MeatVisor

Final Report

Team 6 - HYGER

Josep Blazquez Folch, Jordi Espasa Rosell,

Myriam Chamoun, Sai Saran, Víctor Velasco

UPC

esade

IED Barcelona Escola Superior de Disseny

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Introduction

HYGER is a Highly efficient infrared detection unit based on high-purity black germanium technology. Its great sensitivity and low noise characteristics make it an essential component of scientific instruments, allowing researchers to explore complex light-matter interactions with previously unheard-of accuracy. Additionally, this detector is a desirable solution for many different sectors and applications because of its low manufacturing cost and compatibility with CMOS technology.

Through this research, we shed light on the distinctive features of HYGER and its potential to completely alter a number of fields, ultimately opening the way for a more sophisticated and adaptable photonics environment.

We focused on the Hyperspectral imaging feature of HYGER thus finding a solution calling it Meatvisor. Meatvisor helps reduce meat waste as it detects the viability of meat and more details such as pH and coloration assigning its real validity and not the date marked.

We consider this application to have an impact in the food waste management and quality control field.

HYGER Technology

The HYGER photosensor is an innovative technology developed at Aalto University in Finland, in collaboration with Baltic Scientific Instruments in Latvia and Umicore in Belgium. It serves as a Germanium-based device designed to convert light into electrical signals.

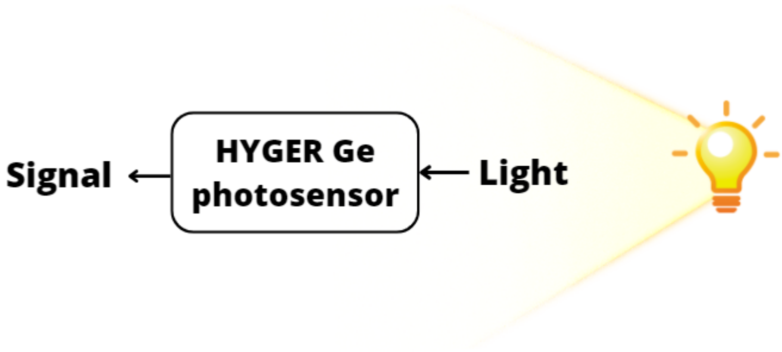

Figure 1. *HYGER Ge photosensor simplified scheme.*

Originally developed for scientific purposes, HYGER was primarily aimed at comparing various photosensors, without specific applications in mind. However, Aalto researcher Fung John later sought to explore potential applications and evaluate its performance relative to other technologies. The objective was to identify potential areas for its utilization, establish a business model, and extend the impact of the ongoing research. Currently, HYGER's Technology Readiness Level (TRL) stands at 4, having been successfully demonstrated in laboratory settings but awaiting real-world implementation.

In the realm of infrared detection, the use of Indium Gallium Arsenide (InGaAs) material is prevalent due to its wide wavelength range of 900 nm to 1700 nm, commonly known as Short-Wavelength Infrared (SWIR). However, the adoption of InGaAs is hampered by its high cost and relatively poor performance compared to Germanium (Ge) photosensors. By achieving comparable performance with Ge photosensors, significant cost reduction can be realized. Notably, Ge-based sensors, such as HYGER, can detect wavelengths up to 1700 nm. This wavelength range aligns with the scope of SWIR Vision's[1] innovative detection technology, which encompasses wavelengths from 400 nm to 2000 nm, similar to the target range of HYGER.

[1] https://www.swirvisionsystems.com/about/what-is-swir/

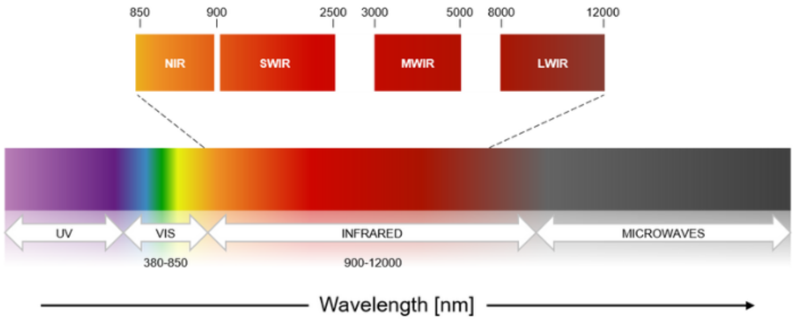

***Figure 2**. Spectral range wavelengths.*

In the fabrication of HYGER, Germanium is employed as the active material for the tiles, responsible for detecting incoming light. A Scanning Electron Microscope (SEM) image illustrates a nano-surface structure with high magnification, demonstrating a nanotextured surface. This nanotexture plays a crucial role in enhancing performance by significantly reducing surface reflectance. While the "minimsurface" exhibited a surface reflectance of 40%, the implementation of the "rectromenium" photodiode achieved a remarkable reduction to less than 1%. This nanostructuring technique has proven to be effective in improving the overall performance of HYGER.

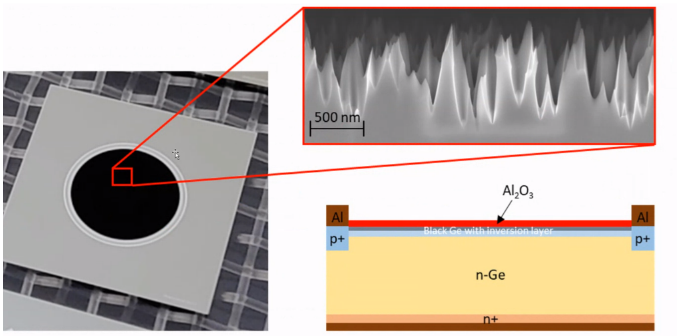

***Figure 3**. HYGER nanostructure.*

The performance of photosensors is directly correlated with its quantum efficiency (QE) and responsivity. HYGER devices exhibit a remarkable capability to **maintain approximately 90% responsivity consistently**, which positions them as potential frontrunners in the current market.

According to the presented Figure, there is a significant drop in silicon QE at approximately 1100 nm, while Germanium experiences a slight decrease at 1700nm. This new technology is believed to have wide-ranging applications.

