M- PACS

TeSI Project 2024 – Meta-HighLight

Collaborative project between ESADE, UPC and IED, in search of new uses for the social impact of new technologies.

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1. Abstract

This project encapsulates the comprehensive work undertaken during the TeSI subject, offering profound insights into the assigned technology, MetaHiLight.

MetaHiLight refers to MEMS optical metasurfaces capable of dynamically controlling the birefringence of tissue. The present document delves into the details of this technology, exploring its potential applications and significance in diverse fields. Through a rigorous reasoning process, the team navigated various concepts and possibilities to arrive at a final idea proposal. This process involved thorough research, analysis, and collaboration to ensure the proposal aligned with the objectives of the project and the capabilities of MetaHiLight technology. The lesson learned are also included in this document.

The final proposed application is also presented in this document, including a study of the Business Plan, Social Impact and Interviews with experts, as well as a prototype of the solution.

2. MetaHilight Technology

Introduction

MetaHiLight is an advanced technology that combines optical metasurfaces and micro-electromechanical systems (MEMS) to innovate the field of optical diagnostics. Optical metasurfaces are precisely engineered nanostructured surfaces that manipulate light in specific ways, such as focusing, directing, or polarizing. MEMS are miniature mechanical devices controlled by electrical signals, capable of precise and rapid movements.

By integrating these two cutting-edge technologies, MetaHiLight achieves compact, efficient, and highly adaptable optical systems that can dynamically control the polarization state of light. This integration paves the way for creating smaller, cheaper, and faster diagnostic tools, particularly enhancing capabilities in fields requiring detailed optical analysis and control.

Initial Designated Applications

MetaHiLight was initially designed for enhancing digital histopathology, particularly in the rapid and accurate screening of tissue samples. The technology aims to develop a standalone system that minimizes the need for extensive preprocessing of samples. By leveraging the precise control of light polarization through metasurface polarimeters and MEMS-based dynamic waveplates, MetaHiLight can provide detailed and efficient tissue diagnostics.

This allows for faster detection and analysis of abnormalities in biological tissues, which is crucial for early and accurate medical diagnoses, such as cancer screening. The compact and integrated nature of the system also makes it more accessible and cost-effective compared to traditional, bulkier diagnostic equipment.

3. Design Process

TeSI, short for Technology for Social Impact, is part of the EU's ATTRACT program, designed to engage diverse student groups in exploring innovative applications for developing technologies. In this case, we have to come up with new ideas for possible alternative uses for MetaHilight technology. Over this 3.5-month program, we immersed ourselves in design thinking principles and applied them to real-world projects. A pivotal moment for our team was visiting CERN, where we not only refined our ideas but also strengthened our bonds as a team. Despite numerous challenges and course corrections throughout the process, we successfully developed our final solution for MetaHilight.

Initial approaches

After understanding the basics of the technology, we as a combined team brainstormed a handful of possible areas of applications and picked a final five. We then regrouped ourselves into groups of two to three people to investigate the respective area deeper.

After a few weeks of parallel work, we returned to our original assigned group and decided to focus on enhancing the efficiency and preciseness of Polarization sensitive optical coherence tomography (PS-OCT) technology.

Multi-disciplinary work groups approach

Our team, composed of students from UPC, IED, and Esade, brings together engineers, designers, and business practitioners. This diverse background presented initial challenges due to our different problem-solving approaches and work styles.

To create an open and effective working environment, we established a shared Teams drive for regularly uploading findings and scheduled weekly meetings to ensure everyone was updated and aligned. Over time, we realized the benefits of our diverse perspectives, allowing us to view issues from multiple angles and work on various parts of the project simultaneously. This approach not only keeps us on track but also enriches our collaborative process.

Interviews with Industry Professionals and Researchers

A key component of our research approach is to understand the current industry method and needs. Each of the team members tried to contact as many experts in their respective research area as possible, including researchers and professionals working in the industry. Whether ending up with pursuing further or discarding the idea directly, these interviews gave us insights on what is happening in the real world and if there’s a problem we could solve with the technology at hand.

CERN-inspired Redirection

We went to CERN with a clear application in mind – using MetaHilight to enhance PS-OCT. However, after talking with the researchers at IdeaSquare, we found an interesting new application in smoke detection. We did a quick investigation and presented in the discussion with Paul, the researcher in MetaHilight. He gave us positive feedback and showed high interest in both applications, so we decided to keep pursuing both fields simultaneously until we could make a final decision.

Final Decision

After spending another two weeks diving into the applications in PS-OCT and smoke detectors, we saw similar development potential in both areas. However, we chose to focus on smoke detectors because it has a higher reach in population, indicating a higher technological and social impact. We also put our findings in PS-OCT in the later part of this report and hope that it can be studied further in the future.

Finding an innovative idea for MetaHiLight that also has a significant social impact was a challenging task. With the several verticals we explored, most either did not require technology as advanced as MetaHiLight or seemed unnecessary to replace current methods. Additionally, we struggled to find sufficient evidence to justify pursuing many of these potential applications further. After extensive research and deliberation, we decided that developing a more advanced smoke detector could be the most interesting and promising application for MetaHiLight.

4. Final approach

This subsection will explore various key points to provide a clear understanding of the project proposal and the technology it utilizes.

a. Aerosol Classification and Smoke Detection

An aerosol is essentially a collection of tiny particles or droplets that are suspended in the air. These particles can be solid (like dust) or liquid (like mist). You can think of aerosols as very tiny bits of stuff floating around in the air that are so small you usually can't see them with the naked eye.

Smoke is a specific type of aerosol that is created when something burns. When organic materials, like wood or leaves, burn, they don't burn completely, and this incomplete combustion produces smoke. Smoke is a mixture of gases and tiny solid and liquid particles suspended in the air, that is why smoke is considered a type of aerosol.

Understanding aerosols, and specifically smoke, is crucial for several reasons. For one, both aerosols and smoke can affect our health and the environment. For example, inhaling these particles can cause respiratory problems. Additionally, they can influence the climate by affecting how sunlight is absorbed or reflected by the Earth’s atmosphere. Recognizing that smoke is a subset of aerosols helps in studying their effects more comprehensively.

