ONE4ALL - Agile and modular cyber-physical technologies supported by data-driven digital tools to reinforce manufacturing resilience

Project nr: **101091877**

D4.2 report about the implementation of the real-time monitorisation system

Version: 1.0

Funded by the European Union

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Characteristics of deliverable	
Title	ONE4ALL
Partner	INNO
Contributors	IBT, IDE, KIT, TUDO, MOL, ORI
Short description of deliverable	Report about the implementation of the real-time monitorisation system
Submission date	30/06/24
Type	Report
Audience	Public
Key words	Sensors, RCPM, AI, machine learning, IIoT, imaging, machine vision

ONE4ALL Key Facts

Acronym	ONE4ALL
Project title	Agile and modular cyber-physical technologies supported by data-driven digital tools to reinforce manufacturing resilience
GA nº	101091877
Starting date	01/01/2023
Duration-months	48
Call (part) identifier	CLIMATE NEUTRAL, CIRCULAR AND DIGITISED PRODUCTION 2022 (HORIZON-CL4-2022-TWIN-TRANSITION-01)
Type of Action	HORIZON-RIA HORIZON Research and Innovation Actions
Topic identifier	HORIZON-CL4-2021-TWIN-TRANSITION-01-03
Consortium	11 organisations, all EU Member States
Model GA type	HORIZON Action Grant Budget-Based

ONE4ALL Consortium Partners

N.	Partner	Acronym	Country
1	IDENER RESEARCH & DEVELOPMENT AGRUPACION DE INTERES ECONOMICO	IDE	ES
2	INNOPHARMA RESEARCH LIMITED	INNO	IE
3	CRIT CENTRO DI RICERCA E INNOVAZIONE TECNOLOGICA SRL	CRIT	IT
4	EXELISIS IKE	EXE	EL
5	SYDDANSK UNIVERSITET	SDU	DK
6	INNOBOTICS SRL	IBT	IT
7	MADAMA OLIVA SRL	MAD	IT
8	HOLOSS - HOLISTIC AND ONTOLOGICALSOLUTIONS FOR SUSTAINABILITY, LDA.	HOLO	PT
9	TECHNISCHE UNIVERSITAT DORTMUND	TUDO	DE
10	Orifarm Supply S.R.O.	ORI	CZ
11	Karlsruher Institut Fuer Technologie	KIT	DE

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Executive Summary

This deliverable 4.2 provides a summary of the work to date, current status, and key planned next steps on Task 4.2 of the ONE4ALL Project.

Task 4.2, led by InnoGlobal (INNO), is responsible for the selection and development of sensors to support the activities of the Reconfigurable Cyber-physical Production Modules (RCPMs) such as in navigation of their environment, as well as other technologies for monitoring the status of the production line to provide information to the Decision Support System (DSS). Along with the selection of appropriate sensors, careful attention is paid to the identification and adoption of appropriate, secure IIoT data transfer technologies to suit both the nature of the sensor as well as the security appropriate to the sensitivity of the data generated.

All of this work fits within the wider scope of work package 4, the development of the RCPMs, as led by InnoBoTics (IBT). Within task 4.2, IBT is providing support and guidance on the integration of sensors with the RCPMs systems, while Idener (IDE) is similarly assisting in the requirements for integration of the sensors with the Intelligent Orchestration Platform (IOP) being developed under work package 3.

An analysis of the application cases identified for the project in collaboration with project partners identified a number of sensor requirements across the lines at both demonstration site facilities. With careful analysis of these sensor requirements, the overall needs have been broken down into three separate, distinct categories, each of which can be addressed with a single sensor type / sensor system solution. In short, these sensor solutions break down to:

- Machine vision sensors for RCPMs and product handling
- High speed vision sensors for olive sorting application
- Wearables for production operator welfare tracking

Regarding the first category, machine vision sensors for RCPMs and product handling, substantial progress has been made in identifying and implementing a highly flexible solution consisting of a network-connected camera module with high-resolution colour imaging and depth mapping capability in the form of the Luxonis Oak-D Pro PoE. The depth mapping capability will provide essential 3D information for navigation and product handling by the RCPM, while the colour imaging will provide sufficient detail for the IOP to carry out quality analysis on product on the line from both the mobile RCPM-mounted cameras and cameras fixed to the line. A hardware sample has been acquired and tested, and the control and telemetry interface specification for communication with the IOP is currently being finalised. Details of the requirements identified, research and development undertaken, and progress to date in this category can be found in chapter 2.

Some progress constraints exist around the high-speed vision sensors for olive sorting application. Issues identifying an appropriate hardware supplier for the product handling requirements under task 4.4 have prevented a definitive requirement specification for the actual imaging hardware from being developed. Nonetheless, due to its high speed of analysis requirements, this sensor solution requires parallel development on an edge-executed AI-driven analysis method, which is possible to research and prototype without a finalised selection of imaging and illumination hardware for the physical line. Significant progress has been made on this aspect of the task, including the generation of image sets to use for Proof Of Concept (POC) method development, manual annotation of these image sets for Machine Learning (ML) model training purposes, development of methods for both segregating input mages to identify individual olives and analysing those olives to identify defects, and deployment of these methods under development to appropriate, specialised edge-AI model execution hardware. This work is detailed further in chapter 3.

Finally, the wearables for production operator welfare tracking sensor category has also made substantial progress, with requirements agreed upon, potential hardware devices reviewed and the leader selected, a fully system prototype developed, and connected to the IOP for testing. Details of this process can be found in chapter 4.

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List of acronyms

AI	Artificial Intelligence
AP	Access Point (networking)
BLE	Bluetooth Low-Energy
CNN	Convolutional Neural Network
CV	Computer Vision
DCS	Decision Support System
DHCP	Dynamic Host Configuration Protocol (networking)
FOV	Field Of View (D - Diagonal, V - Vertical, H – Horizontal)
FPS	Frames Per Second
IIoT	Industrial Internet of Things
IOP	Intelligent Orchestration Platform
IP	Ingress Protection
IR	Infra-Red
JSON	JavaScript Object Notation
LAN	Local Area Network
LoRa	Long Range (radio frequency protocol)
LWT	Last Will and Testament (MQTT disconnect handling functionality)
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
MV	Machine Vision
OTA	Over The Air (remote firmware update capability)
PoE	Power over Ethernet
RCPM	Reconfigurable Cyber-physical Production Modules
RF	Radio Frequency
SDD	Single Shot Multibox Detector (AI image segregation method)
SOO	Sorting Of Olives (application case at MOL)
TCP	Transmission Control Protocol
TLS	Transport Layer Security
TOPS	Trillion / Tera Operations Per Second

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1. Introduction

The ONE4ALL project aims to boost manufacturing plants' transformation, especially small and medium-sized enterprises, towards industry 5.0, reinforcing their resilience under unexpected changes in societal needs. It is done through a human-and-sustainability-centred development of plug-and-produce reconfigurable cyber-physical production modules (RCPMs). Those will consist of self-reconfigurable mobile collaborative robots embedded with IIOT devices for real-time monitoring and interconnectivity.

The potential of ONE4ALL will be demonstrated in two relevant environments from different sectors (agri-food and pharmaceutical), both highly affected by disruption given their high demand level fluctuations and not fully impacted yet by I5.0 transformations.

Work package 4 involves the development of innovative reconfigurable cyber-physical production modules (RCPMs) and is led by robotics company InnoBoTics (IBT). Within task 4.2, InnoGlobal (INNO), with our expertise in vision systems development and IIoT, are responsible for the selection and development of sensors to support the activities of the RCPMs, such as in navigation of their environment and identifying, picking & placing in-process materials, as well as other technologies for monitoring the status of the production line to provide information to the Decision Support System (DSS).

Along with the selection of appropriate sensors, careful attention is paid to the identification and adoption of proper, secure IIoT data transfer technologies to suit both the sensors e.g. low-energy RF for battery-powered sensors, as well as security appropriate to the sensitivity of the data generated.

Where possible, the sensors adopted for more challenging and data-heavy applications e.g. camera-based sensors, are chosen to enable a degree of edge data analysis, including real-time AI model execution at the edge, minimising the data transfer burden on local networks, and supporting maximum scalability.

As certain sensor requirements span multiple use cases and demo sites this chapter will summarise the use cases as they currently stand, outlining the sensor data collection requirements, and then categorise them into logical groupings. These groups, three in total, will then be discussed in detail in the following three chapters, outlining the detailed requirements identified, potential solutions identified & considered, and development work toward implementing the selected solutions.

1.1. Overview of Orifarm Use Cases

1.1.1. ORI Demo 2 – Picking of boxes after manual reworking with quality checks

One of the semi-automated processes Orifarm (ORI) has in place is a system where products are weighed automatically to check whether they fall within the desired specifications. The steps are as follows:

1) Products/packages are loaded onto a conveyor belt.
2) The products move through an automated weighing scale. If the products are not within the expected weight range, then they are rejected and discarded into a non-compliant bin.
3) Products which pass the weight check exit the conveyor belt onto a rotary buffer.
4) From the rotary buffer, the products are picked by a human operator and loaded into boxes.

It is envisaged that a cobot RCPM will aid human operators in picking products from the rotary buffer and loading them into boxes.

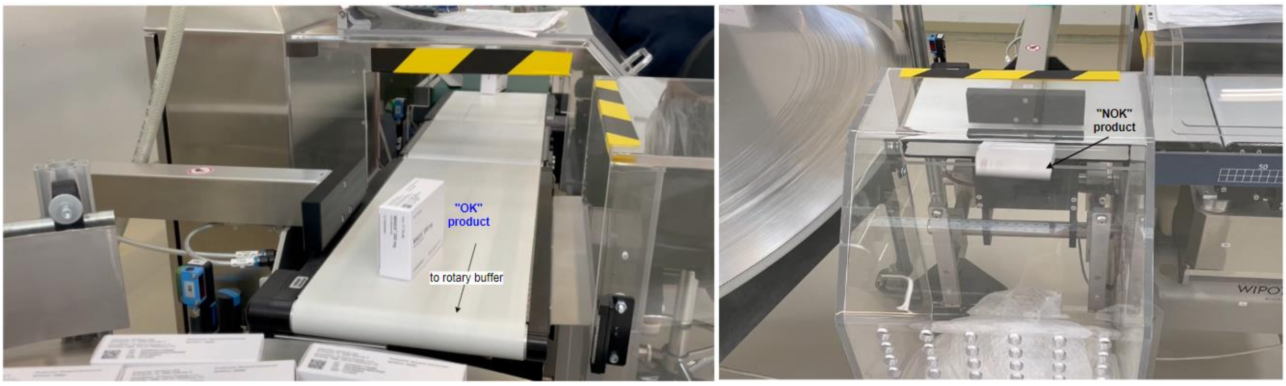

Figure 1 - Automated Weight Check

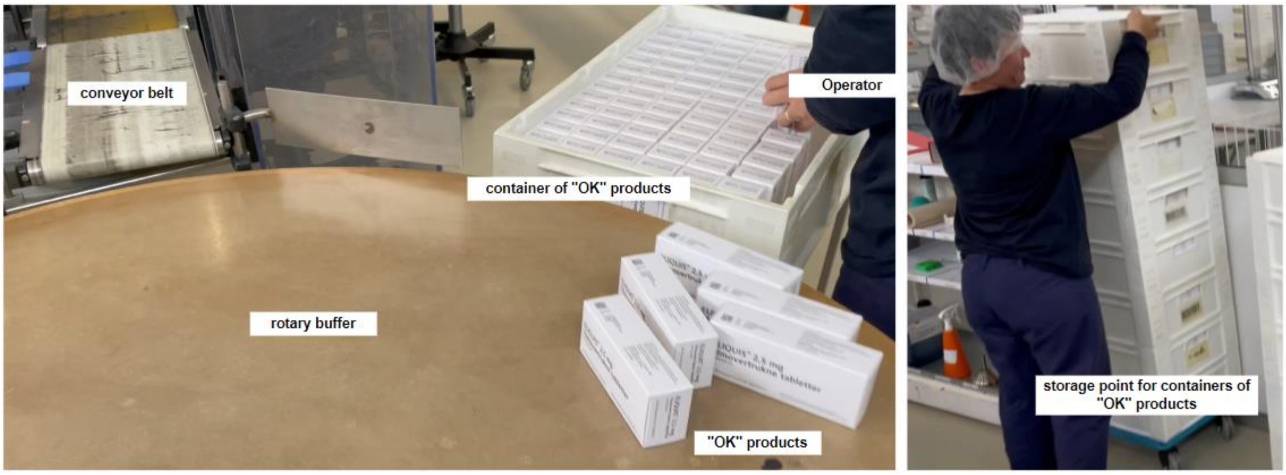

Figure 2 – Demo 2 Rotatory buffer and manual loading of compliant products into containers

It will be necessary for the RCPM to be equipped with a machine vision camera to determine the relative position of products to the manipulator in three dimensions and, similarly, to determine the position and orientation of the container for loading. Implementing an additional fixed camera above the rotary buffer may also be necessary for a clearer perspective (top-down) view of the products on the rotary buffer. Still, the decision has been taken in consultation with IDE and IBT to attempt the application without this additional camera, and to add it only if it proves unfeasible to proceed without it.