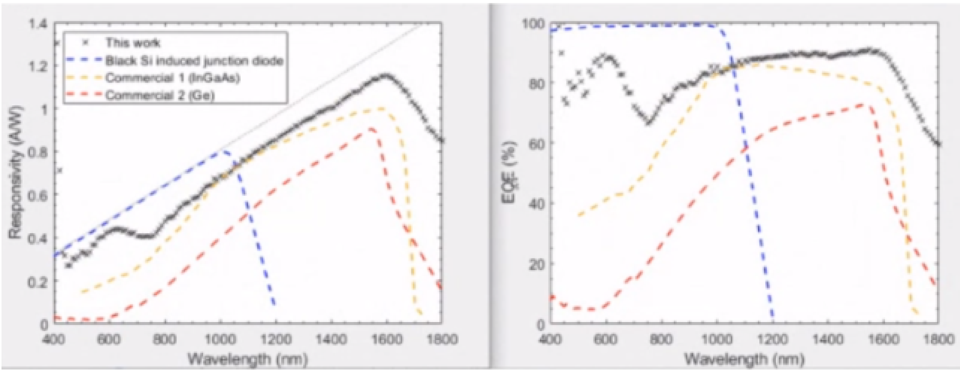

***Figure 4**. Responsibly and EQ comparison of HYGER with commercial photosensor.*

When considering detectors, it is imperative to consider not only signal strength but also noise, as the ultimate goal is to optimize the signal-to-noise ratio. While HYGER is confident that their device offers a substantially higher signal strength compared to existing market options, they express some uncertainty regarding noise levels. Consequently, there are certain limitations to this technology, and efforts are being made to minimize noise in the near future. By enhancing the signal, the signal-to-noise ratio is improved; nevertheless, noise remains a challenge that the researchers intend to address. In some cases and applications, the integration of cooling devices with photodetection systems effectively mitigates noise issues. However, when operating at room temperature, noise levels must be carefully considered.

It would be highly beneficial for researchers to identify compelling justifications for the utility and advantages of a single photodetector capable of covering a wavelength range from 400 nm to 1700 nm.

Application exploration should focus on wavelengths from 1200 nm and above. It should be noted that the reflectance of a surface is dependent on the angle of incidence, with the lowest reflectance observed at normal incident angles. However, as the incident angle increases to 60 or 70 degrees, the reflectance dramatically escalates.

A noteworthy advantage of germanium is its **compatibility with complementary metal-oxide-semiconductor (CMOS) processes**, enabling the utilization of silicon fabrication techniques and mitigating processing costs.

The dimensions of the photodiode chip can be adjusted according to fabrication requirements, allowing for scalability. While the active area typically has a 5mm diameter, integrating it into a CMOS camera necessitates consideration of pixel density. HYGER could be integrated in cameras like in the following Figure.

Figure 5. *Possible HYGER implementation on a camera.*

Competitive Advantages

We explored HYGER technology and conducted a thorough comparison of photosensor materials to identify the superior characteristics of Germanium photosensors compared to other technologies. The accompanying Figure showcases the various photosensor technologies available at Thorlabs. The rise/fall time, which denotes the response speed of the device, holds significant importance in Fiber Optic and Lidar applications. Additionally, dark current (referring to the leakage current when a bias voltage is applied to a photodiode) and NEP (Noise-equivalent power) exhibit noteworthy relevance in other applications. By taking these factors into consideration, we compiled a comprehensive list of competitive advantages offered by HYGER technology to ascertain its potential application areas.

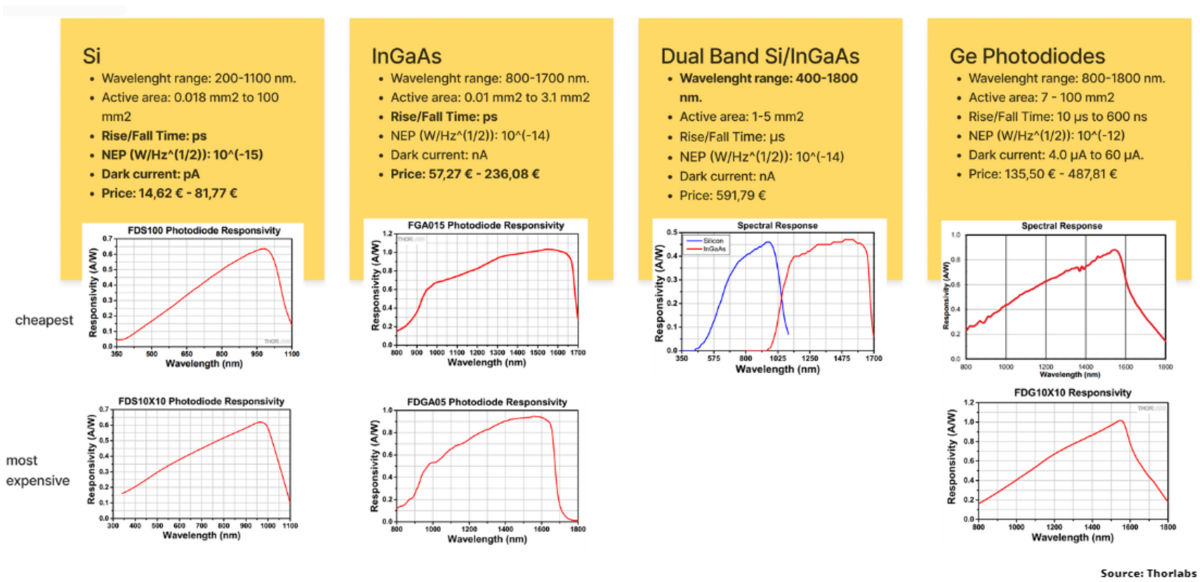

Figure 6. *Photosensor technology comparison.*

1. **Enhanced Quantum Efficiency (QE) and Responsivity** - Reduced Reflectivity:
    a. Requires less energy, leading to decreased battery usage. So, it consumes less energy, which may be useful for smartwatches for infrared sensing.
    b. Enables night vision capabilities in glasses.
    c. Emits less radiation, making it suitable for specific types of X-ray imaging, such as lung pathology screening.
2. **Increased Bandwidth - Expanded Wavelength Range** compared to Silicon:
    a. Enables higher speeds in optical fiber communications.
    b. Facilitates smooth streaming of high-quality videos, and for streaming of video games.
    c. Enables real-time streaming of virtual reality experiences.
    d. Enables remote operations with minimal delays.
    e. Can detect and measure a wider range of wavelengths, enabling applications in various fields such as **spectroscopy** and telecommunications.
3. Lower Construction Costs compared to InGaAs (due to **compatibility with CMOS technology**).
    a. InGaAs is not CMOS compatible.
    b. For **economy of scale**, this is the main competitive advantage.
4. Improved Sustainability compared to InGaAs.
5. Reduced Noise compared to Gallium Arsenide:
    a. Provides higher signal-to-noise ratio, resulting in more accurate and reliable data acquisition and measurement.

The HYGER sensor demonstrates exceptional resolution within a specific spectral range, particularly in the wavelengths spanning from 800 nm to 1800 nm, which encompass the near-infrared (NIR) and short-wave infrared (SWIR) spectra. Notably, the HYGER sensor was designed to be compatible with complementary metal-oxide-semiconductor (CMOS) technology, further augmenting its appeal. The combination of its wide spectral range and CMOS compatibility establishes HYGER as a standout choice among alternative photosensors, rendering it advantageous in various aspects. Consequently, these two prominent strengths position HYGER as an ideal candidate for applications such as **Hyperspectral Imaging**.