Aerosols can be categorized based on their source and what they're made of:

Source:

- Natural Aerosols: These come from nature, such as dust from deserts, salt from sea spray, ash from volcanoes, and pollen from plants.
- Human-Made Aerosols: These come from human activities, like smoke from factories, exhaust from cars, and particles from burning fossil fuels.

Composition:

- Organic Aerosols: Contain carbon and come from both natural sources (like plants) and human activities (like burning wood).
- Inorganic Aerosols: Made up of minerals and other non-carbon substances, such as sulphate or nitrate particles.

Smoke, can also be classified by its source:

Fire Smoke:

- Flaming Fires: Produce hot, soot-rich smoke with very small particles.
- Smouldering Fires: Produce cooler smoke with larger particles that may contain a mix of chemicals.

Non-Fire Smoke:

- Industrial Smoke: Comes from factory emissions and can contain a variety of chemicals.
- Cooking Smoke: Comes from burning food or oils and contains organic particles.

Classifying aerosols and smoke is important because it helps us understand their impacts on health, climate, and the environment, among others. For instance:

1. **Health Effects:** Different types of aerosols and smoke have varying health impacts. Fine particles can get deep into our lungs and even enter our bloodstream, causing various health problems.
2. **Climate Impact**: Aerosols can affect the climate by changing how much sunlight is absorbed or reflected. For example, black carbon from smoke can absorb

sunlight and warm the atmosphere. Moreover, knowing what types of aerosols are in the air helps governments and scientists monitor air quality and develop policies to reduce pollution.

3. **Fire Identification**: Identifying different types of fires is essential as each type requires a specific method for effective extinguishment, ensuring both safety and efficacy. Fires are classified into categories based on the materials involved: Class A (ordinary combustibles like wood and paper), Class B (flammable liquids such as gasoline and oil), Class C (electrical equipment), and Class D (combustible metals). For instance, water is effective for Class A fires but can spread flammable liquids in Class B fires or cause electrical hazards in Class C fires. Instead, Class B fires are best tackled with foam or dry chemical extinguishers, while Class C fires require non-conductive extinguishing agents like CO2. Class D fires, involving metals like magnesium, need special dry powder extinguishers. Proper identification of the fire type ensures that the correct extinguishing method is used, reducing potential damage, and enhancing safety for individuals and property (NFPA) (NFPA) (NFPA) .

As explained in the Final Decision subsection, in our proposal we will focus on smoke identification. The next points will explain the bases of the methods that will be used to identify the type of fire.

b. Polarization and Light Scattering

Before diving into how light interacts with aerosols, let's understand polarization. Light, which we see as brightness, is a type of wave. Like waves in the ocean, light waves have peaks and troughs. Polarization describes the direction these waves vibrate as they travel.

- Unpolarized Light: This is light where the waves vibrate in many directions. Sunlight and most artificial lights are unpolarized. Imagine people holding jump ropes and shaking them in different directions—up and down, side to side, and diagonally—all at the same time.
- Polarized Light: Here, the waves vibrate in one direction. This can happen naturally, like light reflecting off a water surface, or artificially, like through polarized

sunglasses. If everyone holding jump ropes shakes them only up and down, that's polarized light.

In simpler terms, polarization is about the orientation of light waves. Just as a jump rope can move in various directions depending on how it's shaken, light waves can oscillate in different orientations.

Importance of polarization

Polarization is used in lots of applications. The most known ones could be:

- Glare Reduction: Polarized sunglasses are a great example. They reduce glare from surfaces like water or roads by blocking certain orientations of light waves.
- Photography and LCD Screens: Polarization helps photographers manage reflections and enhances the quality of LCD screens by controlling light wave orientations.
- Scientific Measurements: By studying how light's polarization changes when it bounces off objects or passes through them, scientists can learn about those objects' properties, like surface roughness or composition.

Understanding polarization is important because it provides a deeper insight into how light interacts with objects, which is crucial in fields ranging from optics to environmental science.

Scattering in aerosols

Imagine shining a flashlight into a room filled with dust. Instead of just going straight through, some of the light hits the dust particles and bounces off in different directions. This bouncing off is what we call scattering.

Here's a simple breakdown:

- Small Particles (Rayleigh Scattering): When the particles are much smaller than the wavelength of light, like tiny dust or gas molecules, the light scatters in all directions. This is why the sky looks blue; the small molecules scatter blue light more than other colors.

- Larger Particles (Mie Scattering): When the particles are about the same size as the wavelength of light, like water droplets in fog or smoke particles, the scattering is more complex. Most of the light tends to scatter forward, in the same direction the light is traveling, but some scatters in other directions too.

To visualize this, think about shining a flashlight through fog. You see the beam of light clearly because the water droplets are scattering the light in different directions, making the beam visible from the side.

When polarized light is shined into a group of aerosol particles, the way the light's polarization changes gives a lot of information about those particles. For example, smoke from a fire might change the polarization differently than dust or water droplets, helping identify what kind of particles are in the air. Moreover, smoke from a burning battery reacts differently to polarization than smoke originated from a metal. This is useful in environmental monitoring and improving the accuracy of smoke detectors, reducing false alarms from non-fire sources like dust or steam or classifying the type of smoke (fire) in a much faster way while knowing the exact method of its extinction.

c. The Current State of Technology

Smoke detection systems in airplanes primarily utilize optical smoke detectors, which are based on the principle of infrared light scattering. These systems are designed to detect the presence of smoke particles in the air by using an infrared light source and a sensor. When smoke enters the detection chamber, it scatters the infrared light, triggering the alarm. Unlike pellistors, which are catalytic sensors typically used for detecting combustible gases, infrared-based optical smoke detectors are favored in aviation due to their sensitivity to a wide range of smoke particles, rapid response times, and reliability in the diverse and challenging environmental conditions found on aircraft.

