Technology for Social Innovation

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# H-ARGUS

## HYGER for Direct In-field Pest Monitoring

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# Abstract

In this work we are presenting H-ARGUS, a revolutionary network of optic devices that, with the use of the HYGER sensor, are able to perform direct in-field pest detection. This allows to monitor the population of insects in-real time, preventing pest infestations before any substantial damage can be done to the crops.

# 1 Introduction

Technology for Social Innovation (TeSI) is an Attract course that, combining students from 3 universities in Barcelona (Universitat Politècnica de Catalunya, Escola Superior d'Administració i Direcció d'Empreses and Institut Europeu de Disseny), applies the Design Thinking Methodology to give response to problems of today's world. In this case, the challenge was technology based, meaning that teams of students were given a technology, and their aim was to find a non-obvious application that solves a social problem with exponential impact. In the case of this team, the technology given was HYGER.

# 2 The Technology: HYGER

The HYGER photosensor, a groundbreaking technology created through collaboration between Aalto University in Finland, Baltic Scientific Instruments in Latvia, and Umicore in Belgium, represents a significant advancement in the field of optoelectronic devices. Built on top of a passivized germanium surface, HYGER functions as a component engineered to translate light into electrical signals with unprecedented efficiency in the **Near-Infrared (NIR)** spectrum of light (300–1700 nm).

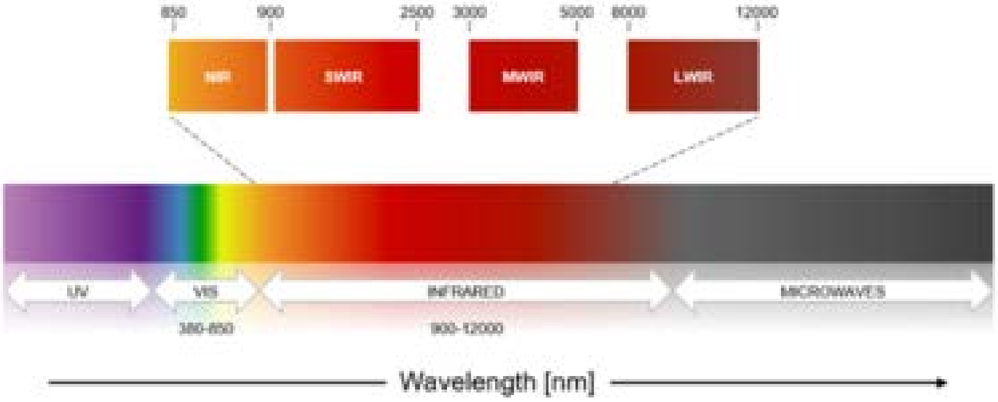
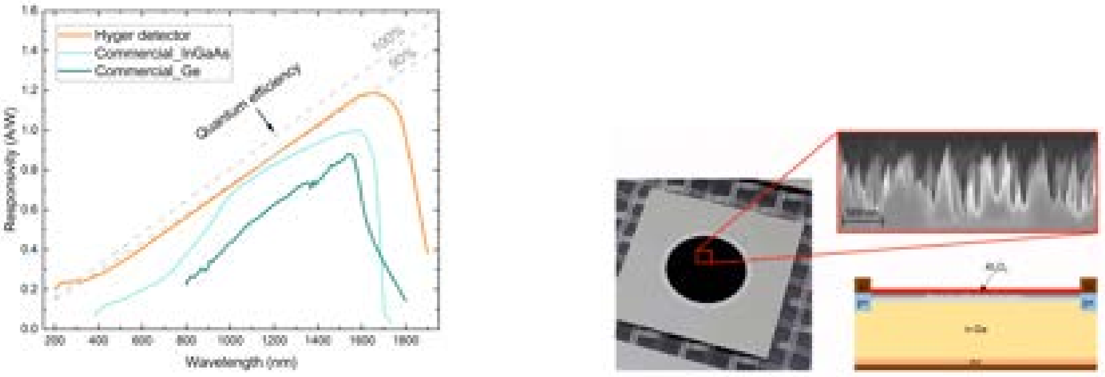


Figure 1: Electromagnetic light spectrum

Initially developed for scientific research purposes, HYGER was primarily focused on comparing different photosensors without specific applications in mind. However, Aalto researcher Fung John later took the initiative to explore potential practical uses and assess its performance relative to other technologies. The aim was to pinpoint potential application areas, establish a viable business model, and, ultimately broaden the impact of ongoing research efforts. HYGER's Technology Readiness Level (TRL) stands at 4, having undergone successful demonstrations in laboratory environments but awaiting real-world deployment.

In the market for infrared photodetectors, Indium Gallium Arsenide (InGaAs) material is widely used due to its extensive wavelength range spanning from 900



(a) HYGER performance in NIR range comparison

(b) HYGER germanium (Ge) passivation

Figure 2: Comparison of HYGER performance and germanium passivation

nm to 1700 nm, referred to as Short-Wavelength Infrared (SWIR). However, the adoption of InGaAs is hindered by its high cost and comparatively inferior performance compared to Germanium (Ge) photosensors. Substantive cost savings can be achieved by obtaining comparable performance to Ge photosensors. Notably, Ge-based sensors like HYGER can detect wavelengths up to 1700 nm, aligning with the scope of SWIR Vision's innovative detection technology, which covers wavelengths ranging from 400 nm to 2000 nm, similar to HYGER's target range.

In the construction of HYGER, Germanium serves as the active material within the tiles, responsible for detecting incoming light. An image captured by a Scanning Electron Microscope (SEM) reveals a nano-surface structure at high magnification, showcasing a finely textured surface. This nanostructure plays a vital role in boosting performance by significantly minimizing surface reflectance. While the original "minimsurface" displayed a surface reflectance of 40%, the incorporation of the "rectromenium" photodiode led to a remarkable reduction to less than 1%. This nanostructuring technique has proven highly effective in enhancing the overall performance of HYGER.

## 3 Application Fields

In the early stages of the process, the team underwent a deep investigation work in order to fully understand, not only the technology itself, but what made it perform better than the competition and how to take advantage of this. Moreover, it was imperative to gather insight on the phenomena that happen in the wavelength band in which HYGER is particularly efficient. After thorough research, we found out that in the Near-Infrared-Range band, covering from 300 to 1700nm, most applications were related to the fact that water absorbs a very high quantity of light, which makes moist objects or surfaces easily contrasted with their environment.

The next stage was a brainstorming session in which we attempted to, having conducted the proper research on the different application fields, come up with a set of particular situations where value and impact could be drawn with a smart use of our sensor. Here are some of the preliminary ideas that were discussed during this work session:

- **Healthcare**: In recent times there has been improvements on multiple fields of medicine thanks to infrared light used in certain measurements and procedures to make them non-invasive for the body. Multiple examples of this can be found, and one that really caught our attention was using NIR technology to detect signs of aneurysm or rupture risk in blood vessels. Changes in NIR fluorescence can give insight on the state of vessel walls, with fairly non-invasive procedures.
- **Underwater leak detection**: Since the interaction of different substances with NIR light are often different, we though of using our sensor in a drone to detect leaks in underwater pipe networks like oil or gas. The limitations in the current approach on dealing with leaks underwater are that there is no reliable mechanism to exactly locate the leak in the pipework, moreover, once it is located, the repairs have to be made manually, which can be extremely dangerous. Hence, the idea was to automate this process, making it safer and more efficient for workers. The main problem with the solution was that the amount of NIR light that reaches the depth of the ocean where the pipe systems are located is very restricted, as water absorbs most of it. However, we found that some similar applications use a compressed air gun to make the measurements.
- **Automotive**: Current computer vision systems installed in certain cars use cameras on the visual spectrum, which is a major limitation in reduced visibility conditions. To help overcome those limitation, a NIR camera could be used to improve the process and detect the road and cars in the environment in the fog or heavy rain. Apart from the dubious viability of this, the idea didn't solve a problem in a new way, but gave a partial improvement to an partially solved problem.
- **Safety**: Similar infrared technology is currently being used to determine the state of structures, especially wood and concrete, which are commonly affected by humidity and moisture. This could also be applied to rescue situations in building which are impacted by a fire or on the edge of collapsing. Although HYGER could be used, its implementation would once again be a partial improvement to a partially solved problem. The team focused on ideas that would have a greater social impact with fewer current attempted solutions, hoping to solve the problem.