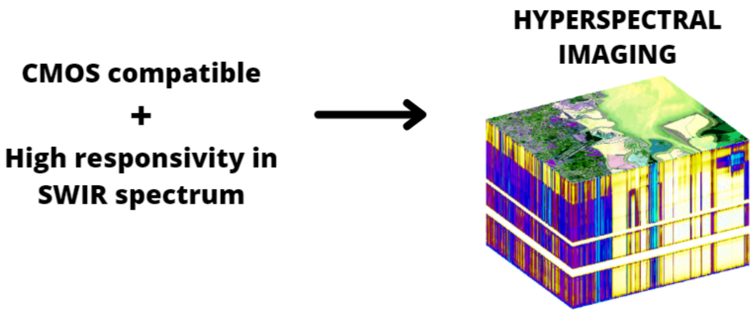

Figure 7. *HYGER competitive advantages.*

Hyperspectral Imaging

Hyperspectral imaging (HSI) is a technique commonly employed in various applications, including the assessment of meat quality. Unlike conventional cameras, which typically capture only three channels corresponding to specific wavelengths of red, blue, and green light, HSI captures a vast range of wavelengths spanning the entire spectrum. This comprehensive collection of spectral information enables us to have a lot more data that can later be used alongside different data processing methods. Moreover, HYGER HSI extends beyond the visible light range, encompassing near-infrared (NIR) and shortwave infrared (SWIR) spectra. These non-visible wavelengths offer unique insights into the properties of meat that would otherwise remain imperceptible through conventional imaging techniques.

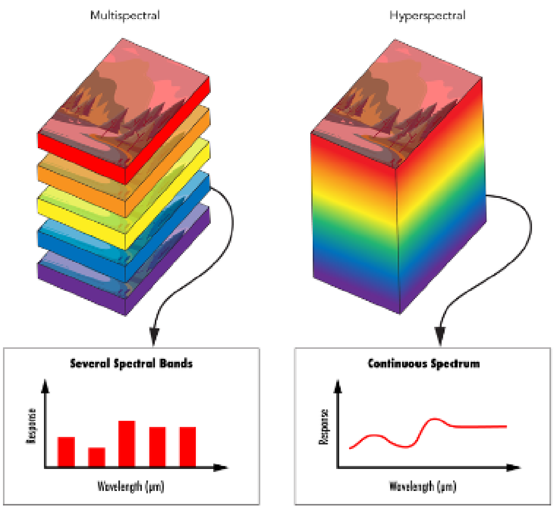

Figure 8. *Multispectral and Hyperspectral Imaging.*

Various applications

At the very beginning of the project we started researching in several areas in which photodetectors are used and comparing the current solutions with HYGER technology. We wanted to see whether HYGER is capable of somehow improving any existing technology that uses photodetectors. Next, there is a summary of the areas that we investigated.

Healthcare

Biomedical sensors can be divided into noninvasive sensors, minimally invasive, and invasive sensors. With HYGER we explored noninvasive sensors for medical applications, which include pulse oximetry, heart-rate monitoring, blood glucose monitoring, arterial pressure monitoring, urinalysis, dental color matching, and exhaled biomarkers monitoring.

Conventional methods for monitoring patients using optoelectronics sensors use expensive components, so state-of-the-art research is focused on the development of sustainable and low-cost solutions, like the organic optoelectronic sensor for pulse oximetry proposed by Lochner et al.[2], Google contact lens sensors for blood glucose monitoring by Farandos et al.[3], and Apple Watch sensor for blood glucose monitoring by Bismuto et al.[4]

The utilization of HYGER technology offers advantages in terms of low power consumption for various applications. Nevertheless, when considering the application of Smartwatches for Healthcare, it is important to note that the primary power consumption does not arise from the infrared (IR) lighting. In healthcare applications such as pulse oximetry, heart-rate monitoring, and arterial blood pressure monitoring, the visible light spectral range is predominantly employed, whereas HYGER technology operates in the shortwave infrared (SWIR) and infrared (IR) range.

Surveillance

Enhanced Detection: HYGER technology enables the detection of thermal energy emitted by objects, allowing surveillance systems to detect and identify targets even in low-light or obscured conditions. This capability is particularly useful for surveillance in darkness or challenging environmental conditions.

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[2] Lochner, C., Khan, Y., Pierre, A. *et al.* All-organic optoelectronic sensor for pulse oximetry. *Nat Commun* 5, 5745 (2014). https://doi.org/10.1038/ncomms6745

[3] Elsherif, Mohamed et al. "Wearable Smart Contact Lenses for Continual Glucose Monitoring: A Review." *Frontiers in medicine* vol. 9 858784. 4 Apr. 2022, doi:10.3389/fmed.2022.858784

[4] Apple Makes Major Progress on No-Prick Blood Glucose Tracking for Its Watch

Improved Recognition: By capturing thermal images, HYGER technology allows for better recognition and identification of objects, people, or animals. The thermal signatures captured can reveal details such as body heat patterns, which can aid in distinguishing individuals or tracking movements.

Increased Coverage: HYGER technology can provide a broader coverage area compared to traditional surveillance methods. The thermal imaging capability allows for the monitoring of larger spaces, enabling comprehensive surveillance over extensive areas. Intruder Detection: Thermal imaging offered by HYGER technology can be effective in detecting intruders or unauthorized individuals in restricted areas. The ability to detect body heat signatures can help identify potential threats or intrusions that may go unnoticed by traditional surveillance systems.

Environmental Monitoring: HYGER technology can also be utilized for environmental monitoring purposes. It enables the detection and tracking of temperature variations, which can be valuable in identifying hotspots, monitoring fire risks, or detecting anomalies in critical infrastructure.

Aerostats

HYGER photodiodes offer unique potential due to their ability to measure light intensity across different parts of the electromagnetic spectrum. This allows for numerous applications in areas like environmental monitoring, forest fire surveillance, precision agriculture, and security and defense. One way to make inroads in all these fields is with the sensors used in aerostats.

In the realm of environmental monitoring, the ability to accurately measure light intensity can provide vital information about air composition and pollutant presence. Companies such as AeroVironment and Precision Hawk have already recognized the value in this, offering solutions for measuring air quality and solar radiation through aerostats equipped with light sensors and high-resolution cameras. The incorporation of HYGER technology into these systems could enhance their sensitivity, potentially offering a higher resolution of environmental data. This could enable a more detailed understanding of pollution distribution, facilitating more efficient allocation of resources in pollution control, and better-informed environmental policy-making.

Similarly, in the critical area of forest fire monitoring, HYGER's ability to detect the intensity of infrared radiation emitted by fires can offer a valuable tool for early fire detection and rapid response. Lockheed Martin is a notable company in this field, offering forest fire monitoring solutions using aerostats equipped with light sensors and high-resolution cameras. Adding HYGER technology to such systems could allow for more precise detection of heat signatures from fires, potentially reducing response times and aiding in the control of these often-devastating environmental events.

In the world of precision agriculture, the ability to accurately measure light intensity can yield invaluable insights into plant health and growth. This kind of information can be used to optimize irrigation, fertilization, and harvesting schedules, thereby improving crop yield and reducing waste. The advent of HYGER photodiodes in this area could allow for an unprecedented level of precision, enabling the development of more sustainable and efficient agricultural practices, and potentially contributing to food security on a global scale.