In addition to the vision requirements necessary to support the cobot's actions, the production operators must also be considered the process's most critical and important components. A requirement expressed by KIT was that a means to monitor operators in an anonymised and aggregated manner be implemented so that the DTs and the DSS has a means of determining stress and/or fatigue levels for production operators. Factoring this data into the production recommendations generated by the DSS will be crucial to ensure that RCPMs are constantly being used to maintain and improve operators' working conditions, focusing on areas of the production line where additional support is needed at any given time.

1.1.2. ORI Demo 3 – Packaging material handling

The second proposed use case involves picking packaging material/supplies from the packaging material warehouse. Currently, this is a manual process; details as follows:

1) The human operator receives a request for specific packaging material from the warehouse.
2) The operator retrieves the container (which holds the packaging material) from the warehouse.
3) The requested quantity of packaging material is retrieved from the container. The container is returned to the warehouse.
4) The gathered packaging material is then sent to the requestor

This process involves significant manual labour. To aid human operators the use of a cobot RCPM has been proposed.

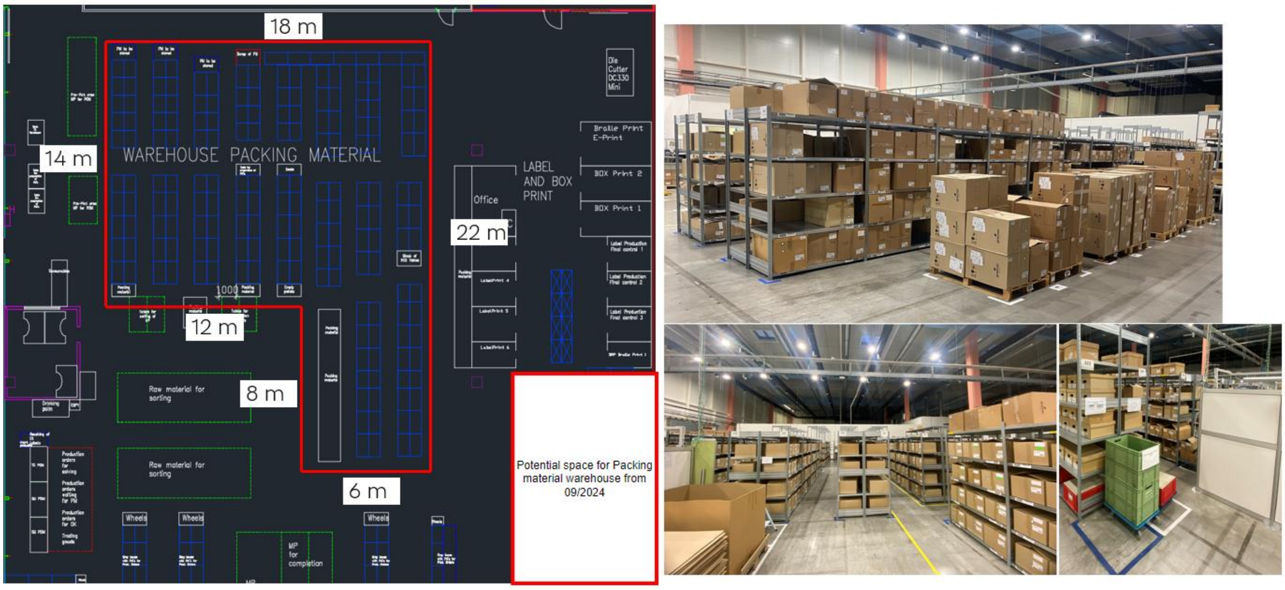

Figure 3 - Demo 3 packaging supplies warehouse

Again it will be necessary for the RCPM to be equipped with a machine vision camera to determine the relative position of products and container boxes with respect to the manipulator in three dimensions. Similarly, monitoring operators stress / fatigue levels to ensure the DSS can consider operator impact in any recommendations made will also be essential.

1.2. *Overview of Madama Oliva Use Cases*

1.2.1. MOL SOO – Sorting of Olives

The goal of sorting olives is to ensure that only the olives that meet a specified qualitative standard and criteria are considered for inclusion in the final product.

The process involves the following steps:

1) Human operators load the olives onto a conveyor belt system.
2) The olives travel on the conveyor belt and are passed through a vision system (Multiscan machine), which performs quality checks. It either accepts or rejects olives based on their quality. Rejected olives are automatically discarded into a container.

3) Upstream of the vision system on the same conveyor belt, one or more human operators perform additional quality checks. Olives which don't meet the desired quality criteria are manually picked and discarded into a container.
4) Olives which pass the quality check proceed to the next stage of processing e.g. treatment / packaging etc.

The existing vision system has limited configurability and often misidentifies quality issues. This leads to the need for human operators to perform additional quality checks. Given the harshness of the working environment due to high levels of moisture/salinity, there is a desire to improve the accuracy and efficiency of the olive sorting process in order to provide relief for the human operators performing inspections. Given the throughput requirements for olive sorting a cobot-based solution is unlikely to achieve the desired performance. Therefore, an alternative olive sorting solution should be proposed, based on the production throughput requirements and product quality needs.

Figure 4 - Sorting Vision System

Figure 5 - Manual Sorting by Human Operator

An imaging-based solution will also be required to address the requirements of this solution, but as the application is significantly different from the Machine Vision (MV) requirements of the RCPMs and at other points on the production lines, a different hardware solution will be necessitated. A high-speed, high-quality machine vision-orientated camera will be required, likely with dedicated image capture hardware and a dedicated PC / micro PC. MV illumination hardware will also be necessary to control and optimise the quality of images captured.

Given the ambient environment at this point on the line, all equipment installed will have to be rated at a high level of Ingress Protection (IP) or housed in an IP enclosure.

Monitoring operators' stress / fatigue levels, particularly during a transitional phase where the advanced olive sorting system may be operating in line with a human operator also carrying out sorting and rejection tasks, will also be key in this application.

1.2.2. MOL EOL – End of Line Application

The end of line (EOL) application at Madama Oliva refers to activities relating to the final stages of production. These activities include quality checks and palletisation on various types of products and packaging.

The current process involves the following tasks carried out by operators (after products are pasteurised and the packaging is dried):

1) Task 1 – Packaging seals are checked for defects
2) Task 2 – Printed lots and expiry dates are checked for correctness and readability
3) Task 3 – Labelling is applied as required
4) Task 4 – Package lids are applied as required
5) Task 5 – Packages are moved into cartons / boxes
6) Task 6 – Cartons / boxes are labelled
7) Task 7 – Boxes are moved onto pallets
8) Task 8 – Empty pasteurisation trays are removed from the conveyor system

To aid operators in performing manual quality checks, the use of a cobot RCPM to pick and inspect the packaging and assist with loading pallets has been proposed.

Figure 6 MOL's end-of-line environment

It will be necessary for the RCPM to be equipped with a machine vision camera to determine the relative position of products to the manipulator in three dimensions and similarly to determine the position and orientation of the containers and pallets for loading. It is also necessary to implement an additional fixed camera above the palletisation area for a clearer perspective (top-down) view of the products on the rotary buffer, and one to two additional cameras on the outlet of the dryers to image package lot numbers and expiry dates for QC purposes. These final cameras may also require some controlled illumination to optimise the capture of the printed labels depending on initial tests in the ambient illumination conditions.

Finally, a means of monitoring operators stress / fatigue levels to ensure the DSS can consider operator impact in any recommendations made will also be key.

1.3. Categorising Sensor Requirements

Per the proceeding use case descriptions, it is clear that several distinct sensor requirements can be identified. Two clear and distinct, in so far as there is a need for:

1. A high-speed, high-quality camera system with accompanying illumination, capture and processing hardware for the MOL SOO application. The selection and work to date on this device and associated analysis methods are discussed in Chapter 3 "High-Speed Vision Sensors for Olive Sorting Application".
2. A solution by which data on the welfare/stress/fatigue level of production operators can be captured for use by the DT and DSS. Multiple potential solutions to this requirement are considered in chapter 4, including a number of small battery-powered wearable devices which can be worn by the production operators on relevant sections of the line at both sites. A

careful balance will have to be struck on this approach to avoid any solution that may be perceived as overly intrusive. The selection and work to date on this device is discussed in chapter 4 "Production Operator Welfare Tracking".

The remaining requirements all concern some form of MV camera system, with and without depth mapping capabilities. Requirements in terms of speed and quality of images are not as significant as those in point 1 above. With careful selection, a single type of depth camera can be chosen to fulfil all of these requirements. A device at an appropriate price point, while still more expensive than a non-depth-measuring camera, should easily offset the higher purchase cost with the efficiency of consolidating the number of different types of sensors to be tested, adapted, installed, and commissioned. The selection and work to date on this device is discussed in chapter 2, "Machine Vision Sensors for RCPMs and Product Handling".

2. Machine Vision Sensors for RCPMs and Product Handling

As part of the ONE4ALL proposed demo cases, Depth / 3D cameras, as identified and implemented by INNO, are proposed for use both onboard each RCPM as well as at various relevant points of the production lines as required to provide sufficient data to the IOP such that it can calculate the movements required for the RCPM to interact with and manipulate products on the line.

The image data from these cameras is also intended to be used to identify and read ARUCO code markers (2D barcodes) used during the navigation of the cobot.

2.1. *Hardware Selection*

2.1.1. Criteria

For the majority of ONE4ALL use case computer-vision requirements, it was determined that the selection of a single camera type with a broad range of capabilities and with flexible functionality would be an efficient and effective means of meeting the vision requirements of the RCPMs and any required key points on the production line. Reducing the time spent selecting multiple different sensors allows a greater focus on the development of other sensors needed and on the limited cases where more specific requirements necessitate the use case particular hardware to be identified or developed.

Therefore, an aggregate requirement specification was developed based on the known details of the production line and RCPM vision system requirements. It should be noted that due to projected framerate and throughput requirements, the MOL Sorting Of Olives (SOO) application was excluded from these aggregated requirements as it was considered highly likely to require more specialised application-specific hardware in the form of high-framerate cameras, appropriate focal length lenses, high bandwidth frame capture interfaces and high-speed illumination sources.

Selection Criteria:

- Required for all identified use cases:
  - Quality colour images with adjustable / auto-focus.
    - Minimum resolution of ~40 pixels per degree to ensure Aruco codes (navigation markers) can be read at a distance of at least 5m.
  - Ingress protection & robust construction.
  - Network connectivity for simple & scalable integration, supporting IIoT approach.
- Potentially beneficial or required for some identified use cases:
  - Depth distance mapping e.g. to determine the position of gripper WRT product in 3 dimensions / determine the height of boxes stacked on pallets from a birds-eye (directly above) viewpoint.
  - Onboard image manipulation e.g. capacity for scaling, cropping depending on specific use case requirements.
  - Onboard neural network capability for potential of a more distributed approach / bandwidth control for scalability.

Depending on the individual application requirements, certain applications / locations on the production line will likely necessitate additional controlled illumination to optimise the clarity of images captured to ensure quality analysis at the IOP level. These requirements must be assessed once sensors are deployed in a representative environment and reference images can be captured.