Out of all the possible ideas that were disregarded in the process, we delved deeper into two of them because we considered them to have greater potential. On one hand, these uses demanded a far smarter and more elegant approach from the technology, in ways the researchers did not originally intend. On the other hand, the potential impact of their implementations was far more substantial, representing a breakthrough in the current state-of-the-art.

## 3.1 Microplastic Detection in Bottled Water

Microplastics, minute plastic particles less than 5 mm in size, have emerged as a significant environmental and public health concern. These tiny pollutants, stemming from the degradation of larger plastic debris and synthetic fibers, infiltrate various ecosystems and ultimately, the human water supply. Recent studies have detected microplastics in sources ranging from rivers and lakes to treated tap water and bottled water, highlighting the pervasive nature of plastic contamination. As these particles make their way into drinking water, questions about their potential impacts on human health and the environment intensify.

What this meant for us, is that there is a problem to be solved, so research in depth was undergone to gather insight on the current measures to tackle the issue, specially in drinking water. In the majority of the households there is either no intention to filter tap water or bottled water is consumed instead. In those where there is a concern for the quality of drinking water, the most widespread solution are reverse osmosis (RO) systems, where a RO membrane is the one in charge to filter pollutants. However, these systems were designed before microplastic were considered a problem, and do not perform any filtration of plastic particles of less than 1mm.

Our idea was to develop a device that, taking advantage of the high efficiency of the HYGER sensor, was able to detect those microplastics in any flow of drinking water. For that, we came across some techniques described in previous works that came across Microplastic Detection, two of those being RAMAN Spectroscopy and NIR Spectroscopy.

### 3.1.1 RAMAN and NIR Spectroscopy

RAMAN and NIR spectroscopy are effective methods for detecting and characterising materials based on their interaction with light. Both approaches analyse the vibrational modes of molecules in a sample, yielding a fingerprint that may be used to determine its composition.

- **RAMAN spectroscopy**: When light interacts with a molecule, it may scatter inelastically. RAMAN spectroscopy detects the tiny energy shift of scattered light, revealing information on the vibrational modes of the molecules in the sample.
- **NIR spectroscopy**: NIR spectroscopy analyses light in the near-infrared band (780 nm to 2500 nm). Molecules in this area absorb light owing to overtone and combination vibrations. NIR spectroscopy can detect functional groups in a material by analysing its absorption spectra.

Table 1: Comparison of RAMAN and NIR spectroscopy

| RAMAN spectroscopy | | NIR spectroscopy | |
|---|---|---|---|
| **Advantages** | **Limitations** | **Advantages** | **Limitations** |
| High chemical specificity enables the identification of various polymer types utilised in microplastics (e.g., polyethylene, polypropylene). | It requires direct contact with the microplastic particle, which limits its usefulness for analysing bulk water samples. Additionally, fluorescence from organic debris in water might interfere with the Raman signal. | Might analyse bigger sample volumes than Raman spectroscopy. It may be utilised for non-destructive testing via the packaging. | Chemical specificity is decreased when compared to Raman spectroscopy. It might be difficult to distinguish between various forms of microplastics and organic debris in the water. |

While Raman and NIR spectroscopy have limits for separate usage in bottled water analysis, HYGER's combination provides potential benefits:

By integrating NIR data with additional information from other sensors (e.g., fluorescence), HYGER may be able to differentiate microplastics from other NIR-absorbing compounds in water. HYGER's miniaturisation potential might lead to the development of portable NIR spectroscopy equipment for on-site microplastic detection in bottled water.

### 3.1.2 Interviews

For more information on the use of RAMAN spectroscopy, we consulted with some researchers. The interviewers suggested that it might not be the most suitable approach for our application. RAMAN spectroscopy is excellent at identifying materials based on their unique chemical fingerprint. However, it can be slower and require longer exposure times for weak signals. At this point in our investigation, we were thinking of detecting polymers in water. Fluorescence from organic debris in water can distort the tests by concealing the signal in microplastics.

NIR Light Spectroscopy is a possible option. It analyses the quantity of light absorbed by the material rather than the precise wavelengths returned, like RAMAN spectroscopy does. NIR may be more suited for determining the overall number of microplastics present without defining their kind.

## 3.2 Agriculture

The HYGER photosensor's ability to detect light in the near-infrared (NIR) band has enormous promise for a variety of agricultural applications. NIR light interacts with plant tissues and soil, and analysing the reflected or absorbed light provides significant information about crop health, soil composition, and water requirements.

- **Monitoring Crop Health:** HYGER may be incorporated into sensors that measure NIR reflectance in plant leaves. Various plant components absorb certain NIR wavelengths. By analysing absorption patterns, it can detect problems such as water stress, nutritional shortages, and even early indicators of illness. Early discovery of these issues enables farmers to take prompt corrective action, hence boosting crop yields and overall farm management.
- **Precision Irrigation:** A lack of water is becoming a major problem in agriculture. HYGER-based sensors can be used in irrigation systems to monitor soil moisture levels in real time. This information may be utilised for precision irrigation, which delivers water just to regions that need it, maximising water efficiency and minimising waste.
- **Soil Analysis:** NIR spectroscopy is a well-established method for determining soil characteristics. The HYGER's capacity to detect NIR light may be used to determine soil moisture content, organic matter composition, and nutrient levels. This information is critical for designing targeted fertiliser application techniques, enhancing soil health, and supporting environmentally friendly agriculture practices.

While potential uses of HYGER in agriculture appear promising, more study is required. This involves conducting field trials to evaluate the sensor's performance in real-world agricultural settings, creating rigorous calibration models to ensure correct data interpretation, and integrating HYGER into current farm management systems. However, one could get more creative on an specific application in this particular field. It has been discussed to use it to monitor crop health, but it doesn't seem an obvious application to use the sensor as a camera to directly detect what causes health problems in crops. The following sections will explore the possibility of using HYGER as a device to perform Direct In-Field Pest Detection.

# 4 Direct In-Field Pest Detection

One of the main impediments for agrarian production world-wide is pest infestation, whether it is in the form of insects, fungi or others. It is estimated that from 20 to 40% of the global production is lost to pests worldwide, which it can be mainly attributed to the current techniques used in agriculture to deal with this situation (Gula, 2023). State-of-the art procedures include rely on specialists or even farmers to visually appreciate damage in the crops or the use of some specific kind of traps. This is what we call **Indirect In-Field Pest Detection**, and here are some of the most common techniques used in today's agricultural production:

- **Visual Inspection**: Regularly inspecting the crops for damage, droppings or the insects themselves, which can be extremely difficult in most cases for the human eye.
- **Sticky Traps**: Tiny cases with some kind of sugary solution to attract insects and catch them. The impact is limited, since they are only able to catch so many.

- **Pheromone Traps**: This is a more sophisticated version of the previous technique, in which instead of having a solution to attract insects, certain types of pheromones are placed in the traps. Even though the results tend to be better, the limitations are similar, and they only work with certain species.
- **Remote Sensing**: In recent years there has been a lot of effort in automating and optimizing visual inspection of the plants. Some projects rely on mounting hyperspectral cameras (normally in the NIR spectrum, since ill plants tend to display particular patterns of NIR fluorescence) on drones, to gather insight on the health state of plants in a more fast and efficient way.

What all this approaches have in common is that they are forced to wait until signs of deterioration in the crops before any treatment can be applied. This not only causes farmers to loose far greater amounts of their overall production, but also forces them to take more violent action, with widespread pesticide treatments that end up worsening the quality of the food and polluting the soil and water sources.

## 4.1 Previous works

As an alternative, we explored what is referred as **Direct In-Field Pest Detection**. With this we describe those techniques whose aim is to identify and monitor insect populations in living plants, as opposed to what we described previously, which attempted to infer the state of those populations by indirect means. These techniques are far more complex, technologically demanding, but represent a breakthrough in the current state in pest control in agricultural production, since they allow earlier and more punctual action.