The potential applications of HYGER photodiodes are not limited to environmental and agricultural areas. The capacity to detect visible light and infrared radiation has significant implications for security and defense applications. The use of aerostats equipped with these advanced photodiodes could provide a superior surveillance system, capable of detecting intruders and other potential security threats in real-time. This could be particularly useful in border security and in the protection of sensitive facilities.

Currently, the trend is to reuse or recycle existing systems, but the potential of HYGER technology may encourage the development of new, advanced solutions. It is recommended to open a dialogue with the aforementioned companies to explore whether HYGER technology could address any unmet needs or enhance their current offerings.

Hyperspectral imaging on IR and SWIR applications

After some weeks of research, we didn't find any area in which HYGER could help to improve the current solution and we got a little bit lost. We didn't know which direction we should follow or in which areas we should investigate, so we decided to take a look carefully at the technical specifications of our technology again.

Finally, after reviewing them several times, we came up with an idea that would clear our minds a bit and that would make us realize in which direction we should carry the project.

Since HYGER provides a wide spectrum range and is CMOS compatible, we believed that the big field in which we should focus ourselves was Hyperspectral Imaging.

Having said that, we started to investigate in parallel in which applications of this technique HYGER would best fit. Next we provide a summary of our research tour about possible applications for HYGER in the hyperspectral imaging field.

Automotive industry

Hyperspectral imaging in the automotive industry is used for detecting possible obstacles in the surroundings of the vehicle.

It is done by capturing the same image in different wavelength ranges, in order to combine them and make a high resolution one. With a small number of images we cannot achieve a good quality one, so sometimes it's impossible to detect if there is an object. It's always good to have a big number of images in order to have more information and generate a more accurate overall image of our target, so the more images we have in different ranges of the spectrum, the better.

The fact of recombining several images made in different wavelengths of the spectrum is achieved by the so-called technique sensor fusion. This technique uses several photodetectors, each one working on a different range, in order to capture the images.

Since HYGER has a good sensitivity in a wide range, we decided to investigate if there is the possibility of combining two photodetectors and use HYGER instead, avoiding the use of unnecessary ones, in order to optimize the hyperspectral imaging in the automotive industry.

We saw that the most common wavelengths used in automotive lidar systems are around 905 nm, 940 nm, and 1550 nm, which is a range covered by HYGER. The majority of commercial automotive lidar systems operate at a wavelength of 905 nm. This wavelength offers a good balance between range, accuracy, and eye-safety requirements. Also, it easily penetrates in fog, rain, and snow. Some lidar systems used in ADAS (Advanced Driving Assistance Systems) and autonomous vehicles operate at 940 nm. This wavelength has a lower interference from ambient light and better performance in adverse weather conditions. However, there is a growing interest in using longer wavelengths (1550 nm). Its advantages are that it has longer range and achieves a better performance in adverse weather conditions, and its drawbacks are that it is more expensive, it has higher power consumption and requires more complex devices.

After doing some research in this topic and in Germanium photodetectors, we realized that the Rise and Fall time of Germanium is too large for being used in a lidar, which requires a Fast Rise/Fall time in order to take decisions in (almost) real time. This is the reason why we decided to give up this topic and focus the research in other hyperspectral imaging areas.

Precision agriculture

As we have previously discussed, the application of HYGER technology in hyperspectral imaging is significant due to its unique capabilities. One such application is within precision agriculture, an industry that heavily utilizes hyperspectral imaging satellites such as Hyperion, with a spectrum range of 400-2500 nm and a 10-nm resolution in 220 bands. Other notable satellites include Sentinel-2, Landsat-8, RapidEye, SPOT-6, GeoEye-1, and Huanjing.

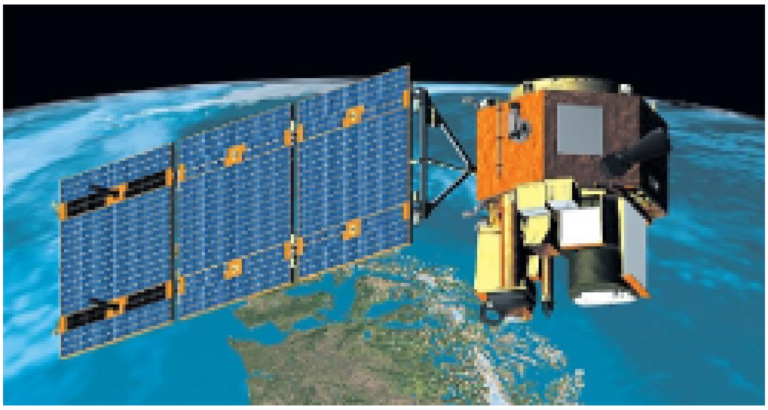

Figure 9. *Satellite for precision agriculture*

The competitive edge of HYGER lies in its versatility in addressing a limitation in these satellites - their inability to directly utilize photodiodes. The issue with many photodiodes, including those on the Hyperion instrument, is that they are typically only sensitive to a narrow band of wavelengths. HYGER, however, shows potential in overcoming this challenge, suggesting a promising future for the technology within this domain.

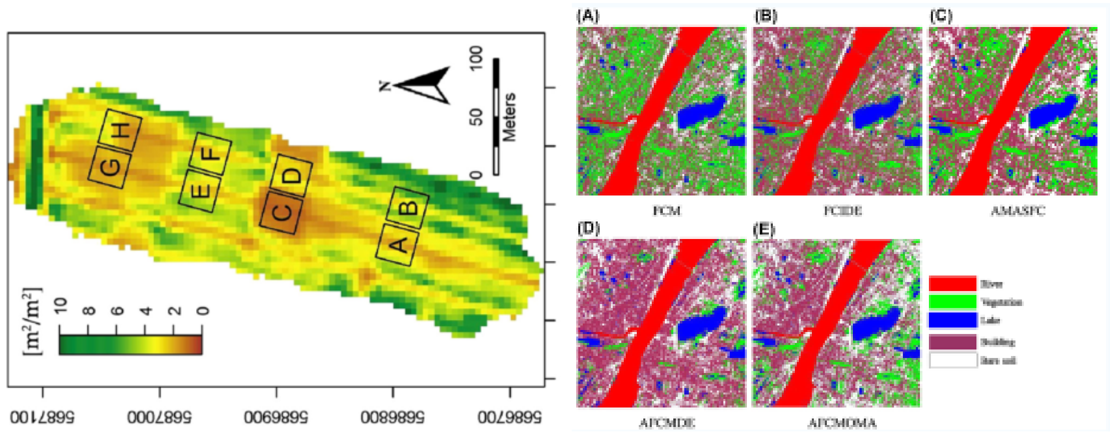

Figure 10. Computer vision processing for precision agriculture.

In our recent consultations with experts Daniel Caballero and Jose Manuel Amigo, the consensus was positive towards the application of HYGER in hyperspectral imaging for precision agriculture. As they stated, the industry is currently leaning towards using multispectral images with quite limited wavelengths, indicating a gap that HYGER could potentially fill. A direct quote from the experts reads, "The new detector (HYGER) could be a solution for obtaining hyperspectral images, especially due to the current trend of the sector."