However, this technologies face critical issues, that could be alleviated by using a more advanced technology:

1. **False Alarms:** Optical detectors can be triggered by non-smoke particulates such as dust, aerosol sprays, or even water vapor. This can lead to false alarms.
2. **Environmental Variability:** Airplanes experience significant variations in pressure, temperature, and humidity, which can affect the sensitivity and accuracy of the detectors.
3. **Smoke Characteristics:** The composition and density of smoke can vary depending on the material burning. Some types of smoke may be less detectable by infrared-based systems, potentially delaying alarm activation. For instance, some examples of smoke that might not be detected with current optical smoke detectors are invisible smoke, low density smoke or smoke coming from chemical vapors.
4. **Cabin Air Flow:** The rapid and constant circulation of air within the cabin can dilute smoke particles, making detection more difficult. This requires detectors to be highly sensitive and strategically placed to effectively monitor potential sources of smoke.

For instance, see below the schematic of the optical detector nowadays used in Boeing passenger and freighter airplanes fire detector systems:

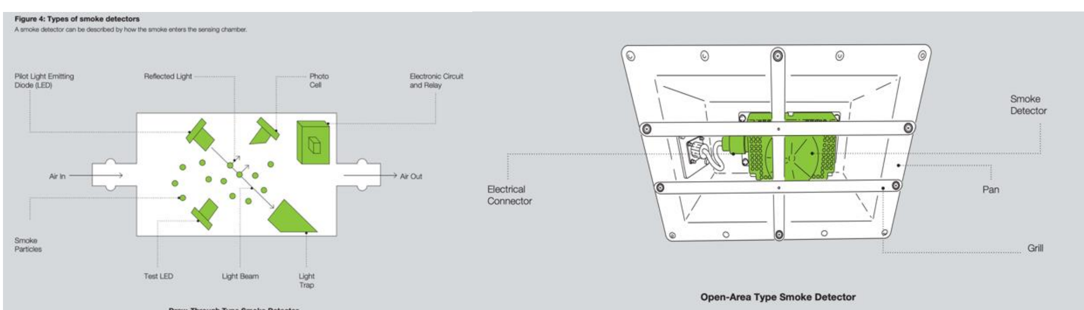

Figure 1. Schema of the optical detector used in Boeing passenger and freighter airplanes fire detector systems

d. Proposed Adaptation of MetaHilight: M-PACS

Our project proposal is called M-PACS that stands for Metasurface - Polarimetric Aerosol Characterization System. Its objective is to monitor and characterize different types of smoke in real time so, when a fire occurs, the alarm is set off as fast as possible indicating which type of fire has been identified. To do so, M-PACS will be analyzing the aerosols of the ambient by emitting a polarized light beam and detecting the variations of the polarization on the scattered signals. M-PACS will be using metasurfaces (explained in the following subsection) to vary the polarization angle of the emitted beam in a very fast way. By analyzing the polarization response to as many polarization angles as possible the most information and precision we will have about the identified aerosol.

The next subsection will delve into the operating principle of MetaHiLight technology, introducing a technical approach on the steps that M-PACS will take to fulfill its objective.

e. Proposed Adaptation of MetaHilight: Operating Principle

The system integrates MEMS mirrors capable of dynamic polarization control into an Optical Coherence Tomography (OCT) setup for inspecting both aerosols and potentially molecules in the air.

1. Polarized Light Generation

The system begins with a polarized light beam generated by an infrared (IR) or near-infrared (NIR) laser.

2. Polarization Control and MEMS Mirrors

The polarized light beam encounters MEMS mirrors capable of dynamically changing their polarization orientation. These mirrors adjust the polarization state based on feedback from the OCT system.

3. Aerosol Inspection Stage

i. The polarized light enters the aerosol chamber containing suspended aerosol particles.
ii. Aerosol particles scatter the light, which returns through the chamber along with information about the aerosol composition and characteristics.
iii. The scattered light, now carrying aerosol-related data, is directed towards the OCT system for analysis.

4. Stokes Matrix Generation and Dynamic Polarization Scanning

i. The system generates the Stokes matrix of the air sample by scanning the light beam through various polarization states using the dynamic capabilities of the MEMS mirrors.
ii. The Stokes matrix captures the complete polarization state of the light beam, including information about polarization ellipticity, orientation, and intensity variations across different polarizations.

Additionally, for future prototypes, a molecular analysis stage could be taken into account, which would allow the classification of gas composition and not only particles in an aerosol. The molecular analysis would require sweeping over different frequencies (wavelengths of light) to detect the frequency of resonance of each gas. This is currently limited by the state of the MetaHiLight technology, where each device is developed for a specific frequency range.

In conclusion, by incorporating the generation of the Stokes matrix and dynamic polarization scanning, the system enhances its capabilities to analyze aerosols and molecules in the air with precision, capturing detailed polarization information for a deeper understanding of the sample composition and properties.

f. Proposed Adaptation of MetaHilight: Value Proposition

The key values that M-PACS provide are:

- **Compact:** Utilizes dynamic MEMS-based metasurfaces, allowing precise control of light polarization in a small form factor ideal for aircraft.
- **Fast:** Changes polarization in less than 0.4 milliseconds, crucial for immediate fire detection and response.
- **Sensitive:** Detects subtle changes in ambient aerosols, enhancing early detection of smoke and potentially harmful gases.
- **Accurate:** Minimizes false alarms compared to traditional smoke detectors, ensuring alerts are triggered only by genuine threats.
- **Robust:** Designed to withstand the demanding conditions of the aerospace industry, including vibration, temperature fluctuations, and pressure changes.

- **Versatile:** Beyond smoke detection, it can be used for air pollution monitoring, harmful gas detection, and other aerosol characterization applications, showcasing its potential for broader safety and health benefits.

g. Prototyping

To showcase and illustrate our idea in a clear and easy to understand way, we planned and executed a few prototypes in different forms.

Tube particles polarization demonstration

Firstly, to visualize the effects of polarization we conducted an experiment consisting of illuminating a tube filled with a mixture of water and sugar (because glucose is a chiral molecule). The tube had linear polarizers at both ends, so that rotating one with respect to the other one certain angles of polarization could be filtered out.