Although it had been previously attempted with multiple other resources, we are interested in the research conducted by Nils Hoffmann, Thomas Schröder, Friedrich Schlüter and Peter Meinlschmidt in 2013, when they published a work on the potential of Thermal Imaging to detect insects in young trees (Hoffmann, et. al. 2013). Thermal Imaging is a an optical technique that uses the different reflectance and absorption patterns in the Infrared Spetrum to infer differences in objects temperature. Specifically, they conducted their research on a particular species of beetle, the Citrus Longhorned Beetle, present in young tree imports in Europe. Infected items with this beetle did not show any signs of illness, which made it particularly demanding of non-invasive Direct Pest Detection solutions.

Two infrared cameras were used (a VarioCAM® hr research 600, (Jenoptik, Germany) and a ThermaCAMTM B20 (FLIR Systems GmbH, Germany)), and the aim was to, by detecting small changes in temperature through the tree, locate the insects and their larvae inside it. Unfortunatelly, the results were not satisfactory, since the study concluded that there were not significant enough temperature differences to know where the insects were placed. However, it was clearly stated that there was potential for thermal imaging to be a viable solution for Direct Pest Detection, and that the technological constraints of that time were the main limitation for the study.


(a) Electromagnetic Spetrum

(b) Thermal Imaging in Penn State study

Figure 3: Thermal Imaging

Later in 2015, further advancements in Thermal Imaging for Direct Pest Detection were made at Penn State University, who used it to determine insects coexistence patterns on wheat plants. For that they used the FLIR T650sc, and they measured the temperature gradients throughout the length of a whole wheat stem, which amounted to ±1.5°C in some cases, as we seen in Fig. 3b. The work was carried out successfully, which gave them insight on insect population patterns on a wheat plant. Nevertheless, it is worth mentioning that the research was not conducted in-field, but in a determined environment with controlled light, temperature and humidity. Overall, even though this is not exactly what is attempted in our project, this proves that the current infrared technology for imaging is reliable for detecting insects in living plants.

## 4.2 NIR Imaging

In the previous section, Thermal Imaging was mentioned as a mainstream method for Direct In-Field Pest Detection. Nevertheless, HYGER as currently conceived is not suitable for the particular use case of thermal imaging. As it is shown in Fig. 3a, the wavelength in which thermal cameras operate goes from 3000nm to 1mm (Thermal IR). Unfortunately, HYGER is a NIR and SWIR sensor, which is particularly effective from 900 to 1700nm as stated in the corresponding section. This is due to the fact that HYGER sensors use a different material, Germanium (Ge), that is responsive to light emitted in this spectrum.

The possibility of altering this approach is argued in other works. Ultimately, the key aspect of the HYGER sensor is not about the material of the surface, but the treatment of the surface itself with the previously mentioned technique called passivation. Through the use of this technique, the surface can retain almost all incoming light which is what allows the sensor to have its groundbreaking efficiency in the NIR range. Hence, it seems reasonable to think that similar treatments could be applied to surfaces made of Mercury Cadmium Telluride (HgCdTe) or Lead Sulfide (PbS), which are more suitable for this particular task. Although intriguing and worthy of consideration, this approach is not going to be further entertained in this work. Instead of altering the materials used, a new method was found within the constriants of the current construction, instead considering the use of HYGER to perform NIR Imaging.

Near-Infrared Imaging combines an optical device (for instance, a lens which is usually equiped with a filter that blocks all light spectres except the NIR) together with a Near-Infrared sensor (like HYGER) to create an array of values which is then reconstructed by a processor into an observable image. In Fig. 4 we can see the basic layout of what an standard example of this process would look like.

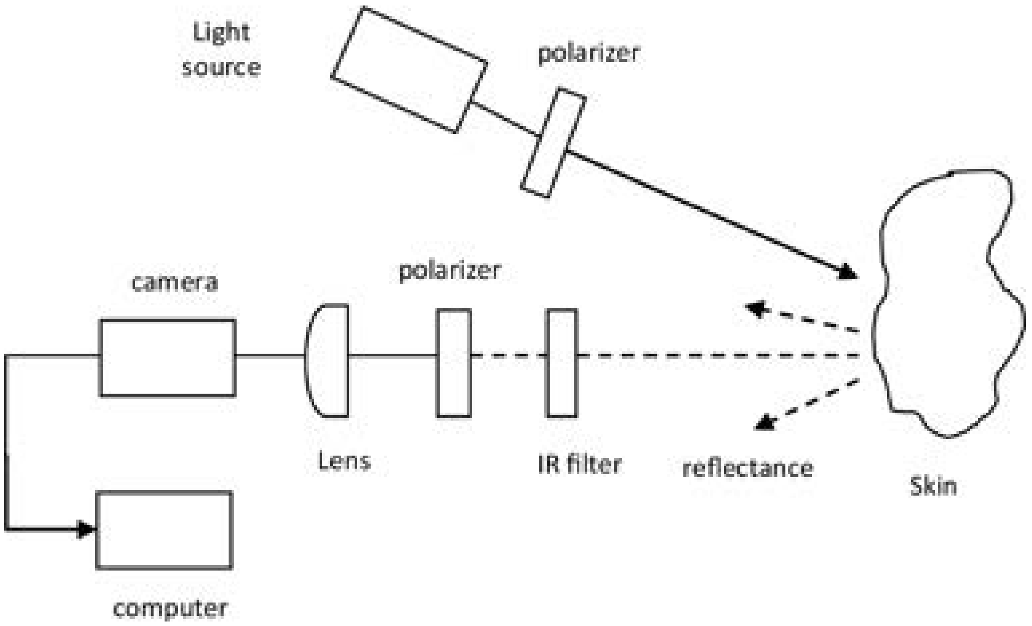


Figure 4: Diagram of a NIR Imaging process for skin cancer detection

The particularity in NIR Imaging is that, even thought it is the closest to the visible light, it represents an electromagnetic spectrum to which the human eye does not have access. This allows NIR images to show features in objects that otherwise can go unadvised. The clearest example is that in NIR images can see through the fog and haze, as well as to facilitate night-vision. Other examples are particular to some specific fields, for instances it can allow to evaluate the moisture content in food, or see through the skin, giving visibility of some particular tissues. In Fig. 5 we can see a comparison of an image taken in the RGB (Red-Green-Blue i.e. visible light) spectrum, and one taken in the NIR band. The differences are clearly identifiable, and it can be appreciated that there is no color in this images. For us, this will not be a limitation.

In our case, we are going to take advantage of the different reflectance properties of insects and plants, in order to identify them in images taken in the NIR spectrum, which is a task that cannot be done in the visible light spectrum, and is particular to the technology we are given. In the following sections we are going to give specifics on the differences of the interactions of plants and particular species of insects that are of interest for this work.

Figure 5: Comparison between RGB Imaging (right) and NIR Imaging (left)

## 4.3 NIR Insect Interaction

In order to use NIR sensors, an infrared flash must be emitted. Near-infrared light, interacts with insects in a variety of ways. While insects are not fully oblivious to NIR, their visual awareness is predominantly focused on the visible light spectrum (400 nm to 780 nm), which is essential for tasks such as navigation and feeding. However, NIR light can alter insect behaviour and physiology via a variety of processes. Ultimately, the brief flash being performed at sparse intervals is assumed to have no impact on insect behavior while being able to detect their location.

- **Thermoregulation:** Insects are cold-blooded organisms that rely on external influences to maintain their body temperature. Some insect species, especially those active during colder months, have photoreceptors that are sensitive to NIR light. They can raise their body temperature more efficiently by absorbing NIR light, allowing for more activity in low-light conditions.

- **Camouflage and Communication:** Some insects can detect NIR light, whereas others may use its qualities to disguise. Certain insect species have developed dark-colored body parts or surface features to reduce NIR reflection, perhaps making them less detectable to predators with some NIR vision. In contrast, certain insects may use NIR reflectance for communication, using specialised body markings or patterns that reflect NIR light to indicate to other insects.