One practical example of HYGER's potential in agriculture comes from its potential application in measuring the sugar content in apples. A Short-Wave Infrared (SWIR) hyperspectral camera equipped with HYGER photodiodes mounted on a drone could assess the sugar content of apples still on the tree. By allowing farmers to forecast the grade and quality of their harvest before the season, such technology could help optimize harvest schedules and market planning, thereby enhancing productivity and reducing waste.

In summary, the application of HYGER photodiodes in precision agriculture, particularly through hyperspectral imaging, holds immense potential. By overcoming the limitations of traditional photodiodes, HYGER could provide more detailed and varied data about crops, contributing significantly to the efficiency and sustainability of agricultural practices. The promising feedback from industry experts further underscores the potential of this technology, highlighting the need for further research and development in this direction. The future of precision agriculture could be greatly influenced by the successful integration of

HYGER technology, leading to increased productivity and more sustainable farming practices.

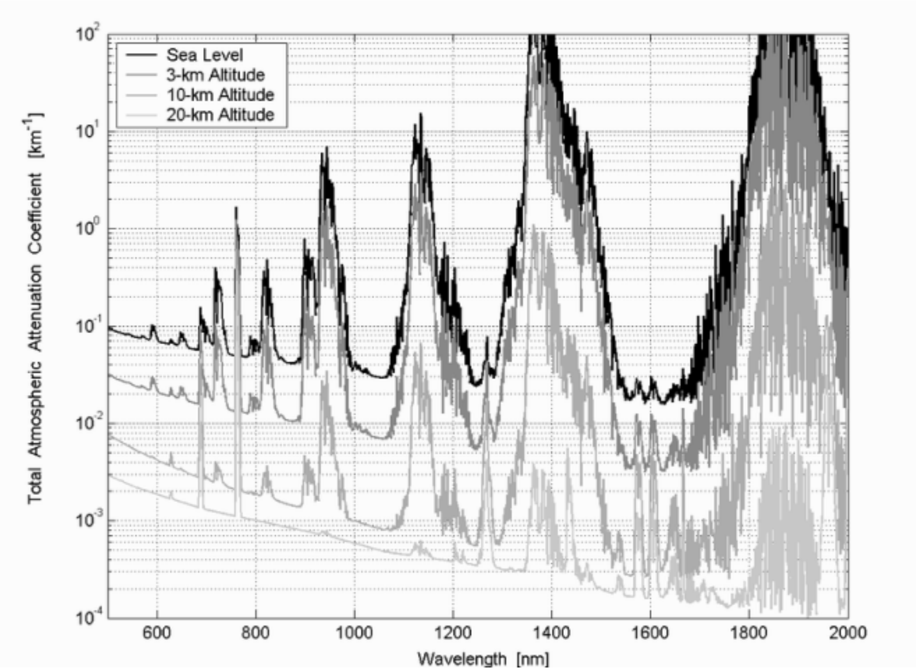

Figure 11. Total Atmospheric Attenuation.

Waste Management

Another application that we found for hyperspectral imaging was waste management, so we came up with the five more important areas of waste management, which are waste sorting, contaminant detection, landfill monitoring, resource recovery and recycling.

Waste sorting involves separating different types of waste materials for proper disposal. Hyperspectral imaging enables automated and efficient identification and classification of waste based on their spectral signatures.

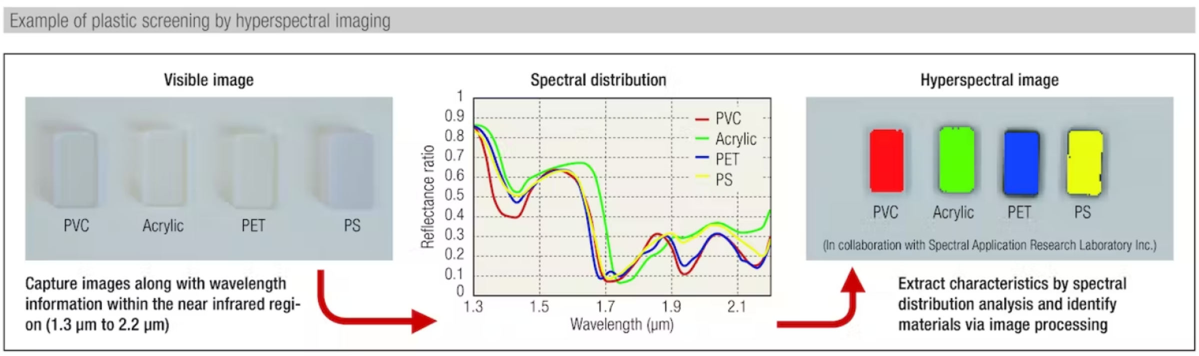

Figure 12. Hyperspectral imaging example for plastic sorting.

Detection of contaminants in waste products can help to prevent environmental damage. Hyperspectral imaging enables the identification and analysis of spectral signatures associated with different contaminants, allowing for reliable and accurate detection.

Hyperspectral imaging can be utilized for landfill monitoring to assess and manage the environmental conditions and potential risks associated with landfill sites. By capturing spectral data from the landfill area, hyperspectral imaging enables the analysis and monitoring of various parameters. It can be used for the following purposes: detection and monitoring of gas emissions, leachate detection, monitoring of the vegetation health, checking landfill surface stability and landfill covering assessment.

Hyperspectral imaging also plays a significant role in resource recovery processes by enabling the identification and extraction of valuable materials from waste streams. It allows for the analysis of spectral characteristics associated with specific resources, facilitating their efficient recovery.

However, among all the listed areas, we decided to focus on recycling. Hyperspectral imaging can play a role in recycling processes by facilitating the sorting, identification, and quality assessment of recyclable materials. Because of the low value of the recycled materials, the devices used in this area should be cost-efficient. HSI is a cheap field and specially HYGER technology, since it has a lower production cost, so we thought that it could perfectly fit in this topic.

After some research, we came up with some papers of hyperspectral imaging applied to the waste recycling sector. We saw that the wavelength range used goes from 1000 to 2500 nm, whereas the HYGER one goes from 400 to 1700 nm, so we thought that this field would be a potential use case for our technology.

However, although we liked the waste management field and we found it very interesting as well as sostenible, we had to put it aside. This is due to the fact that we had another potential application in which we saw more future for HYGER, but we don’t discard the use of it in the waste management sector.

Art Conservation

We researched application of near-infrared spectroscopic imaging for the analysis of drawing constituents. The selected wavelength ranges for some academic studies[5] [6] are 650 to 1040 nm. It is worth noting that the mid-infrared region, spanning from 2500 to 25,000 nm, is commonly utilized for material identification in art conservation. This preference arises from the fact that spectra within this region exhibit highly distinctive characteristics. Additionally, the near-infrared region, ranging from 650 to 2500 nm, has also been employed for materials identification purposes.

Because most of these wavelengths are outside HYGER spectral range, we discontinued our research in this area, also because of the absence of an economy of scale advantage in art conservation.