At that point, decisions will be made on what type(s) of additional illumination may be required and at which locations.

2.1.2. Camera Selection

With the above selection criteria in mind, it was determined that a stereoscopic depth camera would be the most effective and efficient means of meeting the requirements. A stereoscopic depth camera is a device composed of a minimum of two to three separate cameras mounted in such a way that a known alignment and physical distance between two of the camera modules can be used to triangulate points within the imaging area, thus determining their distance from the camera with a high degree of accuracy over a distance of some meters. Modern variants of these devices tend to use two mid-resolution greyscale cameras for depth "mapping", often performed fully within the device on embedded processing hardware, while a third higher resolution colour camera is used to generate a more detailed image of the mapped area. Devices such as these are readily available and reasonably affordable.

Two hardware lines were quickly identified as well suited to the requirements of the ONE4ALL project: the Intel Realsense line and the Luxonis Oak-D line. Both offer a range of stereoscopic cameras, from relatively low-cost units to more challenging ingress-protected industrial units.

Figure 7 Luxonis Oak-D Pro Poe (left) and Intel Realsense D456 (right)

Ultimately, the Oak-D Pro PoE camera was selected for use in the ONE4ALL project due to meeting all of the identified application requirements and offering more excellent colour image resolution and potential for onboard AI model execution as compared with the equivalent "tough" industrial Intel RealSense D456.

The Oak-D Pro PoE offers:

- Imaging sensor specifications (Table 1):

Table 1. Imaging sensors specifications

Central RGB Camera			Stereo Pair Cameras:	
Sensor	IMX378		Sensor	OV9282
FOV (D/H/V)	78° / 66° / 54°		DFOV / HFOV / VFOV	89.5° / 80° / 55°
Resolution	12MP (4056x3040)		Resolution	1MP (1280x800)
Focus	AF: 8cm - ∞		Focus	FF: 19.6cm - ∞
Max Framerate	60 FPS		Max Framerate	120 FPS
Shutter type	Rolling		Shutter Type	Global

- Power over Ethernet (PoE) for single-cable deployment.
- Rugged IP65 rated enclosure.
- 4 TOPS of processing power (1.4 TOPS for AI - RVC2 NN Performance).
- Active stereo: IR dot projector improves depth perception, especially for low-visual-interest surfaces by projecting thousands of IR dots to the scene.
- Night vision: IR illumination LED enables running your AI and CV algorithms in low-light or no-light environments.
- Run any AI model, even custom architectured/built ones (models need to be converted)
- Encoding: H.264, H.265, MJPEG - 4K/30FPS, 1080P/60FPS.
- Computer vision: warp (undistortion), resize, crop via ImageManip node, edge detection, feature tracking. You can also run custom CV functions.
- Stereo depth perception with filtering, post-processing, RGB-depth alignment, and high configurability.
- Ideal depth range: 70 cm - 12 m (see details).
- BNO086 IMU single chip 9 axis sensor with embedded sensor fusion.
- Object tracking: 2D and 3D tracking with ObjectTracker node.
- Industrial grade aluminium housing with Front Gorilla Glass.

2.2. ONE4ALL Depth Camera Functionality Overview

Per discussions with IDE, Image analysis e.g. identification of key objects, markers etc. will be conducted at the IOP level for simplicity and flexibility in development. However, future optimisation opportunities exist with the potential to delegate some or all of the ML-based image analysis conducted to the camera via its on-device Neural Network inferencing (execution of minimised neural network models at the edge).

The required functionality under the ONE4ALL project in-essence involves the periodic provision of colour images and depth/distance matrices (depth images) via MQTT, a simple, fast, and lightweight communication platform selected as the primary means of connectivity for sensors in discussion between INNO and IDE.

A core functionality of MQTT broker connection and periodic "publishing" of colour and depth image pairs will initially be implemented by INNO for initial integration with the IOP and basic proof of concept. Additional controllable functions as outlined in the camera command messages section below will then be added by INNO.

2.3. Interface Definition

2.3.1. Camera outbound messages

Outbound messages will be sent to a device-specific MQTT topic prefaced with either "tele" for telemetry type data or "stat" for status type data – configurable subject to overall IOP topic structure definitions. Data packets will be sent to the following sub-topics depending on camera configuration.

- stat/[specified_device_topic]
  - Status JSON payload including device status e.g. online / offline (managed by MQTT LWT functionality) / starting
    - NB starting state will be set for a minimum of 5 seconds in the event of recovery from a power failure, camera restart etc. It should be used as a

trigger to re-configure any volatile camera configuration parameters which may have been overridden on restart.
            - Setting the retain flag on all command messages sent to the camera will effectively achieve the same functionality provided the MQTT server has not also restarted since the last configuration message was sent.
    - Device IP address for diagnostics / access / configuration
    - Device firmware version
- tele/[specified_device_topic]/image/full_colour
    - Full frame, full resolution 12MP (4056x3040) colour JPG image
    - Device will attempt to deliver images at a rate equal to the set target_fps
- tele/[specified_device_topic]/image/cropped_colour
    - A colour JPG image cropped and scaled per the crop command
        - supports higher frame rates / lower data rates than full_colour images in cases where only a known area of the frame is of interest
    - Will be delivered instead of full_colour image in cases where camera crop command has been set
- tele/[specified_device_topic]/image/full_depth
    - Full frame, full resolution 1MP (1280x800) *greyscale* PNG depth-map image generated in-camera from the stereoscopic greyscale cameras
    - Sent in parallel to each colour image e.g. per target_fps

2.3.2. Camera command messages

As covered above, device functionality aims to provide a highly straightforward plug & play implementation – subject to configuration of the IOP MQTT broker's details on each camera. To this end, once the camera is powered up and connects to the MQTT server, it will begin by default to provide periodic full-resolution colour and depth images, which can be utilised at IOP level for navigation, to identify product for handling etc.

Additional functionality has also been designed to allow for further optimisation where required, e.g. higher frame rates and/or lower bandwidth. Configuration of these technically optional functions is the only reason to send commands to the camera.

NB recommend specifying all parameters for each command sent, and setting message retain flag. Partial params will be processed as updates to the current configuration and may be successfully applied, but in the event of a disconnect, restart etc. this will result in only a partial configuration being applied to the camera on re-subscription to the MQTT command topics, potentially resulting in incorrect data being provided.

- cmnd/[specified_device_topic]/target_fps
    - Expected payload:
        - JSON: { "target_fps": 12 }   or
        - Single numeric value e.g. 12
    - Default value: 2
- cmnd/[specified_device_topic]/image_crop
    - Expected payload:

```
{
  “y_min”: *,
  “y_max”: *,
```

    "x_min": *,
    "x_max": *,
    "scale_factor": *
  }

  - If either y_max or x_max are set to zero no cropped image will be generated and images will be returned on the full_colour & full_depth topics instead
  - Note scale_factor must be an integer value. scale_factor is used to down-scale the specified crop area to further reduce bandwidth use.
    - E.g. if the image size required for analysis at the IOP is 600x600 pixels, but the region of interest in the camera is larger than this, an appropriately sized area in multiples of 600 can be specified e.g. 1800x1800px. A supplied scale_factor of 3 will then provide downscaled 600x600 images of the specified region being sent.
  - default value: all four min/max values = 0, scale_factor = 1, no cropping applied
- cmnd/[specified_device_topic]/image_request
  - Requests the device to deliver a colour & depth image pair per current configuration (e.g. image cropping parameters) immediately rather than waiting for the next frame per target_fps
  - Useful when working at lower frame rates where IOP expects some timed event to occur in the process
  - Use of this command will restart the next frame timer – e.g. the following image will be delivered 1/target_fps seconds later rather than in consistent sequence with the previous image
  - Expected payload: any payload received at this topic will trigger the request
- cmnd/[specified_device_topic]/full_image_request
  - as above in image_request, but command ignores any currently set crop parameters and delivers a full_colour & full_depth image pair
  - Useful when primarily working within an area of interest of the frame, but occasional images of the full FOV are also required
  - Expected payload: any payload received at this topic will trigger the request

3. High-Speed Vision Sensors for Olive Sorting Application

3.1. Application Requirements

As discussed in the deliverable introduction, a requirement exists in respect of the Madama Oliva demo site to conduct a quality-metrics-based sorting of olives, supporting improvement of current Key Performance Indicators (KPIs) on false positive and false negative rejections, throughput and operator time. Unfortunately, identifying a viable apparatus for handling these olives and conducting their physical sorting/rejection under task 4.1 has proven highly challenging. This limits to an extent the effective progress that can be made on this aspect of Task 4.2.

Without finalised product-handling hardware specifications, physical sensor components such as cameras, lenses and illumination cannot be selected with meaningful confidence. However, technical requirements can be generalised to the extent of:

- It is intended that an imaging-based sensor system be used, along with trained AI models, for effective identification of listed fruit defect types.
- Camera: High-quality colour images, high-speed shutter, and high frame rate capable, external TTL trigger likely required.
- Illumination: High CRI, Domed / diffuse to control reflection (TBD), high speed with TTL trigger / continuous depending on camera requirements.

For this reason, work on the selection/implementation of analytical methodologies and selection of analysis hardware has been prioritised, with camera and associated hardware selection to be carried out as soon as sufficient information is available.

Regarding the analysis of product images, it was determined early in the task that speed would be critical in achieving effective performance based on the application's nature and the maximum potential throughput guidelines provided by MOL's analysis. For this reason, INNO determined that edge analysis of product images would be preferable to cloud-based images. This way, potential variables in the upload duration for images to the IOP are negated, providing a shorter and more consistent time from image capture to analysis result, which will actuate the product rejection feature if a defect is detected. It was also agreed between INNO and IDE that INNO would drive the product quality image analysis model development in this olive sorting case, as AI-based particle image analysis is a core competency at INNO. Furthermore, where the implementation of models on edge hardware is concerned, close alignment in terms of hardware selection and software/model development is essential in assuring optimal results.

3.2. Selection of Edge Analysis Hardware

Upon determining that image processing for the SOO use case should take place at the edge rather than in the cloud, a review of available edge AI execution-centric hardware offerings was conducted. While there is no strict limit to the definition of "edge" hardware, given the ambient environment of the olive sorting area, it was determined that small-scale hardware was required, as operation of full-size PCs, rack servers, etc., in that area would be totally unfeasible.

Regarding hardware performance requirements, estimating what may be necessary at this point in the project is highly challenging without representative product images and a well-trained analysis model to benchmark. For this reason, flexibility is an essential aspect of hardware selection. The ability to scale up the processing performance by substituting a more powerful edge analysis module, as well as the ability to potentially scale-out by parallelling multiple camera and analysis module pairs across the width of the sorting line is key to ensuring that ultimate performance targets can be met.

Three ranges/offerings were identified as potentially suitable. These were the Intel Neural compute stick, the Coral Dev Board or Coral USB Accelerator, and the Jetson range from Nvidia. On comparison of device specifications, the Nvidia Jetson product line was determined to offer the broadest processing performance range of the three. The Jetson Orin Nano was found to offer a strong price-performance ratio and so was selected as a starting point for the analytical method development work.