- **Uncertain Role in Navigation:** The role of NIR in insect navigation is a fascinating issue with little proof. While visible light cues are clearly important for insect navigation, some studies show that a few species may use NIR light as a secondary source of information, especially when visible light signals are absent owing to rain or dense vegetation.

- **Potential Defence Mechanism:** In an interesting twist, some research show that insects may be able to detect and respond to NIR radiation released by herbivore-attacked plants. This NIR signal might possibly serve as a warning to insects, allowing them to avoid regions with damaged plants or defend themselves against possible predators.

Expanding on that, we searched the most common pests in the most common crops in Spain, to have specific insight on how those insects interact with NIR light. In Fig. 6 we can see what are the most common infestations grouped by the most common plant types.

| Food Plant Type | | Common Pests | Reference |
|---|---|---|---|
| Vegetables | Tomato, pepper, eggplant | Whitefly, Tuta absoluta (tomato leaf miner), aphids, slugs, snails | Ministerio de Agricultura, Pesca y Alimentación (MAPA): Spanish, but informative on pests: https://www.mapa.gob.es/es/ |
| Fruits | Olive, citrus (orange, lemon), grape | Olive fly, Xylella fastidiosa bacteria (olive quick decline), mealybugs, scale insects, codling moth | Ministerio de Agricultura, Pesca y Alimentación (MAPA): Spanish, but informative on pests: https://www.mapa.gob.es/es/ |
| Grains | Wheat, barley | Grasshoppers, aphids, Sunn pest (Eurygaster integriceps) | Instituto de Ciencias Ambientales y Tecnologías Agrícolas (ICTA-CSIC): Spanish, but informative on pests: https://www.agroes.es/cultivos-agricultura/cultivos-herbaceos-extensivos/trigo/1261-plagas-de-cereales-descripcion-danos-y-control-integrado |
| Nuts | Almond | Weevils, aphids, borers | Instituto de Biología Vegetal y Ecología (IBVE): Spanish, but informative on beneficial wasp: https://www.biomedcentral.com/about/institutional-support/membership/1600020867 |
| Legumes | Chickpea, lentil | Aphids, weevils | Ministerio de Agricultura, Pesca y Alimentación (MAPA): Spanish, but informative on pests: https://www.mapa.gob.es/es/ |

Figure 6: Most common pests in Spain

Now we want to focus on a specific crop and pest, so to set an example it could be considered the most common crop, wheat, and its most common pest, the aphid. Aphids are small insects from the family of the Aphpoideas, whose life cycle is spent in two host plants: one an annual crop and one in a woody plant. They are one of the most destructive pests since, not only do they suck sap out of the plants, they also bring in viruses. Detection of those is really difficult due to its small size. However, they absorb a lot of Near Infrared light, far more than a plant, which makes them very easily identifiable in an NIR image. In Fig. 7 we can see that while the common wheat leaf reflects over 40% of NIR light (in the range of 750 to 1500nm), the grain aphid only reflects over 10%.

## 4.4 Survival-Analysis Models

Once we detect the number insects in the surrounding of a certain location of the field, we need tools to estimate the overall population. For that we describe to approaches: Survival probabilistic models and Machine Learning algorithms.

Classical survival-analysis models have been used for more than 50 years to estimate the duration of such as death in biological systems or failure in mechanical systems. In our case, we can use them to estimate the population of insects at a time $t_n$ given the population (or an estimation) at a time $t_0$. Usually, given a survival or failure time $T$, three functions are used to describe its behavior:

- **The survivor function**: Probability that $T$ (the time that the population is

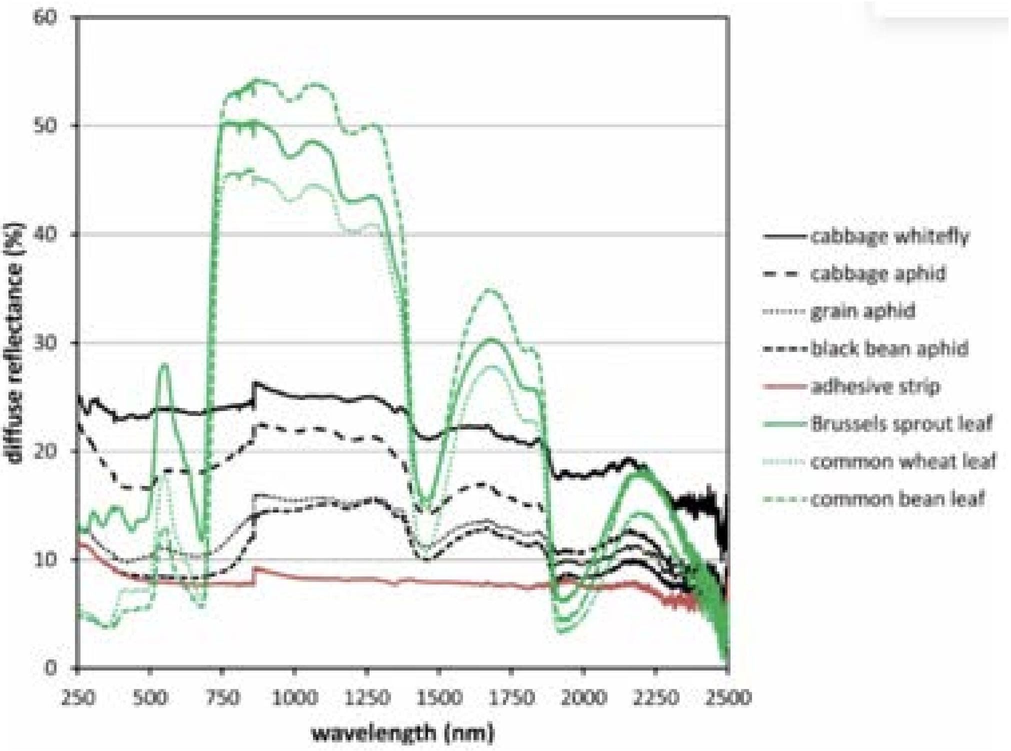


Figure 7: Mean reflectance of multiple leafs and insects

active) is at least a certain value $t$.

$$S(t) = P(T \geq t).$$

- **The probability density function**: In this case corresponds to the distribution of T over time.

$$f(t) = -\frac{dS(t)}{dt}.$$

- **The hazard function**: This describes the instantaneous rate of failure at $T = t$, which is the probability that a system fails at time $t$.

$$\lambda(t) = \frac{f(t)}{S(t)}.$$

Later on, Cox expanded this models with what is called **Proportional Hazards Models (PHM)**, which also take into account a vector of characteristics, such as humidity or temperature. Overall, what this models achieve is an estimation of when a certain event takes place in a certain system. What is of interest for the work is that they can be used, for instance, to determine the time where a population of insects surpass a certain threshold where is dangerous for the field.

Apart from probabilistic models, other approaches could be implemented, probably with a higher accuracy rate, would be Machine Learning algorithms. These kinds of models make use of certain features to predict the outcome of a certain variable.

In our case, it is clear that the variable to predict is the population of insects of the whole field $P$. As features, we would have the number of insects in certain places of the field $P_i$ for $i \in \{1, ..., N\}$ , those same locations $L_i$ for $i \in \{1, ..., N\}$, temperature $T$, humidity $H$... A simplified version of model could look something like this.

$$N = \alpha_1 P_1 + ... + \alpha_N P_N + \beta_1 L_1 + ...\beta_N L_N + \gamma T + \delta H$$

.

where $\alpha_i$, $\beta_i$, $\gamma$ and $\delta$ are the parameters that are estimated by the model in order to predict $N$.

As it is known, any Machine Learning algorithm requires two sets of data to function, a train set, with which the model is trained and the parameters are estimated, and a test set, used to test the performance of the model. In this case some trials would need to be made to gather data to train and test the model, and, once the model performs as desired, it could be deployed. Recent studies have obtained promising results using **Convolutional Neural Networks** (Querriel Arvy Mendoza), a particular example of the models described previously, to classify and monitor insect populations in stored grain pests. The Machine Learning approach is regarded to be the most appropriated one for our work.