The experiment was inspired by the following video: Polarized light in sugar water | Optics puzzles 1

The test setup is shown below, and even if it is not clear why, the same effect that is shown in the video could not be observed:

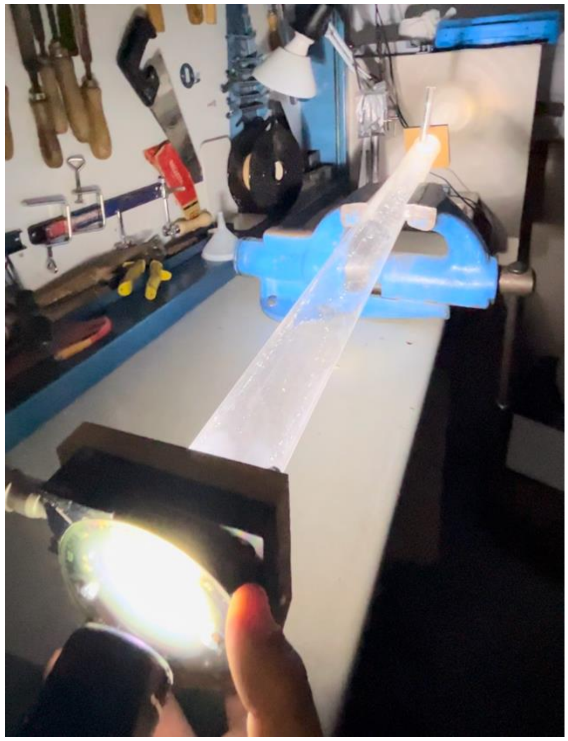

Figure 2. Polarization experiment setup

More interesting results were obtained with the first iteration of this experiment, when the same setup was built at a much smaller scale (a transparent tube with a length of 5 cm and diameter of 2 cm). Again, a transparent tube is filled with water and a sugar solution, with linear polarizing filters placed at both ends of the tube. These filters selectively allow light of a specific polarization orientation to pass through while blocking light of other orientations. One end of the tube is illuminated with a flashlight, polarizing the light in a specific orientation as it enters the tube. As the polarized light travels through the water and sugar solution, the chiral molecules in the solution cause a rotation of the plane of polarization of the light. At the other end of the tube, the observer can see the light that passes through the second polarizing filter. When sugar is present in the water, the plane of polarization of the light passing through the tube is rotated by the chiral molecules. This results in a difference in the orientation of the light compared to the original polarization direction. Consequently, some of the light is blocked by the filter, leading to a reduction in the spectral range observed at the other end of the tube compared to when there is no sugar in the water. This experiment provides a straightforward, yet effective demonstration of the optical rotation caused by chiral molecules in solution and its impact on the spectral range of transmitted light.

Below, the plots in the spectrophotometer can be found. On the left there was only water inside the tube, and on the right, the mixture of sugar and water. It can be observed how the spectral response is reduced in the mixture, compared to the clean sample:

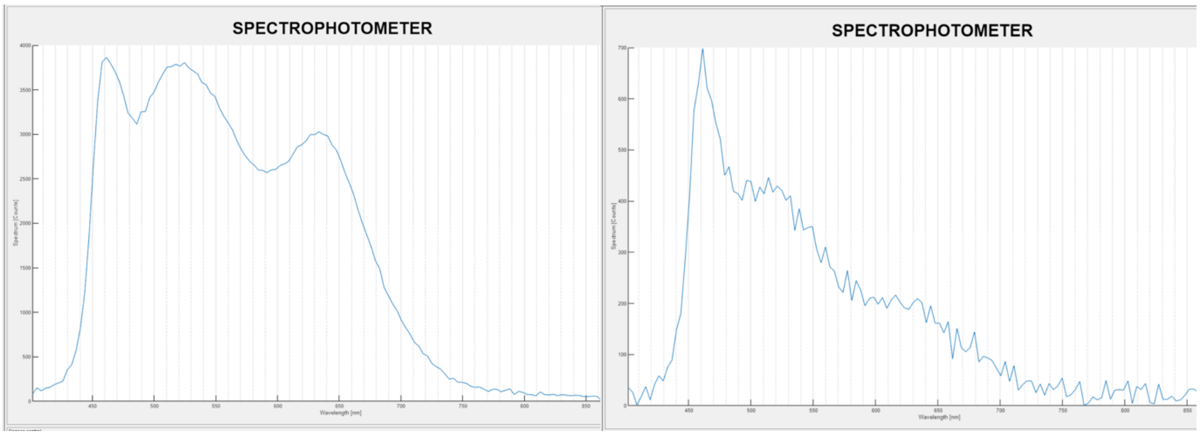

Figure 3. Spectral response of the solution with only water (left) and water and sugar (right)

Implementation demonstration video

As an addition, we made a video showing the interior of an airplane, in which you can hear the noise of the engine and at the same time a fine noise from a smoke exhaust begins to be heard. We see this smoke and how it in turn reaches the M-Pacs detector that is located in the upper area, where it will be analyzed. The signal is sent to the workers who are on this plane before it reaches higher levels.
< https://youtu.be/yoqvqzf0RRA >

Figure 4. Video Implementation in airplane

3D printed detector prototype

For the 3D printed prototype we initially based it on the combination of the current Airliner lavatory ionization smoke(r) detector models and the Tunable T1000 model.

With these two clear model references, we created 2 different versions with everything we needed. These models, larger than the result, had a more rectangular shape and more space for the sound speaker, while at first glance you could see the analysis buttons at the top.

Figure 5. First 3d Models

After a group discussion, it was decided that for better smoke flow and easier entry, the device should be modified to a more spherical shape with inlets on the sides, creating more facilities. The test buttons were moved to the side to avoid touches from outsiders, and the product name and warning LED were added at first glance.