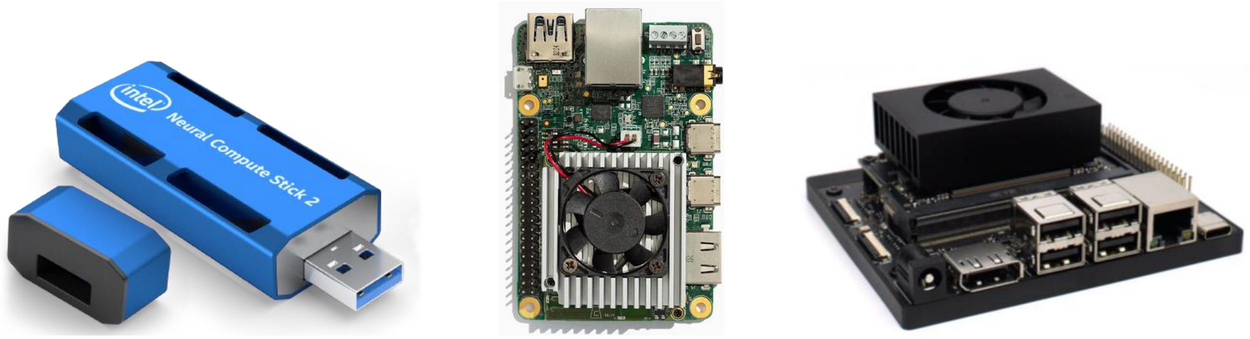

Figure 8 Intel Neural Compute Stick (left), Coral Dev Board (middle), Nvidia Jetson Orin Nano (right)

	Neural Compute Stick 2	Coral Dev Board	Jetson Orin Nano
Main (ML) processor	Movidius Myriad X Vision Processing Unit	Google Edge TPU ML accelerator coprocessor	1024-core NVIDIA Ampere architecture GPU with 32 Tensor Cores
Approximate TOPS (ML model processing power)	4	4	40
Supported frameworks	TensorFlow*, Caffe*, Apache MXNet*, Open Neural Network Exchange (ONNX*), PyTorch*	TensorFlow Lite	TensorFlow, TensorRT, PyTorch, Triton and others
Connectivity	USB 3.0 Type-A N.B. requires an attached PC / micro-PC to operate	Ethernet, USB, display, audio, GPIO – full micro PC	Ethernet, USB, display, audio, GPIO – full micro PC
Status	Discontinued	Available	Available
Approximate bare unit price (€ ex VAT)	€ 180 * Requires accompanying PC	€ 200 * supply constraints	€ 350

Table 2 Comparison of edge AI execution hardware for SOO application

See the reference section for links to detailed specifications for each device.

3.3. Selection of Analytical / Model Development Methodologies

The development of machine learning-driven image analysis models requires the preparation of large training and validation data sets in almost all instances. Datasets must consist of representative images of the relevant objects, annotated/tagged with all related information that the model will ultimately be required to predict. The closer the image sets resemble the final inline product images on which the model will operate, the higher the ultimate success rate of identification is likely to be.

For this reason, it is not practical to attempt to develop a final image analysis model for the identification of defects in olives until an initial data generation run of the handling, imaging and illumination hardware can be carried out and a truly representative image set generated for training and validation purposes.

It is, however, practical and pragmatic; unable to proceed with representative image set generation, to research existing published methodologies which may offer well-suited, efficient approaches to the type of image analysis problem.

To allow some proof of concept work to proceed with testing different potential analytical methods, INNO prepared two POC or non-representative image sets. It is not expected that models developed using these two image sets or a combination thereof will be appropriate for use in the final application at MOL. Still, they constitute a valuable resource in testing model development methods and analysis hardware performance. Suppose an optimal model development method can be identified at this point of the project. In that case, a clear roadmap will exist for building a suitable model for the final application in a shorter period of time, likely limited mostly by the time required to annotate the representative dataset before training.

Generation of POC image set 1 was carried out in-house by INNO by designing and 3D printing a sample plate, which ensured spacing, and orientation of olives placed into it, as a roller-guide type conveyor would. Samples of both black and green olives were purchased for simplicity and expediency. Some of the olives were intentionally damaged to simulate crushed and incomplete fruits, and a mixture of damaged and undamaged olives were arranged into the sample plate. This sample plate was then slid a short distance, causing the olives to roll, while imaging from directly above. This image set was annotated using the tool CVAT. Examples of this image set and annotations can be seen below.

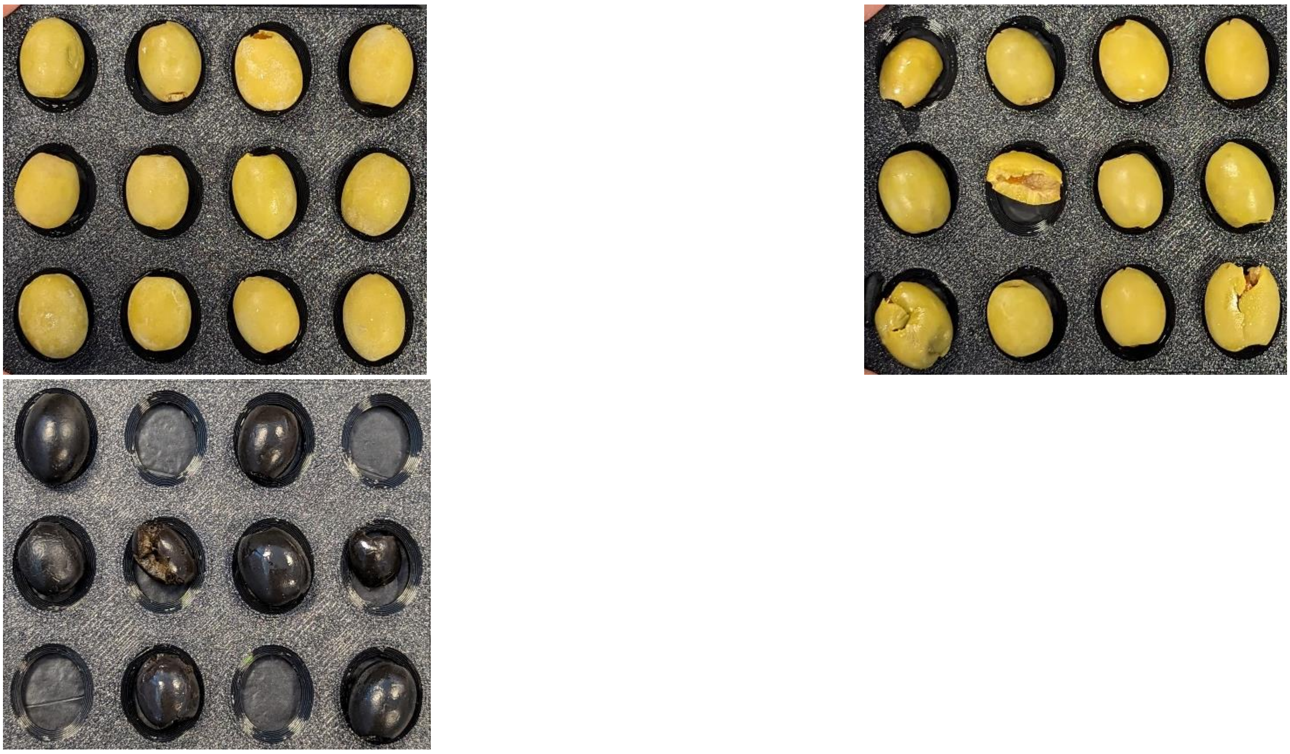

Figure 9 Images from POC image set 1

Figure 10 Annotated image from POC image set 1

POC image set 2 was generated during a visit to MOL's site during M5. In this case, olives were imaged while on the feed conveyor of the existing MultiScan device. This allowed generation of a far larger image set than set 1, though with limited image quality due to the olives' movement speed and the lack of appropriate illumination apparatus. Additionally, during manual annotation, only a very small number of visibly defective olives could be identified in POC image set 2, underscoring the need for the ultimate model training set to be generated inline across a number of different olive types and batches, to ensure that sufficient variety of both good and bad olives can be accounted for. For proof of concept purposes, however, this image set is still valuable.

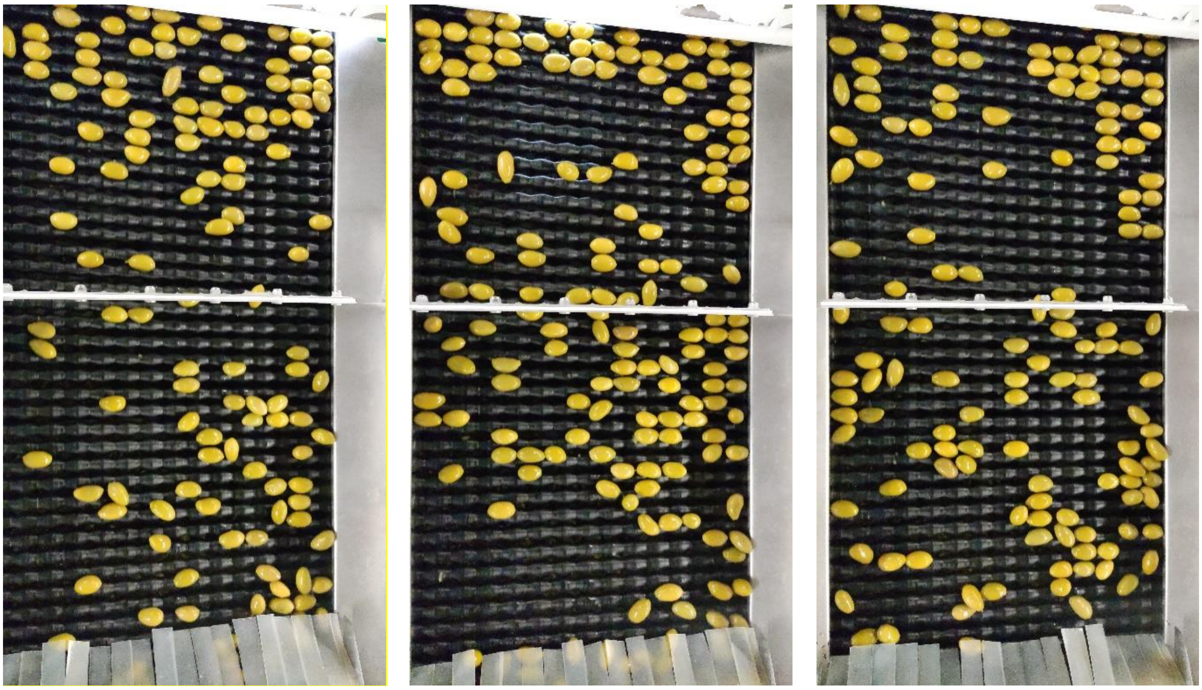

Figure 11 Images from POC image set 2

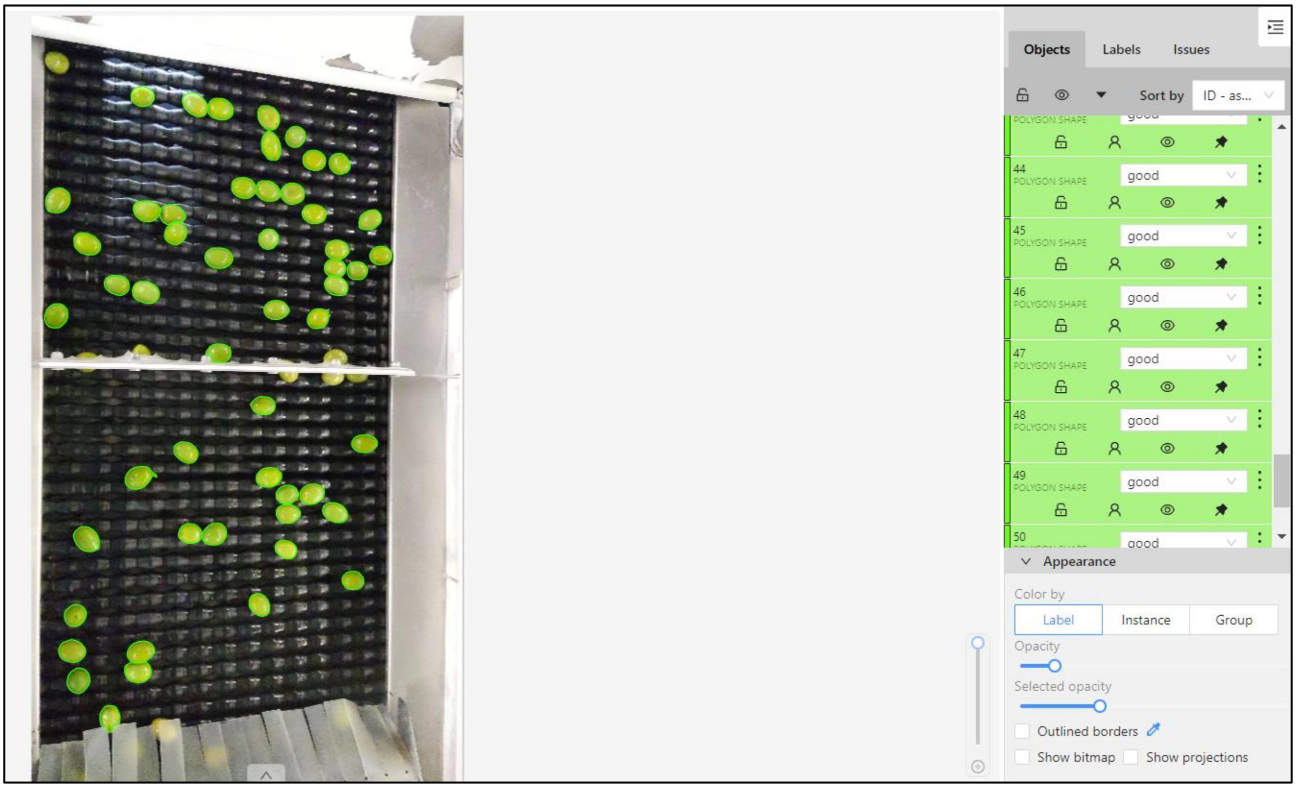

Figure 12 Annotated image from POC image set 2

The task of image analysis and classification can be broken into two distinct stages. Firstly, images from the production line featuring a number of olives and empty spaces must be analysed to identify all of the olives present within the image and their positions. Secondly, each of these olives must be examined for quality metrics, including defects. While this research is focused primarily on defect detection, attributes such as the colour and size of the olives can also be considered critical quality metrics. These attributes are reasonably straightforward to compute through traditional image analysis means using the results of stage one above.