## 4.5 Interviews

In order to get some feedback on our solution and, ultimately, validation, we interviewed an expert with more than 30 years of experience in pest control in worldwide agriculture. She is Ester Abad i Cantero, the Technical Manager of the Agro Department in Comercial Quimica Massó, a catalan chemical company which distributes phytosanitary products across multiple countries in the world.

First think it was useful for us was to know from first hand which is the most common method of detection of pests in-field. Ester pointed out that *"With insect pests in particular, it can be extremely challenging, specially in large fields, since insects that infest crops are perfectly camouflaged with their environment. Farmers don't expect to see them directly"*, to which she added, *"In fruits for example, there are clear signs that there is an infestation in the fruits themselves"*, but as we expected, by that point a huge part of the production is already lost. Then we wanted to know what are the current approaches to deal with insect pests. *"There are specific products that are used as "preventive" treatments, but they are not 100% effective, normally if a farmer sees signs of an infestation, pesticide treatments are applied"*. This describes that current effective solutions are purely reactive, since preventive action does not solve the problem.

Afterwards, we asked Ester for the use that could be given to a network of cameras that could give intelligence on the state of the population of insects, by estimating it knowing the state of determined locations in the field. She admitted that it had great potential, but questioned what the cost would be to give accurate enough estimations, in terms of how many sensors per field would be needed. This is a concern for us too, but we believe that cost of a single device should not be that high, and we expect that the benefit of not loosing up to 40% of the production, plus what is not wasted on pesticides will easily surpass the cost of the network. Furthermore, let it be noted that few devices could give good enough estimations, but, obviously, the more displayed the better the estimation.

Before finishing, we were curious if there were any ideal places on a field to put those sensors to maximize the accuracy of the estimations. To that, Ester responded: *"Obviously insects populations are not born inside the fields, they enter them, so practical places would be in the perimeter of the field. Also near water sources, where a lot of colonies of insects live"*. The interview was really helpful for our work, and we are highly appreciative of the valuable insight that Ester provided. After discussing about the conversation we had, we concluded that we had enough validation to thrust forward with our idea.

# 5 The H-ARGUS

Having conducted the proper research and consulted the pertinent experts on the domain, we present our solution for worldwide pest control. H-ARGUS is a network of optical devices that, performing what has been previously defined as Direct In-Field Pest Detection, allow the real-time monitoring of the population of insects in any given field.

## 5.1 Single device

A single device is in its simplest form, a 360 near-infrared camera, composed by two 180 degree lenses, an adapted version of the HYGER sensor, a NIR flash and a digital processor. The lenses contain a filter that blocks all electromagnetic wavelengths except the NIR spectrum to reduce noise in the images, and are specifically treated with an anti-dust, hydrophobic, scratch-resistant coating, to adapt the device to changing out-door conditions. The process that is undergone by the device is what has been described as NIR Imaging, so the schema of the process is similar to the one in Fig. 4, with the particularity that instead of skin, the targeted objects are the crops in the surroundings and the insects living in them.

In Fig. 8 we can see a representation of the stages in which the device works. The device is rooted into the soil in the middle of the field, surrounded by the crops, and when the light levels are low, at night, the NIR flash pops, illuminating the surroundings and then the camera takes a snapshot, and image. It is crucial than the images are taken at night, for various reasons. Firstly, because this way we ensure that the minimum noise is perceived by the camera, that only is going to capture the NIR light emitted by the flash, reflected in the surrounding objects. Additionally at night crops cool down but insects do not, which makes the difference in NIR reflectance a little higher and, finally, it is when the insects stay more still, which makes the overall task easier, with less overlap. Finally, the image is processed by the processor that, using a computer vision algorithm, can point out the insects in

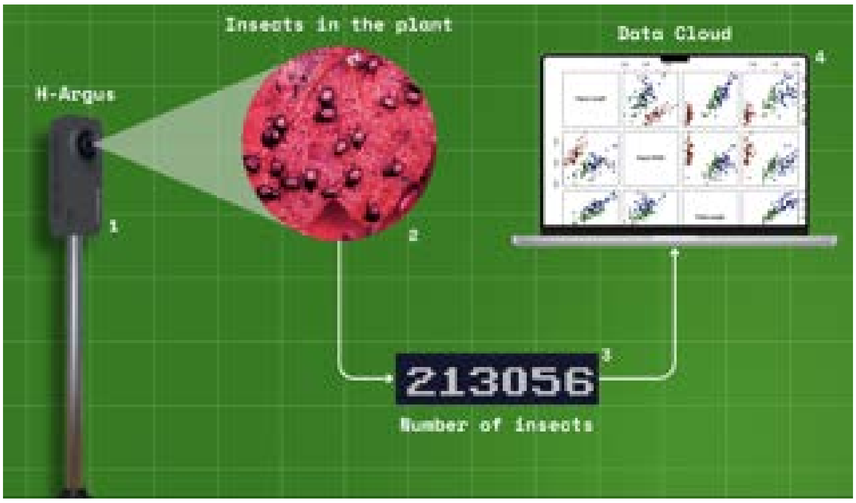


Figure 8: Use case of a single H-ARGUS device

the image and compute a count.

For different crops the are different insects that populate and infest them, and those have different patterns of behavior. For instance, for aphids that usually place themselves in the bottom side of wheat leafs, whilst weevils live outside fruits. Not only that, but also the device has to be functional in all growing stages of all crops, so the height of the camera has to be variable. That's why H-ARGUS features an extensible base stick, which adapts the height to each particular situation and makes the solution generalized to all crops.

## 5.2 Standard layout

The standard layout for H-ARGUS in a real use-case is a network of devices distributed all around the field in specific strategic spots, such as areas next to water sources like rivers or ponds as well as in the exterior part of the field as the expert suggested in the interview. In Fig. 9 we can see a visual abstraction of the described use case. The devices would function synchronously but independently. It is essential that all sensors take the snapshots at the same time, since there could be migrations of insects from one location to another in the field, and the counts could overlap, consequently making the model work faulty information. However, fault tolerance of the system is also vital, in a way that if one device fails the whole network does not fall of and it is still functional.

Hence, given that the computational cost of processing the images is not elevated, we conceived the devices so that the images are processed individually by each sensor, and the only think that is uploaded to the central data cloud is the individual count of insects. That also facilitates data transference a significant amount, and allows us to rely on simple widespread data distribution technologies such as Bluetooth, with no need to be connected to an internet network, which in remote locations can be a limitation.