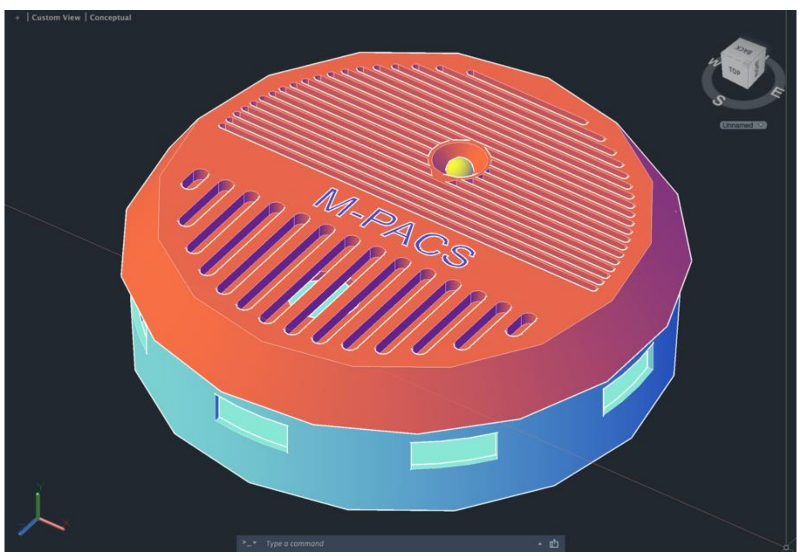

Figure 6. Final 3D model for the prototype

Once the model was made, the printing process began, dividing the upper part of the machine container. For this prototype, only the container box was prevented from not having enough machinery to make a realistic sample inside. The technology was improved with another external prototype.

With the impression made, we paint it to give a resemblance to the final finish, prepare a LED light and write the brand name.

Figure 7. Printed 3D prototype, without the final touches

External to the printed 3D model, let's make a sketch with it in exposed axonometric mode to schematically show the interior.

Poster

For the poster we started with two original ideas, one where only the product was seen or a more explanatory and technical poster where the characteristics of the prototype were explained in detail. Finally, we decided to go in the more technical direction.
The poster is divided into two parts, the upper left explains the technology, how the aviation industry works and the social impact. Next, on the upper right side, we find an axonometric diagram of the product and a diagram of how its interior works.
As an intermediate zone, two renders from the product and the space of use.
Finally, in the lower area, the properties of the M-PACS and the key features.

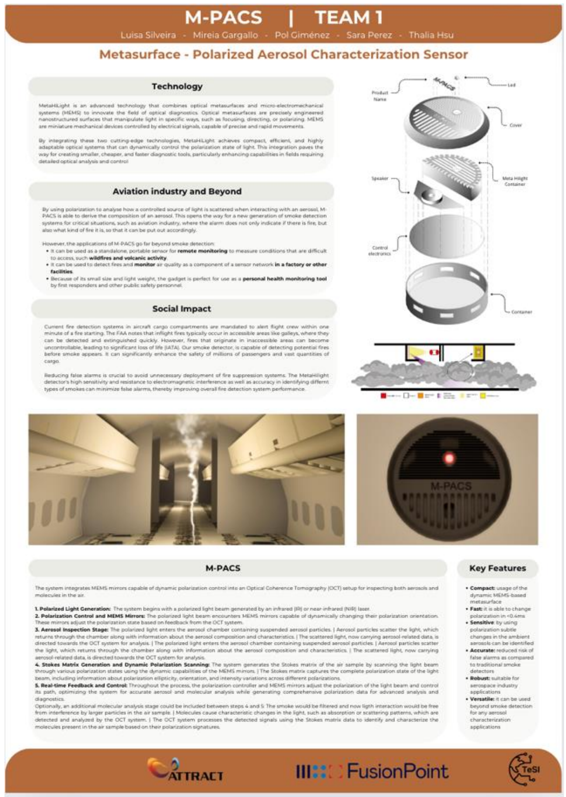

Figure 8. Final view of the Poster

h. Aviation market

In 2023, the global aviation industry saw a significant recovery from the pandemic, with approximately 4.6 billion passengers taking flights, signaling a strong rebound in air travel demand (International Air Transport Association). Despite a slight decline in cargo transportation quantity, the industry still handled 60.3 million metric tons of cargo in 2022, generating a substantial $169 billion in worldwide revenue for cargo airlines (IATA) (World Population Review). This recovery and the economic importance of both passenger and cargo aviation highlight the vitality and growth potential of the aviation sector.

Current fire detection systems in aircraft cargo compartments are mandated to alert flight crew within one minute of a fire starting (IATA). While these systems are effective, inflight fire incidents often stem from electrical failures, overheated equipment, or improper cargo handling. The FAA notes that inflight fires typically occur in accessible areas like galleys, where they can be detected and extinguished quickly. However, fires that originate in inaccessible areas can become uncontrollable, leading to significant loss of life (IATA).

Our advanced smoke detection device aims to complement and enhance existing fire detection systems rather than replace them. By increasing redundancy, we can reduce false alarms and improve the accuracy of detecting aerosols, flames, and fires. This is particularly important in the aviation industry, where multiple detectors monitoring the same area is a common practice to ensure safety.

The ability of our device to detect fires from various sources, including electrical failures, positions it as a critical addition to current safety measures. By targeting a highly regulated market with stringent safety requirements and a growing size, we have a strong foundation to develop and deploy our technology. Our mission is to add value to the existing safety infrastructure, substantially reducing the risk of inflight fires and enhancing overall safety for passengers and cargo.

In conclusion, the aviation industry's recovery and ongoing growth, coupled with the critical need for advanced safety measures, make it an ideal target for our smoke detection technology. This market's demand for optimal safety standards and regulatory compliance provides a significant opportunity for our product to thrive and contribute to the industry's safety advancements.

i. Business Plan

To showcase the business feasibility of the MetaHilight, we developed a sample business model around it, making the key activities consultation of switching in-place fire detection system or complementing it with our product; designing the implementation based on different projects; and actual implementation.