Two possible methods have been explored so far for stage 1, segregation of source images or identification of the olives present.

- A traditional image analysis approach utilises the colour contrast between the fruits and background to identify areas of the image containing olives. This is an efficient and high-speed segregation approach when there is a significant colour variation between the olives and image background, and when olives are physically separated as on a roller-guide conveyor. This method, however, is likely to be less effective with strains of darker-coloured olives and may miss all-together fruits with very significant colour deviations where effective sorting will be essential. If the ultimate handling solution for the fruits does not inherently segregate them e.g. with a roller-guide system this method may not be applicable. Due to its extremely high speed, however, this approach remains worth considering.
- Machine learning-driven image segregation. A common approach to this type of application is by utilising a Mask R-CNN approach, but a Single Shot Multibox Detector (SSD) delivers higher performance and so has been adopted for the POC analysis pipeline. Prototypes of other methods explored, such as R-CNN, will be maintained until an overall SOO application prototype system can be built and tested, as until truly representative images can be generated for testing comparisons of methods remain somewhat abstract.

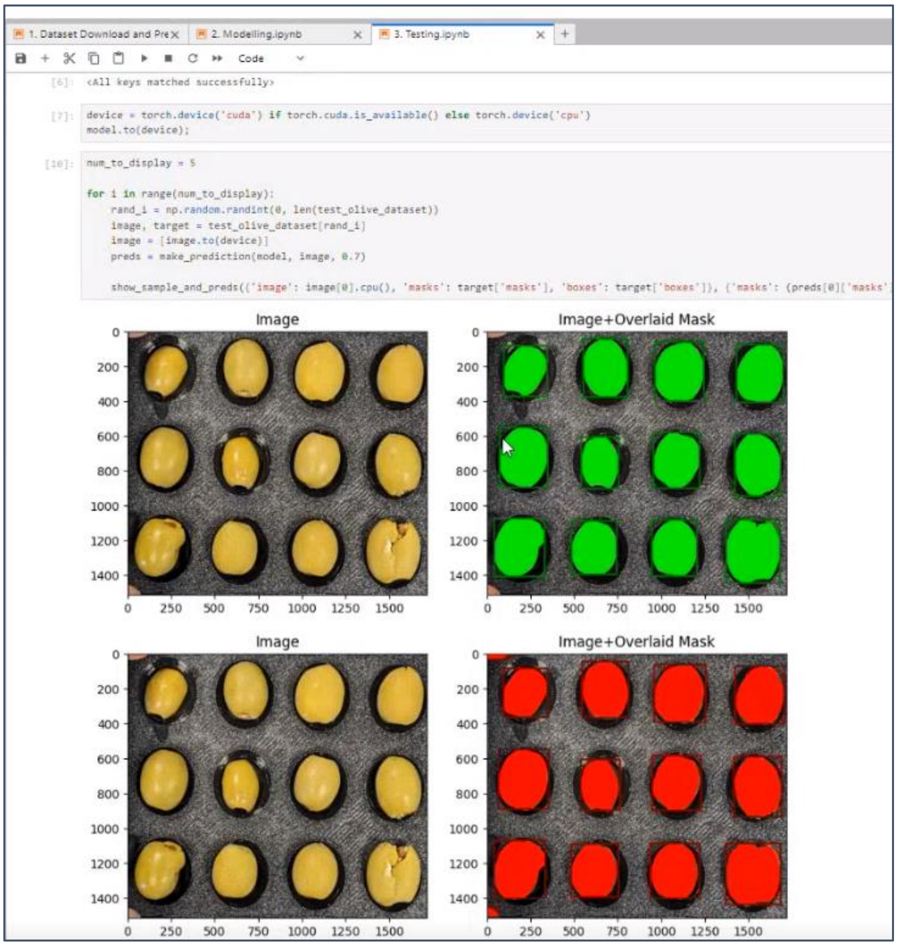

Figure 13 Example result of Mask R-CNN segregation of an image from POC set 1 – ground truth (manual annotations) in green, prediction in red

Stage 2 of the image analysis task, the analysis of each olive for quality metrics, with a particular focus on defects, is well suited to a machine learning defect detection approach in which models are trained on datasets representing "good" quality products only, and defects in sample images are then identified based on deviations from this trained recognition of good objects.

EfficientAD has been identified as a particularly promising approach for high-speed, efficient analysis of real-time product images, where quality metrics must be reported quickly to ensure rejections can be made before the olive passes by the rejection system. The EfficientAD approach relies on pairing two neural networks, a teacher and a student. The teacher network is pre-trained on a full training set of "good" and "defective" images. The student is then trained by the teacher network's output using only "good" images, as shown in Figure 14. The aim is to train the student network to successfully mimic the teacher on "good" images while avoiding generalisation to defective images. Both networks are run in parallel for real-time use, with deviations in the output from the two networks used to identify potential defects as can be seen in Figure 15.

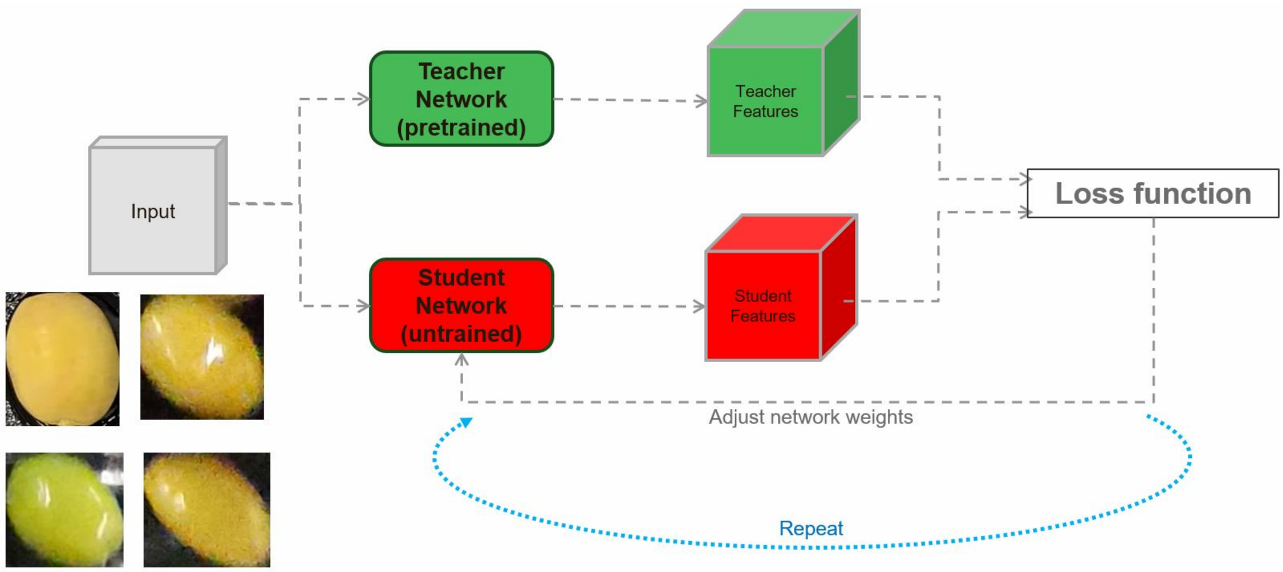

Figure 14 EfficientAD training process

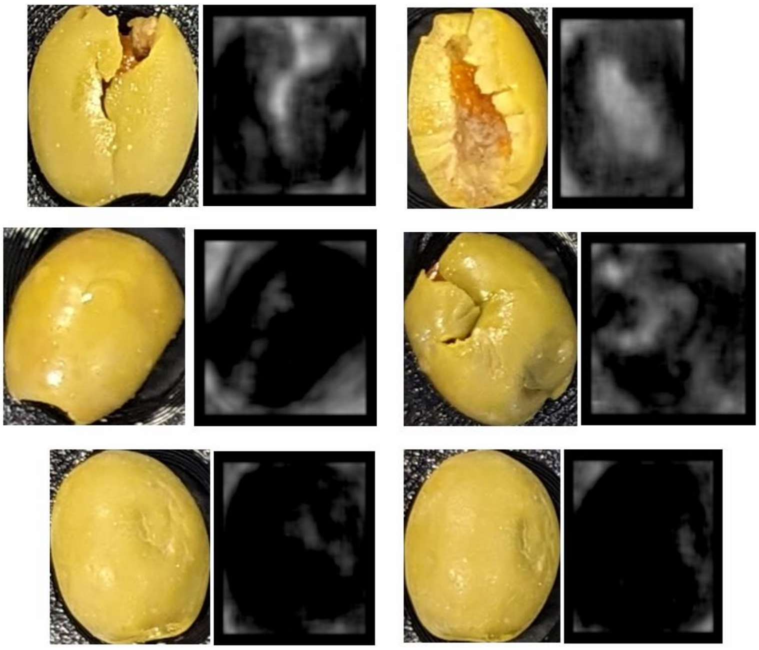

Figure 15 Sample results of POC EfficientAD defect detector / classifier model – greyscale images indicate likelihood of defect by pixel brightness

3.4. Current Status and Next Steps

Current work continues to explore the applicability of the EfficientAD method to olive defect detection based on POC image sets 1 & 2. An initial pipeline has been built and tested (results in Figure 15), but significant optimisations are still required, in parallel with the adaptation and deployment of the pipeline to the Jetson Orin Nano.

Identification of imaging and illumination hardware remains a priority, and INNO continues to work closely with IBT to determine how the product handling requirements will be met and the impact this has on the specifications of imaging and illumination hardware. It is not expected that ordering timelines for this hardware will be overly long, therefor the risks to Task 4.2 associated with this delay in the identification of olive handling hardware are still considered low.

4. Production Operator Welfare Tracking

4.1. Application Requirements

Under WP2, led by KIT, it has been identified that there is a need for additional information on the status of the relevant production lines on both sites to provide meaningful inputs to the digital twins on the status/condition of production operators. For the DSS to make meaningful recommendations on the dynamic assignment of resources in production, an indicator of worker stress levels would be valuable to ensure that where human operators are struggling with throughput rates or becoming tired, the DSS can make a recommendation to support this operator's station with an RCPM, suggest switching operators, schedule a break etc. This helps to ensure the critical focus of the project remains on the human well-being element of Industry 5.0 and not just on technological solutions in the production environment.

In discussions with KIT, three main possibilities for the monitoring operator's well-being were considered.