Meat Quality Control

Finally, among all the areas that we researched on, we decided to focus on Meat Data Expiration inference using HSI. The following section explains this topic in an exhaustive way.

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[5] Attas, Michael & Cloutis, Edward & Collins, Catherine & Goltz, Douglas & Majzels, Claudine & Mansfield, James & Mantsch, Henry. (2003). Near-infrared spectroscopic imaging in art conservation: Investigation of drawing constituents. Journal of Cultural Heritage. 4. 127-136. 10.1016/S1296-2074(03)00024-4.

[6] Hyperspectral Imaging in Art and Antiquities Conservation

MeatVisor

Technology

The motivation to use MeatVisor for quality- and safety-control procedures in meat industry is because traditional techniques, such as instrumental methods and physicochemical and microbiological procedures, are normally destructive, laborious, complex, and time-consuming and, consequently, result in limitations for practical uses especially for on-line applications.[7]

The use of HSI provides non-invasive methods for quality- and safety-control for meat products. All these methods work in the 900-1700 nm spectral range, which matches perfectly with HYGER technology. According to state-of-the-art, multiple quality parameters can be used to enhance the meat expiration date. The properties are:

- Type of meat, like types of lamb muscles,[8] also meat authenticity checking,[9] which is becoming increasingly important with the prevalence of product adulteration.
- Tenderness, pH, and colour of meat.[10]
- Microbial contamination.[11]
- Foreign bodies (Microplastics, PET, PE, PVC, etc.).[12] [13]

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[7] Hassoun, Abdo & Karoui, Romdhane. (2015). Quality Evaluation of Fish and Other Seafood by Traditional and Nondestructive Instrumental Methods: Advantages and Limitations. Critical reviews in food science and nutrition. 57. 10.1080/10408398.2015.1047926.

[8] Kamruzzaman, Mohammed & Elmasry, Gamal & Sun, Da-Wen & Allen, Paul. (2011). Application of NIR hyperspectral imaging for discrimination of lamb muscles. Journal of Food Engineering - J FOOD ENG. 104. 332-340. 10.1016/j.jfoodeng.2010.12.024.

[9] Al-Sarayreh, M., Reis, M.M., Yan, W.Q., & Klette, R. (2020). Potential of deep learning and snapshot hyperspectral imaging for classification of species in meat. *Food Control, 117*, 107332.

[10] Elmasry, Gamal & Sun, Da-Wen & Allen, Paul. (2012). Near-infrared hyperspectral imaging for predicting colour, pH and tenderness of fresh Beef. Journal of Food Engineering. 110. 127–140. 10.1016/j.jfoodeng.2011.11.028.

[11] Barbin, Douglas & Elmasry, Gamal & Sun, Da-Wen & Allen, Paul & Morsy, Noha. (2013). Non-destructive assessment of microbial contamination in porcine meat using NIR hyperspectral imaging. Innovative Food Science & Emerging Technologies. 17. 180–191. 10.1016/j.ifset.2012.11.001.

[12] Zhang, Yituo & Wang, Xue & Shan, Jiajia & Zhao, Junbo & Zhang, Wei & Liu, Lifen & Wu, Fengchang. (2019). Hyperspectral Imaging-Based Method for Rapid Detection of Microplastics in the Intestinal Tracts of Fish. Environmental Science & Technology. 53. 10.1021/acs.est.8b07321.

[13] Zhang, Yituo & Wang, Xue & Shan, Jiajia & Zhao, Junbo & Zhang, Wei & Liu, Lifen & Wu, Fengchang. (2019). Hyperspectral Imaging-Based Method for Rapid Detection of Microplastics in the Intestinal Tracts of Fish. Environmental Science & Technology. 53. 10.1021/acs.est.8b07321.

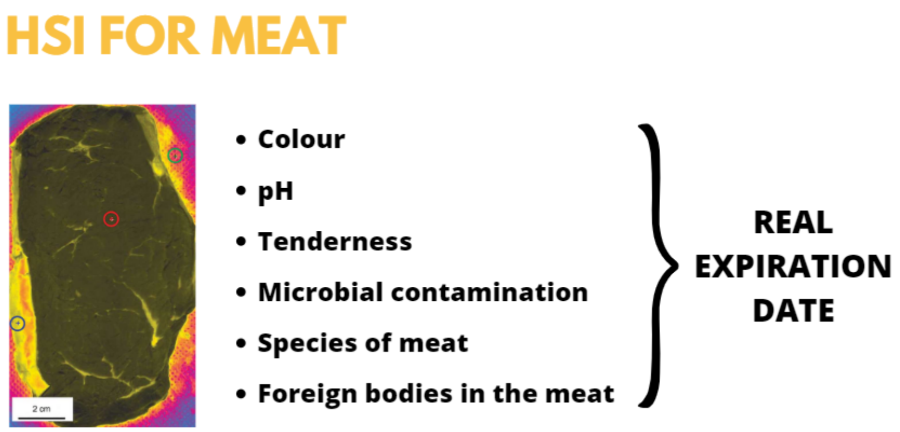

Figure 13. HSI for Meat Real Expiration Date prediction.

Additionally, all these methods are compatible with packed meat in plastic, the absorbance of plastics used for meat packaging only have high absorbance of light outside the HYGER spectral range. These plastics are listed below:

- Polyethylene (PE), spectrum absorption in the 340-550 nm range.
- Polypropylene (PP), higher absorption at wavelengths shorter than 300 nm.
- Polyvinylchloride (PVC), absorbance peaks at 210 and 280 nm.
- Polyester (PET), spectrum absorption in the 260-320 nm range.

The validation process of the Meatvisor approach proposed by HYGER involved consultation with two experts specializing in meat quality assessment: IMQAS and Lenz Instruments. IMQAS is an independent service provider that offers meat inspection, classification, and hygiene assessment test services. Lenz Instruments focuses on developing optical devices specifically designed for meat quality classification.

During our discussions with the IMQAS expert, it was suggested that the utilization of cameras could be beneficial in determining the expiration date of meat. Effective forecasting of meat expiration dates holds great potential in reducing meat waste; however, the main source of wastage occurs within supermarkets due to inadequate storage management. Consequently, our primary target audience for enhancing expiration date forecasting and minimizing meat waste should be supermarkets.

The expert from Lenz Instruments concurred with the insights provided by the IMQAS expert. In this business model, our potential customers encompass both supermarkets and final customers (i.e., individuals purchasing meat at supermarkets). Within the industry, meat is typically classified in factories and subsequently sold to supermarkets. Notably, the expiration date is assigned at the supermarket rather than at the factory. Furthermore, the expert explained the preference for hyperspectral imaging (HSI) over Raman spectroscopy, which could be compatible with HYGER. The main reason for this preference is the significantly longer inference time associated with Raman spectroscopy methods, rendering them impractical when dealing with a large volume of meat and the need to infer meat quality properties efficiently.