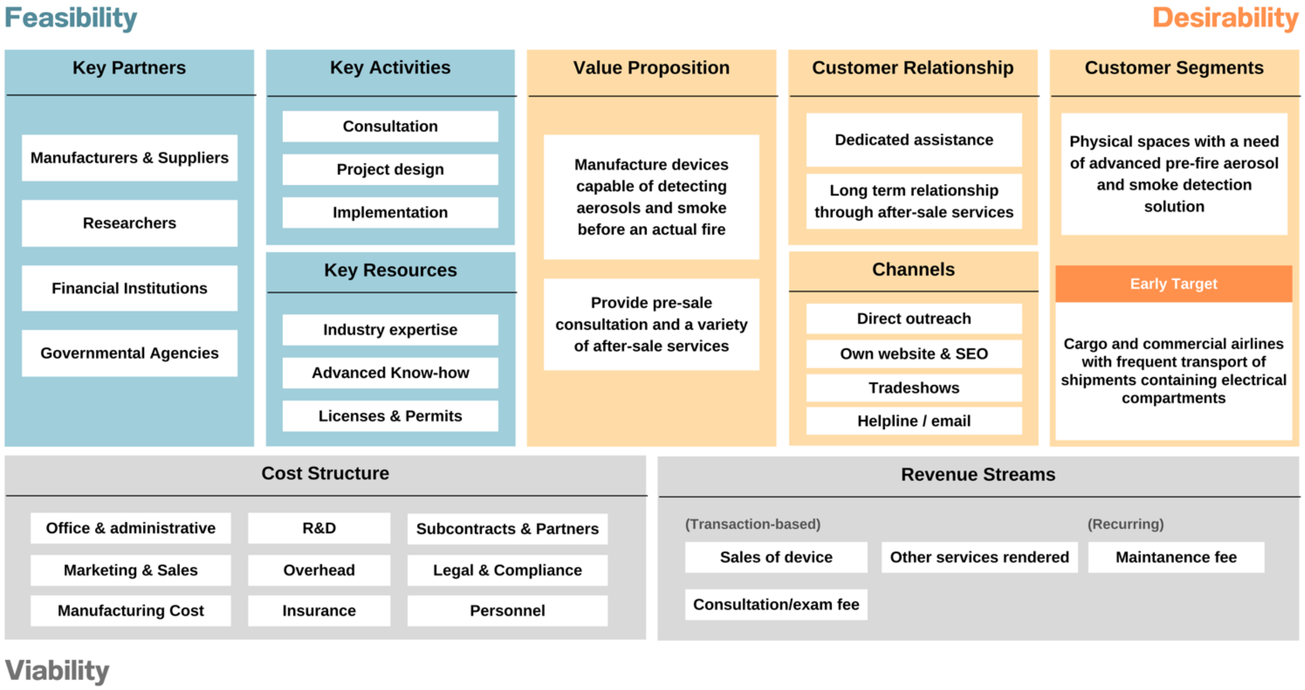

Table 1. Business Model Canva

Value proposition

The core value of our product lies in its ability to detect aerosols and smoke before they escalate into fires, significantly enhancing aviation safety. We also aim to support our customers through dedicated pre-sale consultations and comprehensive after-sale services, ensuring long-term satisfaction and reliability.

Strategic partnerships & key resources

Our business will leverage strategic partnerships with manufacturers, suppliers, researchers, financial institutions, and governmental agencies. These partnerships enable us to produce high-quality components, innovate continuously, secure necessary funding, and comply with aviation regulations. At the same time, we will strive to acquire deep industry expertise, cutting-edge technological know-how, and the necessary licenses and permits to operate within the highly regulated aviation industry.

Customer segments & relationships

Our early and primary customer segment includes cargo and commercial airlines that have a frequent need for advanced pre-fire aerosol and smoke detection solutions, especially those transporting shipments with electrical components. We chose to target this segment early on, because the aviation regulations are very strict, and the consequences of a fire in-flight is significant, hence the companies are constantly finding ways to enhance their current safety measures in place. Due to these characteristics, aerospace is prone to have comparably lower price elasticity. This will enable us to start generating revenue and have the resources to improve the technology and lower the cost and price point. Down the line, we will expand the market to all spaces with a need for advanced aerosol and smoke detection.

We also plan to build strong, long-term relationships with our customers through dedicated assistance and continuous after-sale services. We believe that good customer relationships are cornerstone to a sustainable business.

Cost & revenue structure

Financially, our business model includes costs associated with office operations, R&D, partnerships, marketing, legal compliance, manufacturing, insurance, and personnel. Revenue is generated from the sales of our devices, consultation fees, and recurring maintenance fees, ensuring a balanced and sustainable financial structure.

The average price point for a flame or fire detector in an aircraft is approximately $10,000. If we can show that our advanced smoke detection device integrates with existing systems, this price point is achievable. Although the MetaHilight technology is still under development, researchers indicate that production costs can be kept low. Therefore, targeting a price point of $10,000 will allow us to offer a competitive and profitable product while ensuring high-quality performance and integration with current aviation safety systems.

Future development

The MetaHilight smoke detector, initially targeting the aviation sector, has the potential for broader applications across various industries. This includes sea freight and other physical spaces requiring advanced smoke and fire detection systems.

The maritime shipping industry presents a particularly compelling opportunity. Fires and explosions have become the costliest causes of marine insurance claims, largely due to the growing reliance on lithium-ion batteries, which pose significant fire risks. Unlike cargo planes, which are airborne for up to 14 hours daily, cargo ships can be at sea for weeks or even months. Given the prolonged exposure and the substantial risk of fire, exploring this sector for our MetaHilight technology is highly promising.

Moreover, our product's versatility in detecting various aerosols before they develop into fires or smoke makes it valuable across numerous industries. Any sector requiring enhanced fire prevention solutions could benefit from investing in the MetaHilight detector, making it a versatile addition to safety protocols in diverse settings.

j. Social Impact

Enhanced Safety in Aviation and Other Industries

While airplane safety measures and regulations have continually improved, airlines face the ongoing challenge of integrating advanced technologies to ensure flight safety. Lithium-ion batteries, for instance, have emerged as a significant fire hazard, with 208 reported lithium battery fires between March 1991 and May 2018 (Royal Aeronautical Society). Our MetaHilight smoke detector, capable of detecting potential fires before smoke appears, can significantly enhance the safety of millions of passengers and vast quantities of cargo.

With approximately 100,000 flights globally per day, including over 90,000 passenger flights (IATA), enhancing air travel safety is more critical than ever. Implementing advanced detection technologies like MetaHilight not only bolsters safety but also instills greater confidence in air travel.

Reducing False Alarms

Reducing false alarms is crucial to avoid unnecessary deployment of fire suppression systems, which can be costly and damaging. Foam deluge systems, for example, are effective for actual fires but can incur significant cleanup and repair costs if triggered by false alarms. The MetaHilight detector's high sensitivity and resistance to electromagnetic interference can minimize false alarms, thereby improving overall fire detection system performance and maintaining redundancy.