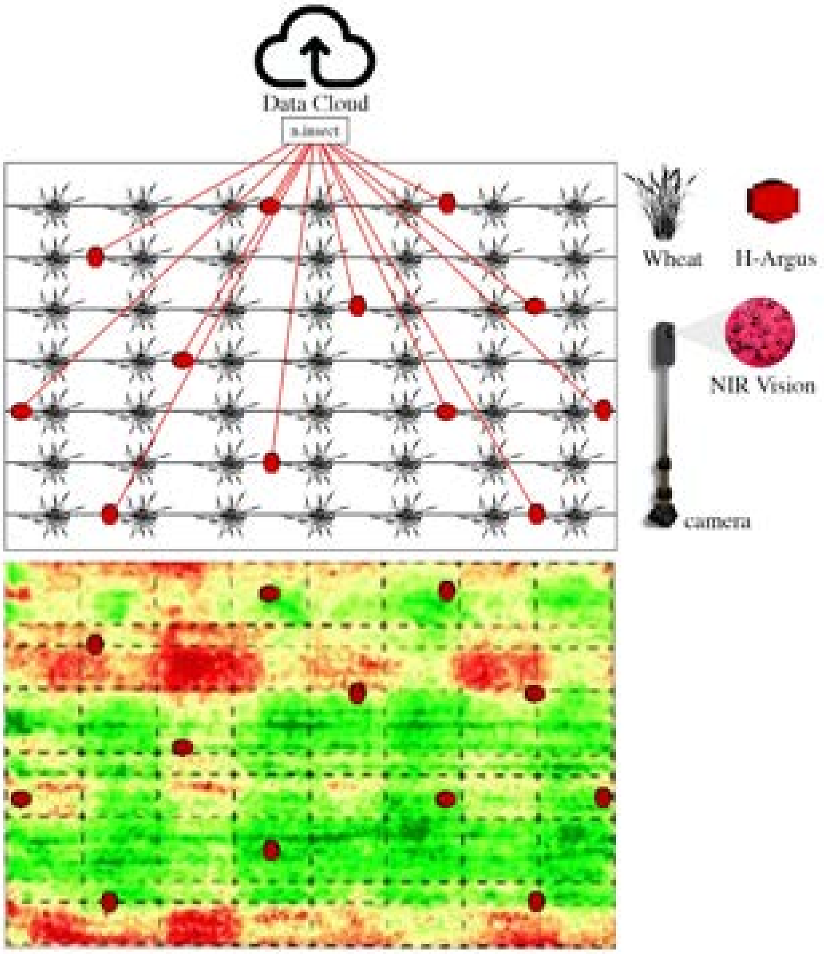


Figure 9: Use case of a full deployment of H-ARGUS

In the final stage, the data cloud is the one that coordinates all the network, with information on the time or light levels to give to the sensor the cue to take the snapshots, gathers all the data and, knowing the relative and absolute positions in the field (which are inputs for the Machine Learning model as well) as well as other features, and runs the model similar to the one described in section 4.4. Finally, it sends a notification to the farmer when the population of insects in the field reaches a dangerous threshold, and precisely indicates the location in which the treatment has to be done.

## 5.3 Brand Identity

The name “Argus” is derived from Argus Panoptes, a giant in Greek mythology known for having a hundred eyes, symbolizing unparalleled vigilance and comprehensive monitoring capabilities. The ”H” stands for ”Hyger,” emphasizing the project’s advanced and enhanced technological prowess. H-Argus employs sophisticated infrared technology, which is represented through the strategic use of green and red colors in its graphics. These colors symbolize the imaging spectrum, highlighting

Figure 10: Mockup Brand Identity

the project's ability to detect and monitor environmental changes and threats with high precision.

In creating a distinctive identity for H-Argus, the logo features the image of a dangerous insect for the wheat. This choice underscores the project's focus on precision, alertness, and the ability to swiftly respond to threats, much like the insect it represents. The logo's font is Panchang, designed by the Indian Type Foundry. This typeface, which includes seven styles, has been specially modified for H-Argus. Key modifications include adjustments to the "G" and "a" sections, improving readability, and making the overall design more user-friendly while maintaining its distinctive appearance.

Title: TT Travels Next Trial Variable Bold, Paragraph: Konstant Grotesk Book, Subtitle: TT Travels Next Trial Variable Regular, Note: Agrandir Narrow This careful selection of fonts and design elements ensures that all communication materials for H-Argus are clear, professional, and visually appealing. The title font, TT Travels Next Trial Variable Bold, provides a strong and commanding presence, perfect for capturing attention and conveying the importance of the project. The paragraph text, set in Konstant Grotesk Book, offers a clean and readable format for detailed information. Subtitles use TT Travels Next Trial Variable Regular, balancing the boldness of the title with a more understated yet still prominent style. For annotations and notions, Agrandir Narrow is used, offering a sleek and modern look that complements the overall aesthetic. H-Argus stands as a testament to the fusion of modern technology, bringing together timeless vigilance and contemporary innovation. Through its well-thought-out design and advanced capabilities, H-Argus is poised to become a leader in the field of infrared monitoring and detection.

## 5.4 User Journey

The user, a wheat farmer, recognizes the need to reduce pesticide usage to save money and increase wheat production. This drives him to seek out more sustainable farming practices. One day, while reading an article in National Geographic about sustainable farming techniques, he learns about biological pest control methods. Intrigued and inspired, he commits to adopting these methods. He begins by attending a local farming workshop to gain more knowledge and practical insights.

After the workshop, the farmer evaluates several biological pest control products. He meticulously compares their effectiveness, cost, and environmental impact, looking for the best solution for his farm. Ultimately, he decides to implement the H-Argus system. He carefully follows the provided instructions and monitors his wheat fields closely, ensuring he adheres to best practices.

As he uses H-Argus, he documents the changes in pest levels and wheat health, taking detailed photos to track progress. Over time, he observes a significant decrease in pest damage and a notable increase in wheat yield. Additionally, he calculates a substantial reduction in his spending on chemical pesticides, which further validates his decision. Impressed with the results, the farmer shares his success story at a local farming cooperative, encouraging other farmers to consider sustainable pest control methods. With his immediate needs met, he identifies a new need: to improve his overall farming efficiency. Motivated by his positive experience with H-Argus, he considers investing in more advanced farming technology to further enhance his productivity and sustainability.

## 5.5 Market Analysis

The use of Smart Technology within the farming industry is growing, but with many technologies requiring high levels of financial investment with the hopes of all encompassing sensors being able to solve a large range of issues they are facing. Unfortunately these technologies continue to focus on general maintenance strategies with minimal focus on more granular, highly accurate information on the health of plants. An example of this is a large IoT farming company in the US, BizIntellia, where their technologies monitor more general processes such as humidity, temperature, and moisture (IoT Sensors). The cost of these long range, highly powerful sensor units are also much more cost prohibitive. With willingness to buy such devices, an array of sensors to monitor insect infestation is an additional investment farmers would be willing to have.

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[3] Estimate Cost of H-ARGUS Sources: (Leroy Merlin, n.d.; Alibaba, n.d.; AliExpress, n.d.; The Pi Hut, n.d.; BricoGeek, n.d.)

| Product per unit Cost | |
|---|---|
| Item | Cost |
| 3D printed casing | 2 |
| Plastic pole | 1.09 |
| Processor | 3 |
| 5000 mAh battery | 4.8 |
| 360 1.4 mm lens + camera[3] | 20.86 |
| 3IR Light | 2.92 |
| Transmitter | 4.95 |
| **TOTAL** | 39.62 |
| Estimated Sale Price: | 65 |

Table 2: Estimated Cost of H-ARGUS

To create an estimate of the price for our product, market thresholds and estimates from prototype creations were utilized. The prices for major technological components was overestimated to create a more conservative expectation on how cheaply the device could be produced. The major component to find an estimation of is the camera and lens. In order to find a proper NIR camera to understand estimated cost, a thermal camera that can understand the desired level input was used as a basis, with the maximum resolution being 1.2 mp (Tequipment, n.d). The NIR camera found had 5mp resolution, making it far better than what is required while still being cost-effective (AliExpress). It must be acknowledged that these numbers are a general estimate and will be different when producing with desired manufacturers and at higher volume but can allow an initial understanding of what could be possible.

## 5.6 Impact

Through the use of H-ARGUS, the new HYGER-powered NIR sensors can make pest-detection in agriculture a smarter and more efficient practice. This is done so by allowing farmers to measure specific metrics to optimize the use of pesticides in their fields. Traditionally, pest management relied on the widespread application of insecticides, often through the practice of crop-dusting where farmers spray all of their plants via plane with these chemicals. This can be extremely costly and environmentally harmful, impacting the water supply, killing organisms and harming the health of many people (U.S. EPA). By using the high-resolution NIR data from H-ARGUS, farmers can pinpoint specific areas likely to be infested and apply insecticides only where needed, allowing for the use of chemicals to be optimized and minimizing their environmental impact. These sensors will make the use of insecticides to decrease as integrating remote sensing data with crop models enhances decision-making processes, allowing for more accurate predictions of pest impact on crop health and yield (Khanal et al., 2020). Not only will this integration improve overall efficiency pesticide use, but also help support more sustainable agricultural practices and overall crop health (Khanal et al., 2020).

| Camera Savings with 50% reduction in Insecticides: | |
|---|---|
| Variables (yearly) | Cost |
| Pesticides/acre | 120 |
| Insecticides/ acre | 40 |
| H-Argus/acre[4] | 6.5 |
| New Insecticides | 20 |
| Savings/Acre from less pesticides | 13.5 |
| Savings for Spain | 391.5 |
| Savings/acre with 1% more crops | 22 |
| Savings for Spain with 2% more crops | 1276 |
| **TOTAL SAVINGS** | 1667.5 |