Impact

The beef meat production chain involves a series of processes aimed at ensuring the safety and quality of meat products from the initial breeding of cattle to their sale in stores. Monitoring the processing environment, equipment, and people cleanliness, testing for bacterial contamination, and preventing cross-contamination are all examples of quality control techniques. To guarantee freshness and quality, the meat products are packaged and stored under controlled circumstances after processing. Proper packaging, labeling, and temperature control are used, and storage facilities are examined on a regular basis. The meat products are subsequently supplied to retailers such as grocery stores and restaurants, where they are kept fresh and safe for eating during transportation. Quality control measures include proper shipping and handling procedures, regular inspections, and product tracking from farm to store shelf.

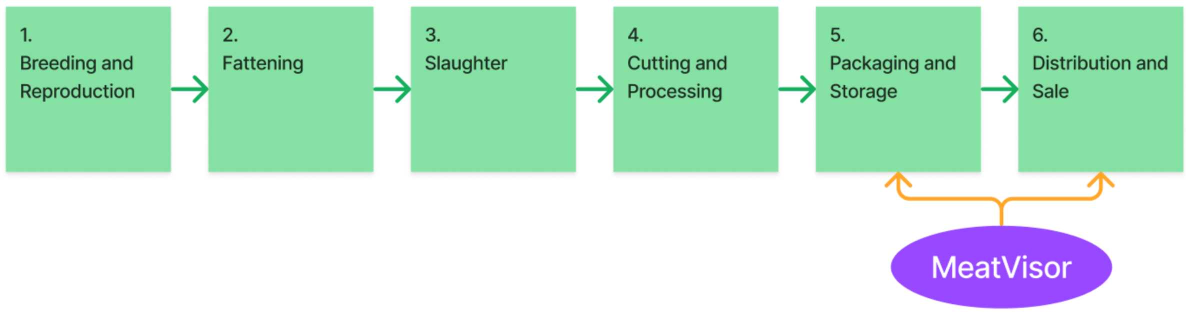

Figure 14. Meat production chain.

Million tons of meat get wasted per year, this happens due to improper handling, inadequate processing and much more.

A study carried out by the European Commission (2018), estimates that up to 10% of food waste generated annually in the EU is linked to date marking.

Not only does meat waste represent a major loss of resources such as energy, but it also accounts for 15% of global greenhouse gas emissions, contributing to environmental pollution that contaminates waterways and soil.

With MeasVisor testing the quality of meat is in a non-intrusive manner. We find MeatVisor to be used in different phases of quality control. In the packaging process before distribution, after the delivery process and before the shelving in the stores, and in the daily quality control on shelves.

Scanning with MeatVisor will give the shelf estimation life in place of putting a premature expiration thus ensuring safety and quality.

Market Analysis

Th**e B2B meat industry** is a large and growing market, driven by consumer demand for fresh and high-quality meat products. **Supermarkets** and **butchers** face challenges in managing meat expiry dates, including wastage, revenue loss, and the risk of selling expired products. With increasing regulatory scrutiny and customer expectations for quality, there is a growing need for a solution like MeatVisor to streamline operations and enhance food safety compliance.

MeatVisor targets supermarkets, butchers, and other B2B meat businesses that deal with perishable meat products. Supermarkets can benefit from MeatVisor's accurate **expiry date prediction** to ensure product freshness, minimize waste, and optimize shelf space. Butchers can use MeatVisor to efficiently manage inventory, avoid stockouts or overstocking, and deliver the highest quality products to their customers.

Figure 15. Butchers.

Business model canvas

Customer segment

- Supermarkets
- Butchers

Value Proposition

- Accurate expiry date detection
- Waste Reduction
- Optimized shelf management
- Enhanced food safety compliance

Key Activities

- Software development
- Image recognition algorithms
- Integration
- Customer support
- Continuous Improvement

Key partnerships

- Meat suppliers
- Industry associations
- Technology providers
- Strategic alliance

Revenue Streams

- Subscription fees
- Licensing models

Cost structure

- Software development
- Hosting and Maintenance
- Personnel

Prototype

We found multiple representation for the same application, we will explain four of those models

Factory-based

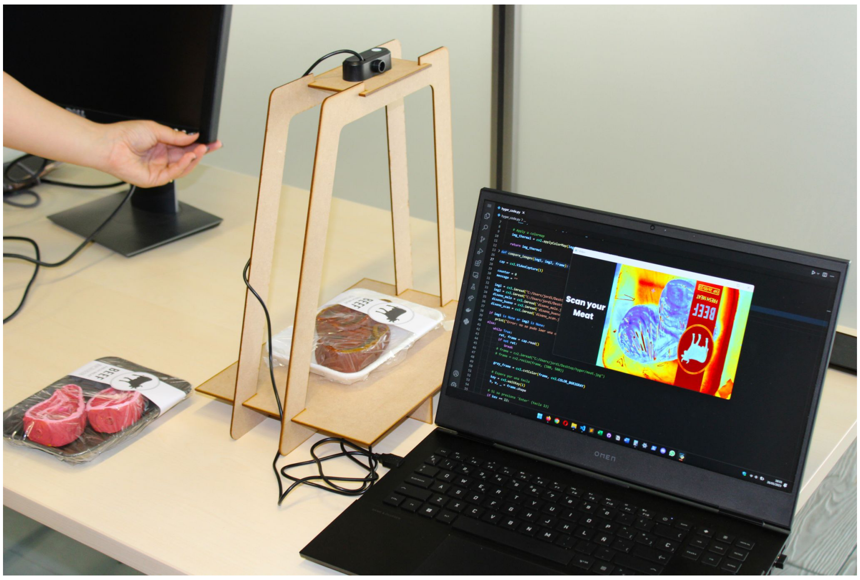

Figure 16. Lo-fi prototype.

Lo-fi prototype to be on the conveyor belt in the factories during the packing process, we laser cut 2,5 mm fibrapan and used a webcam linked to a laptop with a code that works on image recognition. You can also see more details about the prototype, how it tests good and bad meat and our demo video.

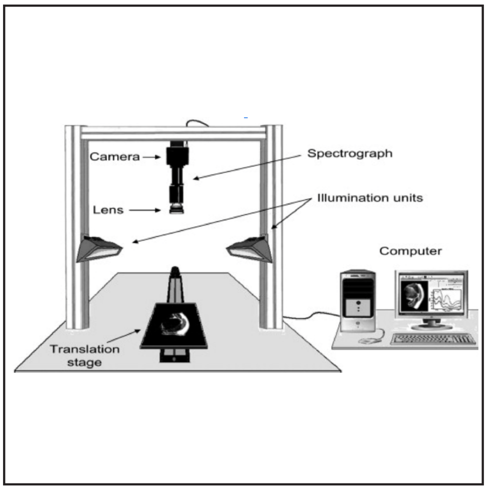

Figure 17. Inspiration of our prototype.

Store Fridge

Meatvisor will be linked to the computer of the quality control manager and will scan every period of time and give out the necessary details.