By integrating our advanced smoke detection technology, we aim to enhance fire safety across various industries, contributing to broader societal benefits by protecting lives, assets, and ensuring operational efficiency. This not only provides a solid business opportunity but also brings substantial social value by improving safety standards globally.

5. Interviews with experts

a. Santiago Gassó

Dr. Gassó is an expert in studying aerosols, clouds, and their interactions using satellite detectors, particularly MODIS and OMI. He graduated from the University of Washington with a focus on geophysics and atmospheric science, where he researched aerosols and the early MODIS aerosol algorithm. His post-doctoral work included developing a module for the Navy Aerosol Assimilation Prediction System (NAAPS) and evaluating its outputs with satellite data through NASA and ONR grants. He has also contributed to the NPOESS Preparatory Project science team and has been part of the OMI science team since 2008. From 2009 to 2011, he led a working group for NASA's proposed Aerosol, Clouds, and Ecosystems (ACE) mission.

We contacted Dr. Gassó because he was the main contributor to the following article *“Circular polarization in atmospheric aerosols”.* From the interview, we wanted to gain knowledge on aerosol characterization and the importance of polarization scanning for it. We prepared a set of questions based on his article. Remarkable insights from Dr. Gassó can be found below:

According to Dr. Gassó, while speed is not overly critical for these observations because the atmosphere changes on the order of one minute, there are advantages to faster data collection.

"For space observations of the Earth, speed is not very critical because the atmosphere changes in the order of one minute," Dr. Gassó explained. "However, you can gather more information if you are fast because you will be able to scan more frequencies."

Dr. Gassó provided specifics on typical capture times for satellites. "Typical capture times for satellites at 700 km from Earth range from 20 milliseconds to 100 milliseconds," he noted. This range allows for the collection of detailed and diverse atmospheric data, enhancing the overall quality and utility of the observations.

Dr. Gassó's insights highlight the balance between the speed of data acquisition and the nature of atmospheric changes, emphasizing that while rapid data capture can enhance information richness, the inherent variability of the atmosphere allows for effective observation even at slower speeds.

According to Dr. Gassó, a comprehensive analysis of aerosols requires determining the quantity, size, and composition of the particles.

"To analyze an aerosol, you need to work out the quantity, the size of the particles, and the composition," Dr. Gassó explained. He noted that current technologies allow for rough estimations of size and quantity but fall short in simultaneously determining the composition. "Nowadays, we can have a rough estimation of the size and the quantity but not the composition at the same time. For instance, in Earth observations, marine salt is easily confused with dust."

Dr. Gassó also commented on the limitations of available techniques for aerosol characterization. "The range of available techniques nowadays for characterization of aerosols is reduced and some techniques are not ideal," he stated. One such technique involves trapping a particle from the aerosol in a laser. "By doing so, the properties of the sample are being changed because we are not observing it as part of a group of particles anymore," he pointed out. This isolation can alter the inherent properties of the particle, leading to less accurate observations.

Dr. Gassó's insights highlight the challenges and limitations in current aerosol analysis methods, underscoring the need for improved techniques that can provide more accurate and comprehensive data on aerosol properties.

We also discussed the spectral characteristics of gases and aerosols in the atmosphere. Dr. Gassó explained that while gases tend to have specific frequencies of resonance, aerosols exhibit different behavior.

"Gases tend to have a frequency of resonance," Dr. Gassó noted, highlighting the distinct spectral signatures that gases exhibit, which can be used to identify and analyze their presence in the atmosphere.

In contrast, aerosols do not change much spectrally unless they contain certain specific materials. "Aerosols do not change much spectrally unless they contain some specific matter that produces the effect," Dr. Gassó explained. This means that while aerosols generally have less distinct spectral features, the presence of particular substances within them can cause notable spectral changes.

Dr. Gassó explained the traditional and emerging techniques for analyzing scattered light.

"Traditionally, linear polarization has been used because it gives a stronger signal," Dr. Gassó noted. This method has been favored for its ability to produce clear and strong signals, making it easier to analyze atmospheric particles and gases.

However, Dr. Gassó also highlighted the advantages of analyzing circular polarization. "By analyzing circular polarization, multiple scattering effects can be observed, such as second-order scattering effects," he explained. This approach allows for the detection of more complex scattering phenomena, providing deeper insights into the interactions between light and atmospheric particles.

Additionally, Dr. Gassó pointed out that some biological molecules are chiral, meaning they can polarize light circularly. "For instance, glucose or pollen aerosols are chiral and they polarize light circularly," he said. This characteristic of chiral molecules adds another layer of information that can be captured through circular polarization analysis.

Dr. Gassó's insights emphasize the evolving techniques in polarization analysis, highlighting the benefits of both linear and circular polarization in enhancing our understanding of atmospheric processes and the composition of aerosols.

b. Desislava Dantcheva

We had the opportunity to speak with Desislava Dantcheva, an aerospace engineer with seven years of experience in the CAMO engineering department at Volotea. With her extensive background in aircraft maintenance and operations, Ms. Dantcheva provided valuable insights into the challenges posed by smoke detection systems in airplanes and the issue of false alarms. She also discussed the potential for improving these systems with more versatile smoke detectors.

During our conversation, Ms. Dantcheva shed light on the current state of smoke detection systems in airplanes. "In aviation, we mainly use optical smoke detectors because they are sensitive to a wide range of smoke particles," she explained.

However, Ms. Dantcheva acknowledged that these systems often face challenges. "One major issue with these smoke detectors is the frequency of false alarms. They can be triggered by non-smoke particles like dust, aerosol sprays, or even water vapor, which can cause unnecessary alarms and potential disruptions," she said.

Environmental factors further complicate the situation. "Airplanes go through significant changes in pressure, temperature, and humidity. All these factors can impact the performance of smoke detectors, making it a real challenge to maintain consistent functionality," she noted.

In addition to smoke detection systems, Ms. Dantcheva highlighted the critical importance of the Fuel Tank Inerting System (FTIS). "FTIS is essential for preventing fuel tank explosions by reducing the oxygen concentration within the fuel tanks. This system is crucial for the safety of the aircraft," she explained.