Table 3: Calculated Savings of using H-ARGUS in Spain

Assuming the H-ARGUS is implemented with one unit every 10 acres, we expect this technology to have a large impact on the workflow of farmers and save them money in a variety of ways. By now using a more proactive and technologically savvy approach to pest control, crops can be sprayed with insecticides at just the right time and only in the necessary areas. This will allow fewer insecticides to be used by the farmers, offsetting much of the investment into H-ARGUS. It must be clarified that these estimates are only for the first year. With a life-cycle of many years, the savings resulting from the use of H-ARGUS will become even greater as the only costs will be maintenance and repair. Using estimates from the cost of insecticides and the amount of acres they were used on in a US study, these baseline values were created (Paulson, et. al., 2023). This alongside research, estimating the monetary impact of pests on crops currently allowed for a general expectation of how powerful the use of H-ARGUS could be (Gula, 2023). Spain was used as the case study, with 29 million acres having permanent crops, with the primary crops having pests tested to absorb NIR light at a rate for HYGER to differentiate the insect from the crop (Lloyd, n.d.). Through the use of this innovation, not only will there be monetary improvements for farmers, but many positive environmental externalities as well. By reducing the use of insecticides, there will be fewer chances of chemicals being present in the food we eat and in our water supply. With the chemicals often running off into the local watershed, various species living near agricultural areas can be positively impacted by this technology, as well as improving the quality of many water sources relied upon by humans. This shift supports more environmentally sustainable farming practices, resulting in healthier ecosystems and cleaner water sources.

## 5.7 Business Model Canvas

### Customer Segment

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[4] Calculated Savings of Using H-ARGUS in SPAIN Sources: (Cassou, 2022; Gula, 2023; Paulson, et. al., 2023; Lloyd, N, n.d.)

- Industrial farms hoping to improve bottom line
- Agricultural co-ops working to improve pest management and sustainability
- Environmental organizations working with farms to become more eco-friendly

**Value Proposition**

- Early detection for decreased loss of crops
- Allowing for more precise and cost-efficient use of insecticides

**Key Activities**

- Conducting extensive field trials
- Software development of ML algorithms for infestation risk
- Training and support for farmers with implementation of product

**Key Partnerships**

- Continued collaboration with Aalto University, Baltic Scientific Instruments, and Umicore for continuous R&D support
- Find support through advertising and funding via NGOs and sustainable government initiatives

**Revenue Streams**

- Direct sales by farms
- Possible subscription services for maintenance and software
- Sponsors hoping to decrease environmental impact of agriculture

**Cost Structure**

- Research and development of camera creation and software
- Manufacturing and design
- Marketing and distribution

# 6 Prototyping

In this prototype, we use computer vision algorithms to identify black spots (insects or other characteristics) on a leaf. The detection system is built with a Raspberry Pi and a camera module, making it ideal for low-cost, portable use in agriculture or biological research.

## 6.1 Devices and tools

- **Raspberry Pi**: is a flexible and economical single-board computer that is frequently used in DIY projects and educational contexts. It offers the processing capacity required to efficiently execute computer vision algorithms.

- **Camera Module 2**: Attached to the Raspberry Pi, this module takes high-resolution photos of the leaf for study.

- **Libcamera-still**: A command-line utility for capturing photos using the Raspberry Pi Camera Module.

- **OpenCV** is an open-source computer vision library that includes tools for image processing, object detection, and other vision-related activities.

The purpose of this image processing code sample using OpenCV is to extract useful information from grayscale photos, particularly when recognising characteristics like leaves. The procedure begins with picture capture via libcamera-still, in which the Raspberry Pi takes an image and stores it in a specific location. Initially, grayscale conversion decreases computing load and memory needs when compared to colour pictures while emphasising structural features such as texture and form. Gaussian blur is used to reduce high-frequency noise and smooth edges, allowing contour identification. Thresholding is then done inversely to produce a binary picture that distinguishes foreground and background. By separating extreme outside contours and compressing segments, the algorithm determines the biggest contour, which is usually the leaf. Using HSV colour space provides for the exact characterization of dark regions in the image, which is critical for later analysis. Morphological procedures help to fill gaps and eliminate noise, increasing the clarity of identified features. Finally, dark contours are recognised by filtering out tiny spots as noise and determining whether they coincide with the leaf contours.

## 6.2 Code

Here we give the Python code used in the prototype, which is interpreted by the RaspberryPi:

```python
import cv2
import numpy as np
import subprocess
import os

def capture_image():
    # Capture an image using libcamera-still
    subprocess.run(['libcamera-still', '-o', '/home/cbi4ai/Desktop/pi/leaf.jpg', '--timeout', '1'])
    return '/home/cbi4ai/Desktop/pi/leaf.jpg'

def count_spots(image_path):
    # Check if the image file exists
    if not os.path.isfile(image_path):
```

```
        print("Error: Image file not found.")
        return

    # Load the image
    image = cv2.imread(image_path)

    # Check if the image is loaded successfully
    if image is None:
        print("Error: Unable to load the image.")
        return

    # Reduce image resolution for faster processing (optional)
    image = cv2.resize(image, None, fx=0.2, fy=0.2, interpolation=cv2.INTER_AREA)

    # Convert to grayscale
    gray = cv2.cvtColor(image, cv2.COLOR_BGR2GRAY)

    # Apply Gaussian blur to reduce noise and improve contour detection
    blurred = cv2.GaussianBlur(gray, (11, 11), 0)

    # Apply thresholding to create a binary image
    _, leaf_thresh = cv2.threshold(blurred, 150, 255, cv2.THRESH_BINARY_INV)

    # Find contours for the leaf
    contours, _ = cv2.findContours(leaf_thresh, cv2.RETR_EXTERNAL, cv2.CHAIN_APPROX_SIMPLE)
 if not contours:
        print("Error: No contours found.")
        return

    # Find the largest contour, which should be the leaf
    largest_contour = max(contours, key=cv2.contourArea)

    # Draw the largest contour to delimit the leaf shape
    output = image.copy()
    cv2.drawContours(output, [largest_contour], -1, (255, 0, 0), 2)  # Draw in blue color for distinction

    # Define HSV range for dark spots
    hsv = cv2.cvtColor(image, cv2.COLOR_BGR2HSV)
    dark_lower = np.array([0, 0, 0])
    dark_upper = np.array([180, 255, 50])

    # Create a mask for dark spots
    dark_mask = cv2.inRange(hsv, dark_lower, dark_upper)

    # Apply morphological operations to remove noise and fill gaps in dark spots
    kernel = np.ones((5, 5), np.uint8)
    dark_mask = cv2.morphologyEx(dark_mask, cv2.MORPH_CLOSE, kernel)
    dark_mask = cv2.morphologyEx(dark_mask, cv2.MORPH_OPEN, kernel)

```

```python
    # Find contours on the dark spot mask
    dark_contours, _ = cv2.findContours(dark_mask, cv2.RETR_EXTERNAL, cv2.CHAIN_APPROX_SIMPLE)

    # Draw contours and count the dark spots inside the leaf
    count = 0
    for contour in dark_contours:
        # Ignore small contours that may be noise
        if cv2.contourArea(contour) > 50:
            # Check if any point of the contour is inside the leaf
            is_inside = any(cv2.pointPolygonTest(largest_contour, (int(point[0][0]), int(point[0][1])), False) >= 0 for point in contour)
            if is_inside:
                count += 1
                cv2.drawContours(output, [contour], -1, (0, 255, 0), 2)
# Add text indicating the number of spots detected
    text = f'Number of insects detected: {count}'
    cv2.putText(output, text, (10, 30), cv2.FONT_HERSHEY_SIMPLEX, 0.8, (0, 255, 0), 2)

    # Display the result
    cv2.imshow('Detected Insects', output)

    # Save the output image
    cv2.imwrite('/home/cbi4ai/Desktop/pi/leaf_with_spots.jpg', output)

    # Wait until a key is pressed and close the display window
    cv2.waitKey(0)
    cv2.destroyAllWindows()

if __name__ == "__main__":
    image_path = capture_image()
    if image_path:
        count_spots(image_path)
```

Listing 1: Python code

## 6.3 Basic Blueprint

The prototype development of the H-Argus system begins with creating a conceptual blueprint. This blueprint outlines the general positioning of all major components, ensuring an efficient layout for the infrared monitoring technology. Key elements such as sensor arrays, data processing units, and power sources are strategically positioned to optimize performance and ease of maintenance. The blueprint is a foundational guide, ensuring all components are cohesively integrated into the final design.