A. An imaging based approach utilising a camera with a view of the operator's face and performing pupil tracking / visual heart rate measurement / expression-based stress analysis
B. A fitness-tracker / smart-watch style wristband as a means of measuring metrics such as heart rate, motion, and ambient conditions such as pressure and temperature, which can be utilised to model comfort and stress
C. A physical experience-feedback interface such as the "smiley-button" experience feedback devices often used in retail settings, which operators could use periodically to indicate their comfort / stress levels. Combined with production throughput and environmental data this could be used to build a general operator stress prediction model

The three options above were considered in terms of technical feasibility, efficacy, and personal impact on the operators. The perspective was that regardless of how technically effective a monitoring solution might be, if operators felt that it was an imposition or overreaching, it was likely to both encounter resistance to adoption as well as to actually contribute to the stress levels it is attempting to measure. Technical i.e. data protection measures can be utilised to ensure individual data is appropriately protected and that only aggregated data is presented to IOP end users where individuals are not identifiable. However, these measures are still likely ineffective in fully allaying concerns driven by a monitoring system perceived as overly invasive.

For the above reason, option A was ruled out. While potentially highly effective at collecting a range of operator well-being signals, as well as potentially being simple, flexible and adaptable in use; the invasiveness of requiring a camera to be placed in view of the operator's face at all times while working was considered likely to encounter push-back and to contribute to operator stress. While images could be used for immediate analysis only and not stored, and data could be effectively anonymised it was seen as unlikely that this explanation would fully allay operators fears.

Of the remaining options, option B was selected as being an effective means of sourcing real-time data which could be used toward stress and fatigue calculation, while being seen as minimally invasive. In discussions with KIT and representatives from each of the demonstration sites it was felt that use of the fitness trackers was unlikely to be seen as an issue by production personnel. Option C, while certainly the least invasive, is limited by its inability to provide true real-time welfare data on operators, requiring them to break from their task and potentially move away from their station to provide updated information. This in turn would limit the DSS capacity to monitor for and address developing high stress-situations on the line.

Option C will however be kept in consideration in the event that operators express concerns over the use of fitness trackers, or if engagement / use of the trackers is low.

4.2. Requirement Specifications & Hardware Identification

With the basic approach of fitness tracker devices identified, a cyclic approach to requirements specifications was adopted. Initially, a loose requirement around monitoring some variables related to both operator well-being/stress level and immediate environmental conditions was adopted as a starting point to determine what sensor options were available to select from the market. Based on this analysis, the key features of potentially viable devices were then considered for overall value and technical feasibility with the final device selection.

Only a small number of potential devices were identified, resulting in a short selection process. While a wide range of sports, fitness and health-orientated smart-watches / wristbands exist on the consumer market, these devices are almost exclusively designed to be used by an individual user in a one-to-one via a paired, proprietary smartphone application and associated cloud services. Utilising multiple devices of this type and attempting to integrate their data with the IOP in a many-to-one configuration while potentially possible would create multiple layers of complexity and third-party service dependencies, which in turn risks loss of functionality in the event that changes are made to these third-party service APIs or devices stop being supported etc. For this reason, common smart-watches and fitness trackers such as the Apple Watch, Samsung Galaxy watch (and all other Wear OS-based devices), Fitbit, Garmin and Xiaomi.

Devices supporting the ANT+ standard were also considered. ANT+ is a wireless standard developed for interconnecting fitness equipment from different vendors e.g. a means of pairing a wireless heart rate monitor with a treadmill. It was thought that fitness trackers supporting ANT+ could be used along with a USB ANT+ receiver to capture data and forward it to the IOP. This option was however ruled out after some research as, other than heart rate monitors, limited sensor options exist supporting the ANT+ standard. Additionally, it appears that many newer models of exercise equipment are dropping the ANT+ standard for Bluetooth Low-Energy (BLE), so adoption of the ANT+ standard at this point within the ONE4ALL project was considered unwise.

Research for potential devices, therefore, focussed on wearable devices designed to be open-source or "hackable" with the ability to run custom code or easily-developed applications onboard. Contenders included wearable dev-boards from Lilygo and the Bangle.JS2 from Espurino, identified and suggested by KIT.

Figure 16 Bangle.JS2

Figure 17 Lilygo T-Watch S3

	Lilygo T-Watch	Espurino Bangle.JS2
Processor	ESP32 S3	Nordic nRF52840 ARM Cortex M4
Battery capacity	470mAh	175mAh
Battery runtime (predicted)	Use dependant ~ up to 2 days	~ Several days up to 4 weeks
Multi-axis accelerometer	Yes - BMA423	Yes - Kionix KX023
Heart rate sensor	None	Yes - Vcare VC31 / VC31B
Pressure/temperature sensor	None	Yes - Bosch BMP280 / Goertek SPL06
Wi-Fi connectivity	Yes – b/g/n	None
Bluetooth connectivity	Yes – BLE V5.0	Yes - BLE
LoRa connectivity	Yes – all common frequencies	None

Ingress protection rating	None	IP67
Development environment	C++ (Arduino), Micropython	JavaScript
App / software availability	Limited availability of complete software / operating system solutions. Wide Arduino / ESP32 compatible library support.	Open source app store (Bangle.JS App Loader), online IDE with virtual testing environment

Table 3 Lilygo T-Watch & Espurino Bangle.JS2 key (relevant) feature differences

Despite the Lilygo providing the more accessible development environment and being more directly integratable via either a direct MQTT connection via Wi-Fi to the IOP, or MQTT via LoRa through a relay hub, the Bangle.JS2 was selected as the better suited device. Its heart rate and ambient sensors will provide more data to analyse operator welfare, and its ingress protection rating will likely be crucial in certain areas of the MOL production facility.

In discussion with KIT heart rate, pressure and temperature were identified as the sensor variables most worth implementing, and so have been selected as the requirement to send to the IOP. Additionally, device battery level was selected as it is important that a low device battery can be identified before disconnection / failure so that a prompt may be provided to recharge the tracker.

4.2.1. Relaying data from the Bangle.JS2 to the IOP

As there is no means of directly networking the Bangle.JS2 with the IOP to support an MQTT connection for telemetry, it is necessary to add an additional node to the system capable of receiving data from the Bangle via its only available wireless protocol, BLE, and relaying it to the IOP. While this has necessitated additional development work, it allows the battery-powered Bangle device to operate at extremely low power levels compared to a direct Wi-Fi connection, providing significantly greater battery runtime than the alternative T-Watch would have been capable of operating via either Wi-Fi or LoRa.

Initially, commercial options and open source projects were explored to provide the required functionality; a gateway or relay between BLE communication and MQTT. Plenty of USB or built-in BLE solutions exist for Windows and Linux based systems, but with the broad range of protocols within BLE, a turnkey solution could not be found for relaying the type of data for this application. Further, customisation of any of these existing solutions to handle the required data types is rendered significantly more challenging by their deep integration with OS Bluetooth drivers. Finally, if these customisations could be robustly and reliably implemented, it would necessitate one or more Windows or Linux computers to be placed in the demo site production areas, creating overlapping BLE coverage to receive data from the Bangle devices, facing several practical challenges, including environmental, cost, complexity and maintenance.

Instead, a more IIoT-centric solution was adopted using a small, low-power, low-cost microcontroller board as a Silicognito WESP32 V7. The WESP32 board features an ESP32 microcontroller and supporting Power over Ethernet (PoE) circuitry, giving the board Wi-Fi, Bluetooth and wired networking capabilities. Firmware must be custom-developed as available operating systems for this type of microcontroller offer only fundamental functionality. Still, development is extremely well supported in the open-source community via a wide range of software libraries. A firmware named "BLE2MQTT" was developed to run on the WESP32 board, delivering the required data relaying functionality.

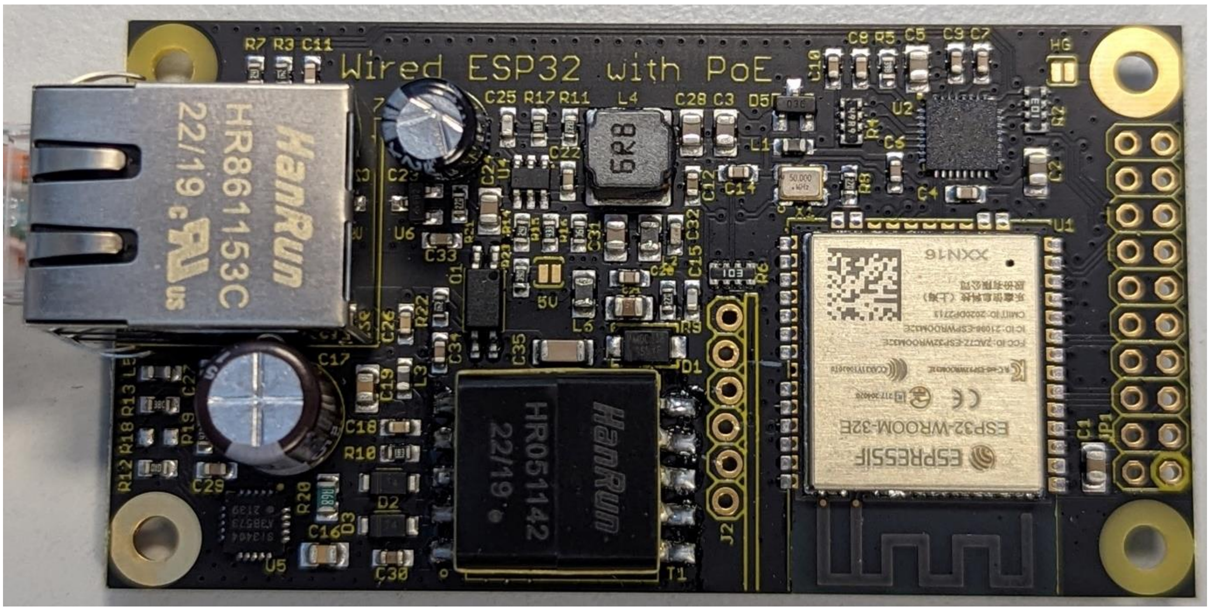

Figure 18 Silicognito WESP32 V7

4.3. Development of Required Features

Upon identification of the hardware elements covered above, the following steps to prototype a system to deliver the required data to the IOP were followed:

- Identify an existing Bangle.JS application to gather required data variables (heart rate, temperature, pressure) and transmit them via BLE, ensuring data in transit is secure e.g. encrypted
    - If no existing application can be identified:
        - Develop/adapt a custom application to deliver this functionality
        - Identify & leverage existing BLE standards in so far as is possible for the secure transmission of this data
- Develop a BLE2MQTT WESP32-compatible firmware supporting relaying of secure BLE heart rate, temperature, pressure and other data from multiple Bangle.JS2 devices to the IOP via secure (TLS) MQTT.

While several apps in the Bangle.JS App Loader provided heart rate measurement (via a native OS function) and reporting via BLE standards, all were limited in their ability to provide any additional data e.g. temperature / pressure. Based on a review of existing Bluetooth / BLE open standards, it was determined that only one existing communication standard supported the requirements of:

- Secure (encrypted) data
- Operates in beacon mode without requiring bi-directional connection to relay (allowing further improved battery life for fitness trackers and more feasible to implement multiple relays for greater coverage this way)
- Supports required variables (heart rate, pressure, temperature) with flexibility to add others if additional requirements are later identified

This was the BTHome open standard, developed to allow low-energy sensor devices to broadcast their data to one or more monitoring devices. Despite its use of broadcast functionality the standard supports optional encryption indicated by the first payload byte. When implemented, the receiving device must know the encryption key to decode the data sent. Further, the standard allows for property-agnostic count and raw datatypes, allowing for atypical or custom variable types to be sent and received, provided the schema of both the sending and receiving devices is known. See the references and Resources section for a link to the standard specification.

A new "ONE4ALL" application for the Bangle.JS2 was written with reference to the codebase of an existing unencrypted temperature and pressure reporting application in the Bangle.JS GitHub "BTHome Temperature and Pressure". Additional values for heart rate, heart rate measurement confidence, and device battery level were obtained and added to the BLE beacon payload per the BTHome standard, and encryption was implemented.

Figure 19 ONE4ALL app in Bangle.JS2 application launcher menu (left) and ONE4ALL app running on Bangle.JS2 (right).