She sees potential for integrating advanced smoke detection technologies into FTIS. "I definitely see room for application here. Incorporating more sophisticated smoke detectors within FTIS could provide an added layer of safety by ensuring early detection of any combustion-related incidents within the fuel tank area," Ms. Dantcheva proposed.

Despite these challenges, Ms. Dantcheva is optimistic about the potential for improving smoke detection systems. "There's definitely room for improvement. For example, combining different types of detectors or integrating additional sensors could help address some of these issues. A more versatile smoke detection system could enhance overall safety by providing more accurate monitoring," she suggested.

6. Alternative feasible applications

In this part of the report, we will briefly discuss the applications we dropped due to various considerations, but still think they could be interesting to investigate and have the potential to be further developed. We will only discuss the ideas that were most investigated and are most promising, other preliminary ideas are not included.

c. Meat Quality Detection

As food quality has been everyone’s concern, we divided the value chain and looked into each part of the product’s journey, from the production at origin; to shipping; to final distribution at the supermarket.

At shipping, there are already technologies monitoring the conditions of the cargos, and space limitations and product variety make it hard to implement polarization devices inside the cargos. As for the supermarkets, their potential is also limited due to the vast number of different products and different quality requirements. It became clear that to start off with this idea, we must focus on one type of product.

After some investigation, we are confident that meat quality control is the most promising one, especially for pre-selection for processing meat. From the feasibility point of view, several studies support that the meat quality could be determined by the different states of polarization. And from the desirability point of view, as we talked to several industry practitioners, they agreed that it could be useful to have the automated tool to determine different quality in meat, since they are doing the selection process for different processed meat products manually for the time being.

Hence, meat quality detection could be a viable option for future development. However, we decided to drop this application to pursue PS-OCT application as it seemed to be more promising.

d. Optical Coherence Tomography Enhancement

Polarization sensitive optical coherence tomography (PS-OCT) was also one of the main focuses of our later investigations. Having the category existing, it is apparent that using polarization in the optical coherence tomography is feasible and is already being studied.

Polarization-sensitive optical coherence tomography (PS-OCT) holds significant potential over traditional optical coherence tomography (OCT) systems for ocular inspection. While conventional OCT provides high-resolution cross-sectional images of ocular structures, PS-OCT adds the ability to measure and visualize the birefringence properties of tissues. This capability is particularly valuable in detecting and analyzing subtle changes in the retinal nerve fiber layer and other ocular tissues, which can be indicative of early-stage glaucoma or other optic neuropathies. By capturing the polarization state of light reflected from the eye, PS-OCT can enhance contrast and provide additional information on tissue composition and integrity, leading to more comprehensive and accurate diagnostics in ophthalmology.

Moreover, there is a company in Australia, *Cylite*, which has already conducted some experiments regarding PS-OCT that show significant potential. However, when we contacted them, they mentioned that they were currently occupied with other projects, which temporarily halted their research in this area. Despite this pause, the promising results from their initial experiments indicate a bright future for PS-OCT in revolutionizing ocular inspection techniques.

In the end, we were contemplating between developing our final application around PS-OCT or aviation fire detection. We finally chose the latter, purely based on PS-OCT is already a well-studied space, and our application can only add a marginal value to OCT systems, while it will have more reach and social impact in fire detection systems.

7. Conclusion

a. Student reflection

In the beginning of this 12-week project, we were all excited but also not knowing what to expect. It is safe to say that after all the ups and downs and several reroutes – just as Mireia already told us in the beginning – we all stepped out of the comfort zone and could happily claim the sweet victory. As a team, we all feel that TeSI is very different from the educational system we have encountered before. It is a continuous effort where frustrations and setting up stop-loss points are expected, and where the team is so diverse you cannot use your past experiences to interact with everyone.

On a team level, we learned a few things. First, it is okay to have different ideas, it is also okay to pivot as we go. Most importantly, it is totally fine to drop the ideas when we hit a dead-end, because no effort is pointless. It is very easy to think a certain application could have a huge potential, but as we investigate more, we understand that either the technology might not be the best solution in the scenario; or that the industry reality shows that the status quo is working well for them, and our product adds no value. It is of course frustrating to give up an idea when you have worked so much for it, but we learned that the process of reaching this conclusion also adds value to our later exploration, and to the technology researchers. However, it brings us to the second point, that it is also important to set deadlines and stop-loss points to know when and where to redirect our focus to. Before the CERN trip, we finally limited ideas to 2, from a chaotic 9 topics. At CERN, we decided to do a second round of brainstorming, and came up with another idea. After CERN, we restarted all the exploration steps, and finally decided on one, just a little over two weeks before the final presentation. We could develop a more well-rounded solution and focus more on the prototyping and designing of the product's specs.

We also wish that this could be a longer program, where we could comfortably have time to explore and develop our solutions, since we felt we would benefit from having it just one or two weeks longer. With that said, we still did our best to maximize the time we had and built a solution and prototypes that we could be proud of.

b. Conclusion

In our project, we leveraged the MetaHiLight technology. MetaHilight principle is the use of metasurfaces to dynamically change the polarization of light beams. We used this technology to address the need for rapid and accurate smoke detection and classification. The aim of this innovative approach is to develop a device that can quickly identify fires and determine their sources, facilitating the immediate and appropriate selection of extinguishing methods. Such a capability is particularly important in aircraft, where a rapid and accurate fire response can prevent potential disasters and significantly improve safety on board.

The key advantage of M-PACS is its ability to characterize aerosols, particularly smoke, by analyzing the polarization changes of scattered light. This detailed characterization not only helps to identify the type of fire, but also ensures that the correct extinguishing technique is used, optimizing the efficiency and effectiveness of the response. By implementing this technology in aircraft, we can significantly reduce the risks associated with in-flight fires, protecting lives and property.

Beyond its primary use in fire detection, the potential applications of our device are extensive. The precise aerosol characterization capability of M-PACS makes it a valuable tool for monitoring air pollution and detecting harmful gases. This broader applicability highlights the versatility of the technology, which offers significant benefits for environmental monitoring and public health protection.

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