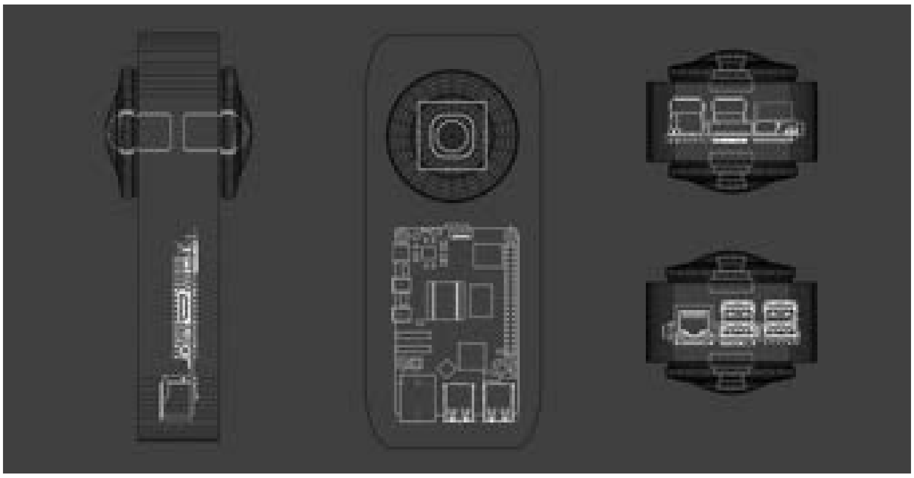

Figure 11: Inside Section

## 6.4 3D Modeling

Once the blueprint was ready, I moved on and started creating a 3D model using Blender. Starting with basic shapes, I gradually refined the design, paying close attention to dimensions and proportions to match the real-world requirements. After achieving the desired form, I created the UV map and unwrapped the model. This step was crucial for texturing and ensuring that all surfaces of the model were accurately represented, which would later aid in the detailed finishing touches.

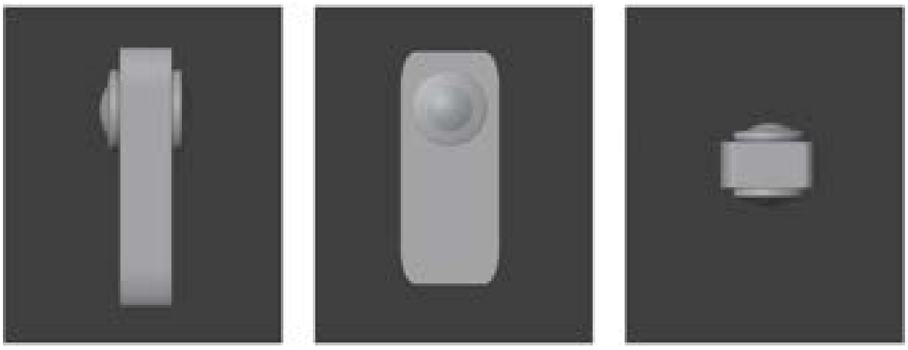

Figure 12: 3D basic model

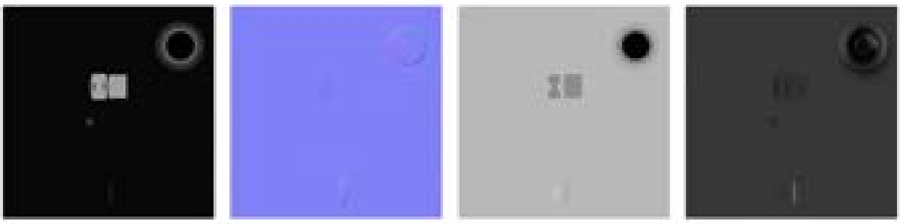

Figure 13: Uv texture

Figure 14: 3D Render

## 6.5 3D Printing

The final step was 3D printing the prototype. To ensure compatibility, I based the design on the dimensions of a 360-degree camera, specifically the Insta360. For the printing process, I chose PLA material due to its affordability, ease of use, and reliable performance. I set the layer height to 0.5 mm, which provided a good balance between detail and print speed. The 3D printing process went smoothly, and the resulting prototype was both functional and aesthetically pleasing, aligning perfectly with the initial blueprint and 3D model created in Blender.

Figure 15: 3d printing prototype

## 6.6 Prototype in the Environment

In our project, developing the prototype in a 3D environment was crucial, especially when considering the specific case study of wheat crops.

To begin, I scoured various online resources to download 3D assets of wheat plants. These assets were invaluable as they provided realistic representations of wheat at different stages of growth, allowing me to accurately depict the crop's appearance and behavior within the virtual environment. Additionally, I obtained HDRI images of wheat fields, capturing both day and night situations. These HDRI images served as the backdrop for the 3D environment, providing realistic lighting and ambiance that closely mirrored the conditions in which wheat crops thrive.

I placed the 3D models of fields of wheat in the virtual environment, ensuring that their positioning and arrangement accurately reflected real-world agricultural settings. The HDRI images were then integrated to provide dynamic lighting conditions, allowing for realistic rendering of the wheat crops under varying times of day and weather conditions. This immersive 3D environment not only facilitated the visualization of the prototype.

Figure 16: environment

Figure 17: render

## 6.7 Video Prototype

Creating three distinct videos was a significant part of our project, each serving a unique purpose in showcasing our prototype and promoting its capabilities. The first video, a concept rubamatic, was crafted to provide a clear and concise explanation of our prototype. Using a combination of animations, voiceovers, we highlighted the key features and functionalities of our prototype, making it easy for viewers to understand its purpose and potential impact in the agricultural sector.

For the second video, we opted for a graphic video with text motion, designed specifically to promote H-Argus, our advanced technology for agricultural monitoring. This video featured dynamic graphics and engaging animations, accompanied by compelling text overlays that emphasized the benefits of H-Argus.

The third video took a different approach, presenting our prototype within its intended environment through a captivating 360-degree video. Created using video stock of a wheat field, this immersive video allowed viewers to experience firsthand how our prototype operates in real-world conditions. With the ability to pan and rotate the camera view, viewers were able to explore the entire environment, gaining a deeper understanding of how our prototype integrates seamlessly into agricultural settings. This immersive experience not only demonstrated the effectiveness of our prototype but also served as a powerful marketing tool, showcasing its potential to revolutionize farming practices.

- Google Drive Video Folder`https://drive.google.com/drive/folders/1wGu90tbQV7bgE3ijRWlX70tkM7OGCuRU?usp=sharing`

# 7 Conclusion

The creation of H-ARGUS utilizing HYGER technology will create more smart and sustainable farming practices. Through the integration of this revolutionary sensor, a unique product in the farming industry can be created to comprehensively monitor farms of any size. This is a departure from traditional techniques in the farming industry that rely on visual inspections or indirect pest detection techniques, which are often inefficient and reactionary.

This product offers a proactive technique, giving farmers the ability to decrease their use of insecticides and the amount of crops they lose each year. Lowering the use of insecticides is extremely beneficial to the environment and the farmers but has been a necessary evil to maximize production. By creating opportunities to remove the necessity of such excessive use of insecticides, there will be large direct and indirect impacts to the farming industry.

This product is only successful due to the utilization of black germanium within HYGER sensors. This material's sensitivity in the NIR spectrum allows for a cheaper and more effective sensor to be created. These two factors make the product much easier for farms to adopt. With the ability to more accurately count the number of insects, better models can be created about if and when an infestation will occur. As a less expensive product than what competitors can make, while having better results. H-ARGUS can create a more sustainable, cost-effective, and efficient future for the farming industry.

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