4.3.1. Relay Firmware & Features

Per the requirements outlined above for relaying data from the Bangle encrypted BLE interface to the IOP over MQTT, ESP32-compatible firmware was written to meet this requirement. An on-device web portal was also implemented to support configuration. Features include:

- Username & password required to access configuration interface.
- Configuration of MQTT broker address & credentials.
- Togglable TLS (MQTT connection encryption) setting.
- MQTT root topic configuration to allow each relay device to publish to a unique configurable topic.
- Setting for beacon scan interval (measurement period) – controls how frequently the relay scans for updated data from any Bangle.js2 bands in range.
- Fixed IP configuration to be used depending on demo site network integration requirements.

Additional firmware features also include:

- OTA firmware update capability to allow for straightforward future maintenance and troubleshooting.
- A device status topic including LAN IP address valuable in DHCP environments.
- An MQTT LWT functionality to clearly indicate unavailable state on an unplanned disconnect or device failure.

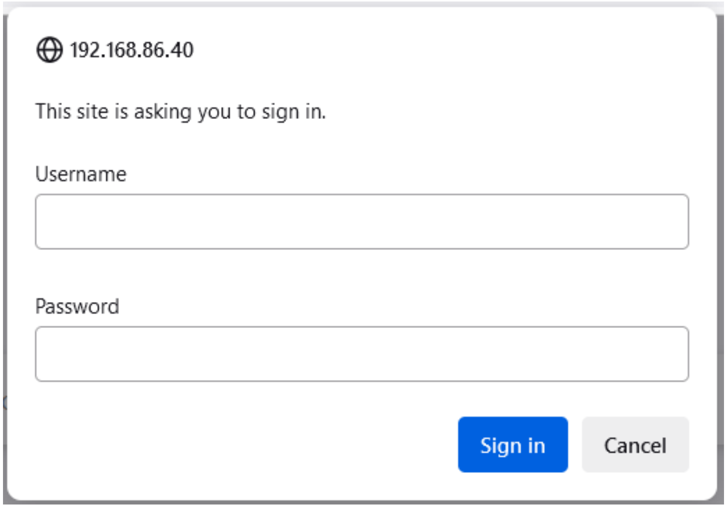

Figure 20 Screenshot of security popup to access BLE2MQTT configuration web interface

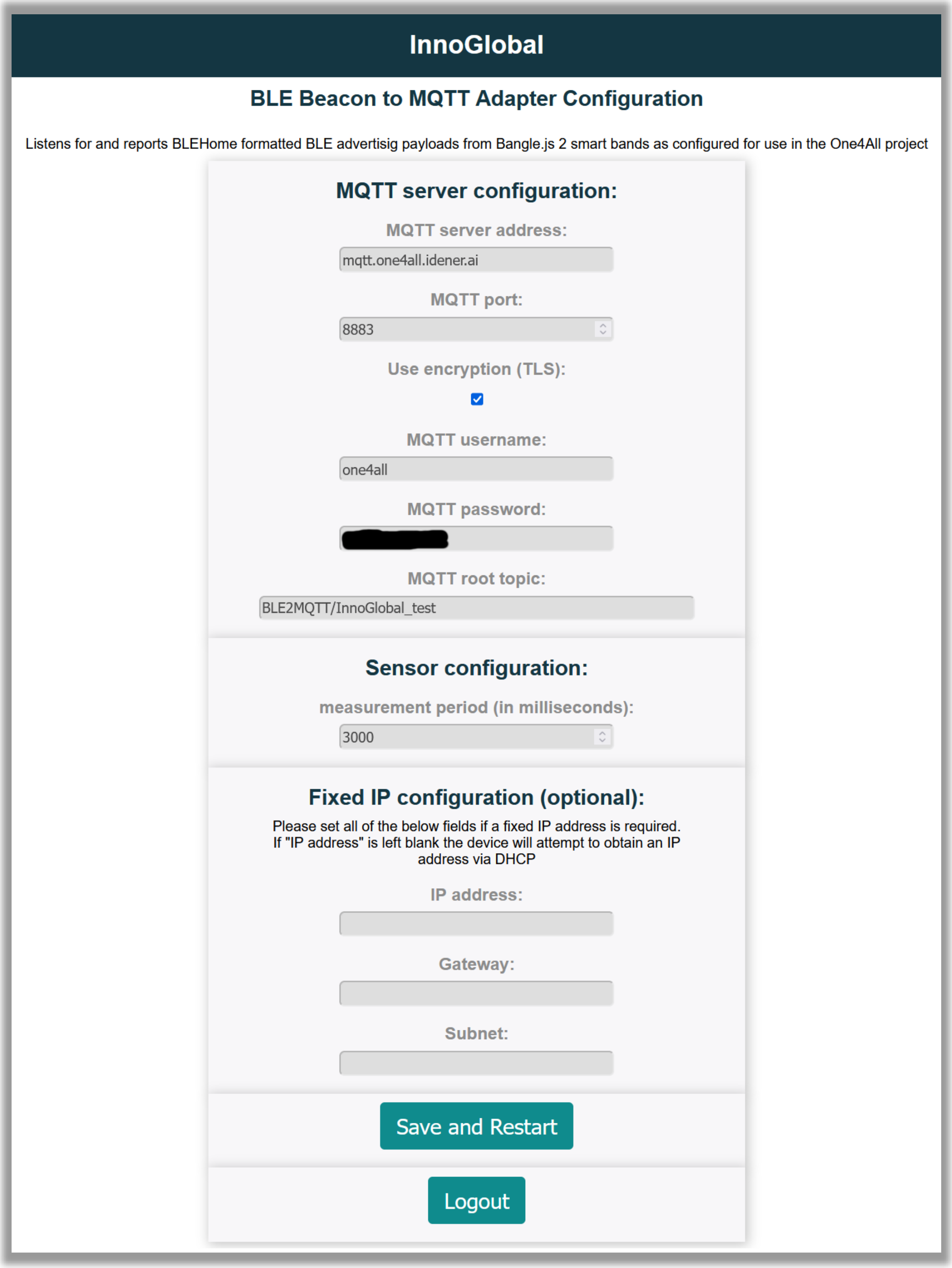

Figure 21 Screenshot of BLE2MQTT configuration web interface

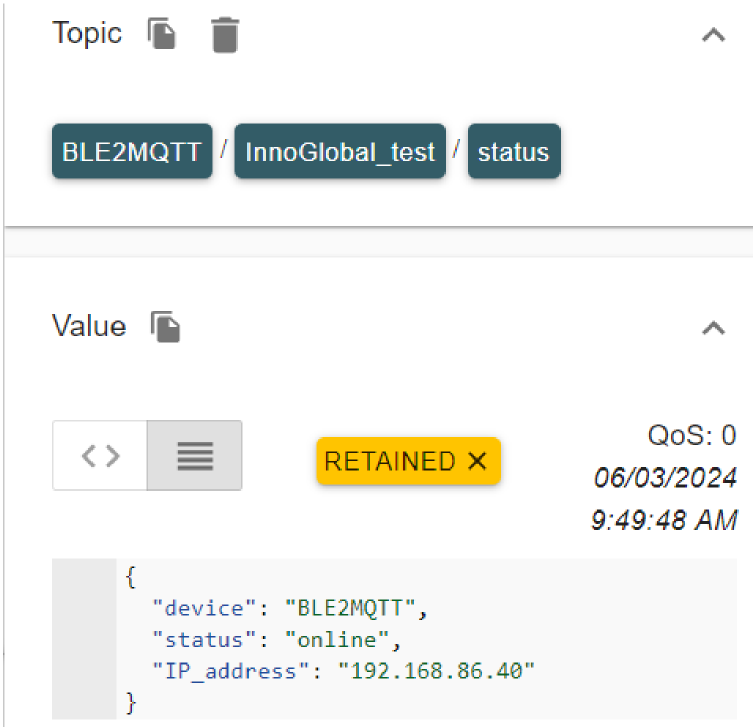

Figure 22 Example status payload from BLE2MQTT relay

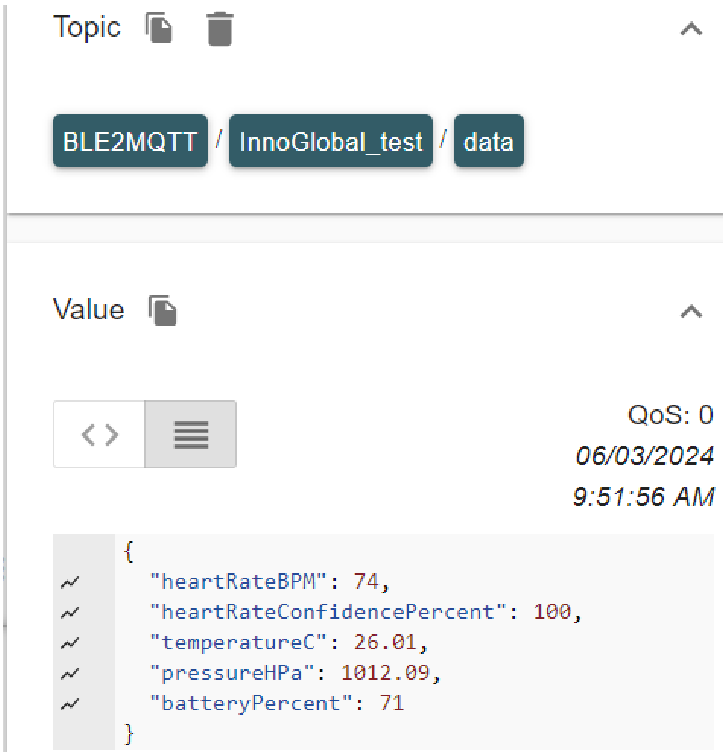

Figure 23 Example of an MQTT JSON payload at IOP relayed from Bangle.JS2 One4All application

4.4. *Current Status and Next Steps*

As of May 2024, IDE made a secure IOP MQTT broker available, and the prototype BLE2MQTT relay has been successfully connected to this. Two Bangle.JS2 bands have been loaded with the ONE4ALL app and are in service, broadcasting data for relay to the IOP. INNO and IDE have validated This data at the IOP MQTT broker.

The effective transmission range of the Bangle.JS2 BLE beacon functionality/reception range of the BLE2MQTT relay devices remains to be determined. The environment highly impacts the range of these signals, e.g. physical obstructions, and other RF noise/signals in the same frequency range (2.4 GHz), so line-of-sight maximum range testing is of limited value. Likely, the final installation locations as well as the range of coverage required, will need to be assessed for signal coverage before the definitive number of relay devices can be determined.

Finally, some deviations between the measured heart rate of the Bangle.JS2 and that from a Google Pixel Watch 2 have been identified. While some variability in measured heart rates from wrist-mounted devices such as these is to be expected, it remains to be seen whether the level of precision from the Bangle.JS2 is sufficient for effective use by the DSS. Ultimately the practicality and usability of this data will have to be determined in collaboration with KIT as a key input to their digital twins, which form the backbone of the DSS.

As an operational prototype already exists for this solution, the remaining steps to completion of this sensor system are quite simple:

- The data produced by this prototype system, and particularly the utility of that data, must be validated with KIT.
- An appropriate enclosure and mounting system must be identified for the BLE2MQTT relay module(s), which currently consist of an unprotected printed circuit board.
- The number of Bangle.JS2 bands required at each demo site must be determined and purchased, along with an appropriate number of WESP32 modules to use as relays. These Bangle.JS2s and WESP32s must also be configured and deployed.
- It is likely that a convenient batch charging solution for the Bangle.JS2 bands will be required at one or more locations on each demo site, so if time is available, a shadow-board-type design with integrated/captive magnetic charging interfaces will be designed and produced.

5. Sensor Connectivity to IOP

Planning of sensor connection topology has been conducted in parallel with senor selection. While ease of connectivity is a crucial factor in sensor selection, in some cases, such as the operator welfare monitoring devices discussed in Chapter 4 above compromises on ease of connectivity had to be made to ensure sensors capable of monitoring sufficient parameters could be acquired. Overall, an IIoT approach has been taken to connectivity, either selecting sensors which support network TCP based connection protocols or selecting/implementing local adapters such as the BLE2MQTT relay(s) to adapt sensor data to such protocols.

