hardware" is still ill-defined as Bonvoisin et al. (2017) mention in their research. Their main findings were that complete documentation and the accessibility to it are essential to using the term Open-Source Hardware. Due to the varying nature of open-source hardware projects, there is no definitive guideline that can be used to assess whether this project can be called open-source hardware or not. However, the DIN SPEC 3105 standard can help to provide recommendations for a complete package of information for publication as open-source hardware. This project has adhered to this standard as closely as possible. Just as the method of open development aims for large scale impact and inclusiveness, so does the method of context variation by design. Similar to the data cases in the study of Kersten (2020), this project is developed for different use cases and embraces complexity to create a design that can be adapted to various contexts and allows for future scalability.

6.3 Recommendation

This project adds to the resources available for plastic recycling infrastructures. No matter whether the design in this thesis will be used by many people or just one person, it is still a good example of applicable innovation using minimal resources. The result is an overall net positive effect on plastic recycling. Having said that, there is still a long way to go to improve the quality of the Plastic Scanner.

At this stage of the project the possible contributions from the field of industrial design engineering are stagnating. For now it is important that experts from different fields propose potential improvements. In the case of this thesis the input of those working in the field of electrical engineering and machine learning would be especially valuable. To that end the project is designed in such a way that contributions from experts can be easily implemented into the ecosystem, and new versions of the scanner can be released at any time.

Once the handheld scanner results in equal or improved quality of measurements when compared to the lab prototype (ReReMeter), the handheld scanner can be tested in the field. When this testing is carried out, two other validations can also be performed: production logic and knowledge transfer.

The principle of local manufacturing can be tested by manufacturing the handheld scanner at the desired location, verifying the production logic. The principle of open development can be tested by having the users collect the open-source documentation on site and transferring it to the manufacturer, verifying the knowledge transfer. Multiple recycling workspaces around the world are ready and eagerly waiting to be given the green light to start field testing the handheld plastic scanner. To be continued!


Daisychained breakout boards.


Breakout board with standard mount and connector.

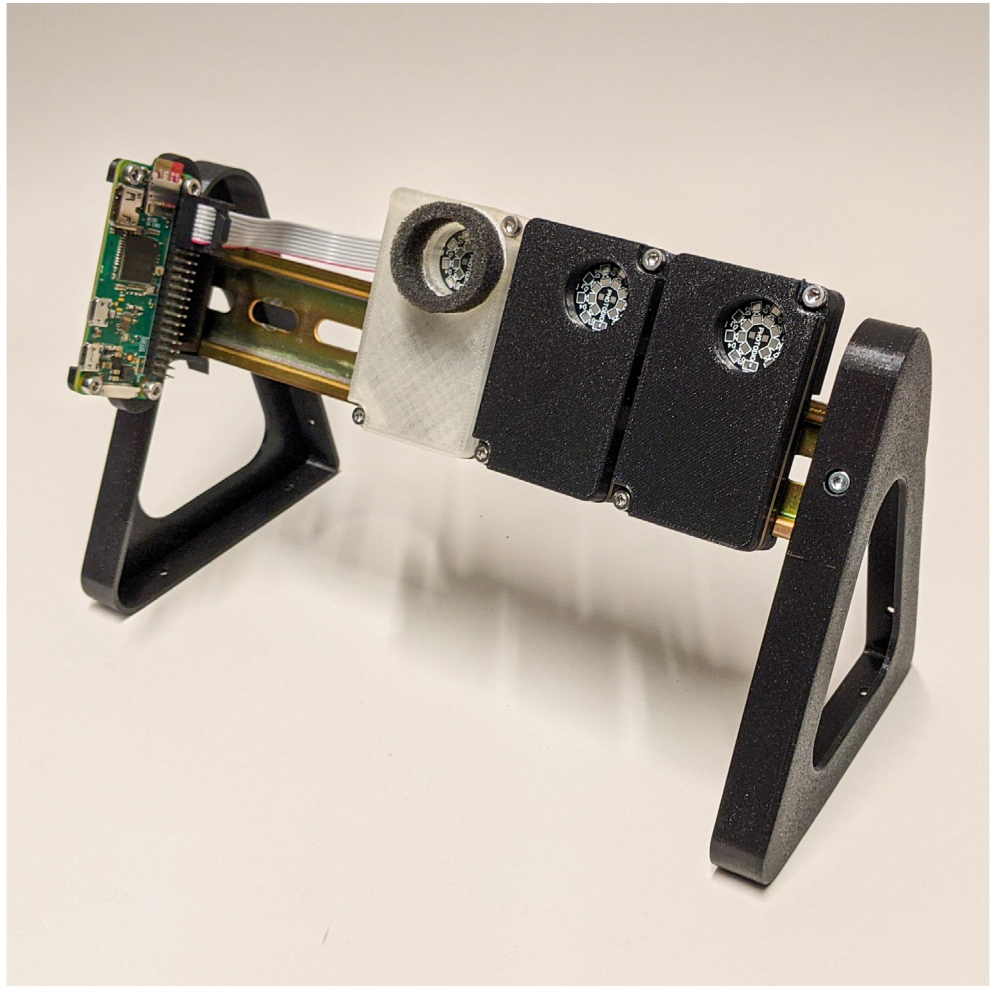

Breakout board adapted to context for small factory recycling.

Photo by Christopher Vega on Unsplash

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