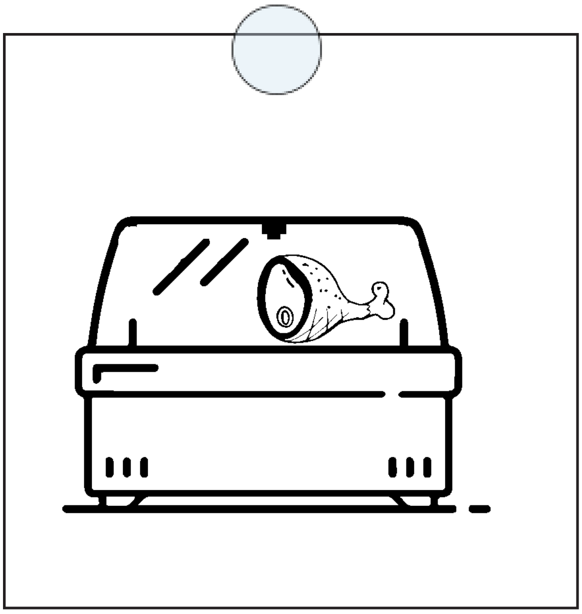

Figure 18. MeatVisor in store meat fridge

Portable Device

During the shelving and de-shelving process instead of throwing away the products because they reached the expiration date, they scan and see if it is valid for more days or not.

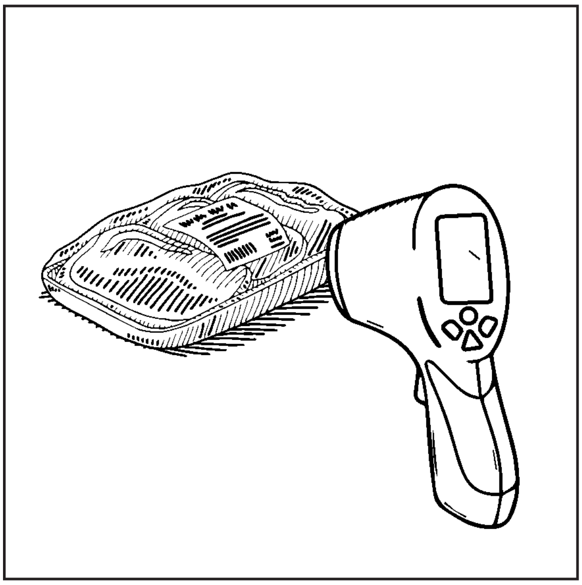

Figure 19. Handheld MeatVisor.

Future Prototype

It was one of the first ideas we had, we think in the future it will be useful to be bought by consumers so they can track their meat they bought or want to buy.

Figure 20. Phone attachment Meatvisor.

Code

This script appears to be designed to assess the quality of meat using live video feed from a webcam. Here's a breakdown of the code:

Importing necessary modules:

```python
import cv2

import numpy as np
```

The script starts by importing two essential libraries: OpenCV (cv2) for processing images and videos, and NumPy (np) for handling numerical computations and arrays.

Initializing webcam capture:

```python
cap = cv2.VideoCapture(0)
```

This line initializes a VideoCapture object, cap, which starts the webcam to capture video. The argument 0 is used to specify the first webcam of the system.

Defining variables:

```python
counter = 0

message = ""
```

These lines initialize two variables, counter and message, that will be used later in the script.

Defining a processing function:

```python
def pseudo_hyperspectral_filter(image):

        ...

        return filtered_image
```

This function applies a pseudo-hyperspectral filter to an input image. It works by converting the image to Lab color space, splitting the image into its L, a, and b channels, performing histogram equalization on the L channel, and then merging the processed L channel with the original a and b channels. The processed image is then converted back to the BGR color space before being returned.

Processing video frames in a loop:

```python
while True:

        ...
```

This is the main loop of the script, where each frame of the video is processed.

Reading from the webcam:

```python
ret, frame = cap.read()

if not ret:

    break
```

This block of code reads a frame from the webcam. If no frame is successfully read (ret is False), the loop is broken and the script ends.

Defining region of interest (ROI):

```python
h, w, _ = frame.shape

region_start = (w//2 - 50, h//2 - 50)

region_end = (w//2 + 50, h//2 + 50)

cv2.rectangle(frame, region_start, region_end, (255, 255, 255), 2)
```

The script then defines a square region of interest (ROI) in the middle of the frame, and draws a rectangle around this ROI on the original frame.

Inspecting the ROI and assessing meat quality:

```python

if key == 13:

        ...
```

If the 'Enter' key (ASCII code 13) is pressed, the script crops the frame to the defined ROI and converts it to the HSV color space. It then checks whether any pixel in the ROI falls within the HSV ranges defined for "bad" (green hue range) or "good" (red hue range) meat. Depending on the outcome, it sets the `message` and `valid` variables accordingly, and starts a counter to display the message for a certain period.

Displaying the message:

```python
if counter > 0:

        ...

        counter -= 1
```

If the counter is greater than zero, the script displays the message on the frame and decreases the counter by one.

Displaying the frame and ending the script

```python
ret, frame = cap.read()

if not ret:

    break
```

Future goals

B2C Market Expansion: Develop a strategy to enter the B2C market, targeting individual consumers, home chefs, and small-scale restaurants. This will allow MeatVisor to reach a wider customer base and cater to the growing demand for accurate expiry date information and optimized meat management at the consumer level.

Mobile Application Development: Create a user-friendly mobile application for MeatVisor to provide convenient access to expiry date detection, real-time alerts, and inventory management features. This mobile app will cater to the needs of B2C customers who prefer mobile solutions for their everyday needs and enhance their overall experience. s

Enhanced Product Offerings: Continuously innovate and expand the features and services of MeatVisor. This may include advanced analytics capabilities, personalized recommendations, and integration with other food-related applications or platforms. By offering a comprehensive solution, MeatVisor can attract and retain both B2B and B2C customers. Additionally, if the spectral range of MeatVisor and HYGER can be expanded, the quality assessment of the food can be improved.

Geographical Expansion: Explore opportunities to expand MeatVisor's presence into new geographical regions. By targeting diverse markets, both domestically and internationally, MeatVisor can tap into different customer segments and capture a broader customer base. This expansion will require adapting the solution to meet regional requirements and establishing partnerships with local stakeholders.

Reflection of learning

Harnessing High-Tech Solutions: The MeatVisor project has demonstrated the power of leveraging high-tech solutions, such as image recognition algorithms and data analysis, to address critical challenges in the meat industry. This highlights the potential of advanced technologies to improve operational efficiency, food safety, and decision-making processes.

User-Centric Design: In this project have consistently prioritized a user-centric design approach, recognizing the significance of understanding the requirements and preferences of the target users. By gaining deep insights into the needs and preferences of supermarkets, butchers, and other B2B meat businesses, the students have acquired the knowledge necessary to develop MeatVisor as an intuitive and user-friendly solution that precisely caters to their specific demands.

Interdisciplinary Research: The MeatVisor project has fostered knowledge from students from various disciplines, such as technology, design, and business. This interdisciplinary approach has enriched the project by combining diverse expertise and perspectives, leading to innovative solutions and comprehensive insights into the challenges faced by the food industry.