MQTT (Message Queuing Telemetry Transport), a lightweight telemetry protocol utilising TCP, has been chosen as the preferred method of communicating sensor data to the IOP. MQTT offers an easily implemented, lightweight and scalable means of secure multipoint data exchange through a publish/subscribe topic model via an MQTT "broker". Message "payloads" can consist of any data format, but JSON is preferred in this implementation where appropriate, as it offers an easily debugged human-readable data format. Examples of JSON MQTT payloads can be seen in Figure 22 and Figure 23 above. Currently, the only likely exceptions foreseen to this payload format are for image data, where significant efficiency gains can be made by transmitting the image in binary rather than parsing it to JSON.

5.1. Connection of Sensors on the RCPM

Due to existing connectivity constraints and the risks associated with added technical complexity, in discussion between INNO and IBT it was decided that the machine vision camera and any other sensors required onboard the Cobot should not be integrated with the cobot's internal network but should use an independent network connection. Other than utilising the Cobot's onboard power supply, INNO's sensors will be an entirely separate system.

The Oak-D Pro PoE camera connects via an ethernet cable, requiring a wired ethernet connection with PoE to be available locally. While simple for fixed installations this necessitates a PoE injector or PoE switch to be installed on the cobot. For connection of these devices in turn to the site Wi-Fi network a Wi-Fi access point (AP) which can be operated in bridge mode is also required. This is a Wi-Fi router designed to create a wireless "bridge" between two wired networks, in this case the site network and the network onboard the cobot.

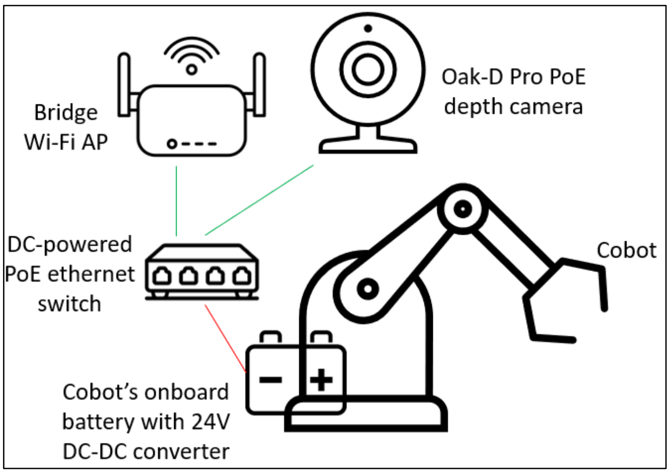

Figure 24 Planned communication topology for RCPM-based sensor(s)

5.2. Demo Site Connection Topologies

The current overall connection topology plan for the use cases at each demo site can be seen in Figure 25 and Figure 26 below.

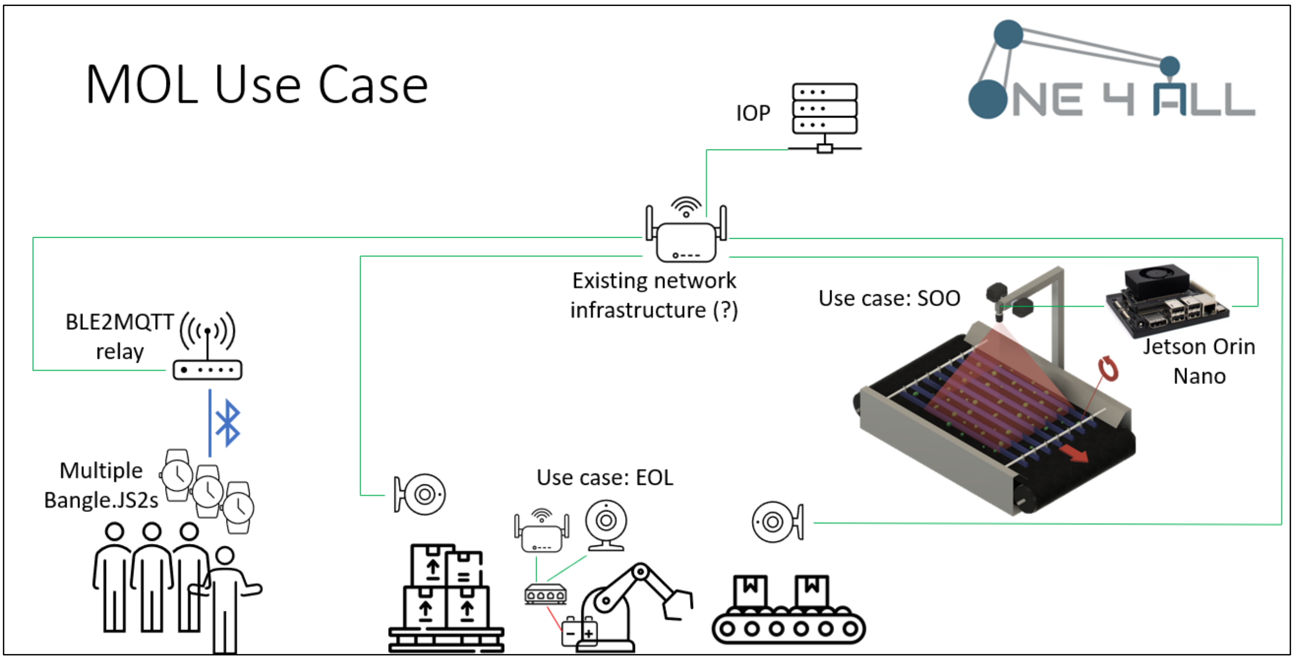

Figure 25 Planned communication topology for sensors in MOL use case

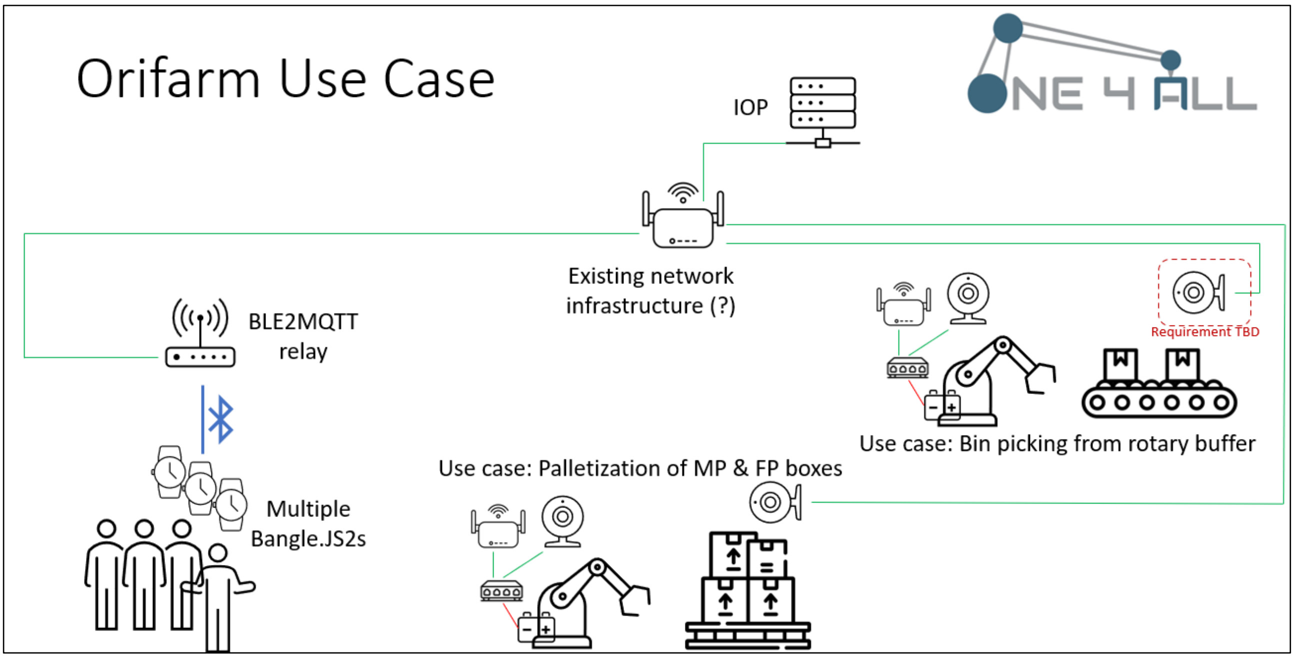

Figure 26 Planned communication topology for sensors in ORI use case

5.3. Current Status and Next Steps

The above connection topology plans have been developed and discussed with both IDE and IBT from a technical standpoint. They form a component of the overall application integration plan, which must be finalised in collaboration with the demo sites. Discussions on the integration of ONE4ALL technologies with existing IT / OT infrastructure with ORI are underway.

It is still possible that technical or security constraints at one or both of the demo sites may prevent the above connection plans from being implemented. Limited Wi-Fi coverage or particular security requirements could prevent the sensor and RCPM devices from integrating with an existing site network. This is identified as a possible risk to delivery, but as several alternate options are available to effectively isolate the sensor and RCPM networking infrastructure from existing demo site systems if required the impact of this risk can be managed effectively.

An appropriate DC-powered PoE network switch has been identified (Linovision 5-port) and will be acquired shortly for full testing. This switch meets all the requirements to be powered by the onboard DC power supply of the RCPM while providing PoE power to both the camera and Bridge Wi-Fi AP.

A number of potentially suitable bridge Wi-Fi APs have been identified. These will be prioritised and the leader acquired for testing shortly.

Conclusion

Task 4.2 is progressing overall as planned, with sensor requirements identified for relevant application case needs, and solution approaches chosen for these requirements. INNO will continue to assess the demo site application cases as technical approaches develop, under both tasks 2.2 and this task 4.2, and be ready to adapt existing quality metrics and sensor implementations or to identify new solutions to additional requirements if and when identified.

The current state and next steps for each sensor category identified for implementation have been detailed in the final sections of each of the chapters above. They so will not be specifically listed here for brevity. Still, in summary, very significant progress has been made against all identified sensor requirements within the ONE4ALL project, with technical risks well managed thus far. The path to completion on two of the three sensor type requirements outlined in this report remains clear, with a high degree of confidence that effective, cost-efficient and highly flexible sensor solutions can be deployed in a timely manner to the demo sites to meet the project's requirements. While some uncertainties are blocking progress on one element of the SOO application, key progress has still been made toward advancing and de-risking these sensor requirements. INNO has confidence that the overall technical uncertainties with this application can be overcome with an efficient and novel solution.

References and Resources

1. MQTT. (2024). MQTT Specifications [Online]. Available: https://mqtt.org/mqtt-specification/
2. Intel, "Intel® Neural Compute Stick 2," NCS2 datasheet, 2017 [Revised July. 2019].
3. Google. "Coral Dev Board datasheet," Coral Dev Board datasheet. 2020 [Revised December 2022].
4. Nvidia, "Jetson Orin Nano Datasheet," Jetson Orin Nano datasheet. 2023
5. Lilygo. (2024). T-Watch S3 [Online]. Available: https://www.lilygo.cc/products/t-watch-s3
6. Espurino. (2024). Bangle.js 2 [Online]. Available: http://www.espruino.com/Bangle.js2
7. BTHome. (2024). BLE advertising in the BTHome v2 format [Online]. Available: https://bthome.io/format/
8. K. He, G. Gkioxari, P. Dollár and R. Girshick, "Mask R-CNN," 2017 IEEE International Conference on Computer Vision (ICCV), Venice, Italy, 2017, pp. 2980-2988, doi: 10.1109/ICCV.2017.322.
9. Wei Liu, Dragomir Anguelov, Dumitru Erhan, Christian Szegedy, Scott Reed, Cheng-Yang Fu, Alexander C. Berg. "SDD: Single Shot Multibox Detector", Lecture Notes in Computer Science, 2016: Springer International Publishing, 2015, pp. 21-37.
10. Killian Batzner, Lars Heckler, Rebecca Konig. (2023, March). "EfficienAD: Accurate Visual Anomoly Detection at Millisecond-Level Latencies" in IEEE/CVF Winter Conference on Applications of Computer Vision (WACV), 2024, pp. 128-138.