Integrated Sensors Kit for Investigation of Perishable Produce Shelf-Life Extension

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***Abstract*— This paper details the process of designing, testing and developing an integrated sensors kit for recording a range of environmental parameters within a newly developed transportation unit called FreshBox. It has been designed to extend product shelf life as well as other improvements on conventional food storage and transportation. The sensors kit is transported within the FreshBox container and monitors the ambient environmental features to which the produce is exposed. CO_2, O_2, temperature and humidity levels are all recorded locally on a memory card and uploaded to the cloud at a later stage via a smart phone app. The unit has been tested during transportation of fresh fruit and vegetables between Spain and Germany.**

Keywords*— Fruit and vegetable transportation, longer shelf-life, environment parameters, sensors

I. INTRODUCTION

The LIFE+ FreshBox project is part of the European Union's LIFE+ programme. The aims of the project are to "improve the sustainability of the distribution of fresh produce to create a more competitive sector that can offer better products to the final consumer." and "to reduce food waste, extend fresh produce shelf life and quality and reduce fuel/energy consumption" [1] through the design and development of a FreshBox container. The container has several distinguishing characteristics:

It is light-weight and manufactured using energy saving technologies and recyclable material.

The smart/active container ensures that the fresh produce is stored and transported in ideal environmental conditions.

The innovative integrated sensor kit monitors the key environmental conditions within the Freshbox and store the data for later analysis and traceability.

Freshbox allows fresh produce to be harvested at a more mature stage than conventional storage methods so the customer benefits from a higher quality end product.

The project team consists of an international partnership of six organisations: four from Spain, one from Germany and one from Ireland and each with their own set of skills and experience. The project "adds value for the EU because it is in line with the current EU Legislation and other European programmes related to reducing food waste and a more sustainable Europe" [1].

The following sections detail the research [2-6] undertaken to identify and select sensors to match the project goals and philosophy. The relevant technical requirements are as follows:

Sensor sensitivity to environmental change, life time of the sensor which typically included sensitivity over time and also the need for incremental calibration, form factor of the sensor (i.e. physical dimension), attribute of interrogation (i.e. does the sensor actually measure the attribute of interest or does it obtain its results through correlated figures), sensor cost, sensor durability, sensor power consumption .

II. SENSORS FUNCTIONALITY AND INITIAL FINDINGS

A. *Carbon Dioxide*

The Consortium partners decided that the optimum range for CO_2 sensitivity should be 0-20%. CO_2 sensor technology ranges from non-dispersive (NDIR) sensors for gas detection to heating elements with solid electrolyte. Heating elements presented an immediate technical challenge with the requirement for a large power source. Many CO_2 sensors must be maintained at a constant high temperature in order to obtain data and this will put an increased strain on the power source, in this case, a rechargeable battery. A total of seventeen sensors were shortlisted with three in particular identified as being very suitable for the project. These devices included built-in temperature and humidity sensors.

B. *Oxygen*

It was concluded by the Consortium that the optimum range for O_2 sensitivity should be 1-20%. A set of oxygen sensors was shortlisted, all of which work on a galvanic cell system. Using this system, the sensors do not impinge on the oxygen atmosphere. Importantly, none of the sensors under review required a warm-up time and they also have very low power requirements which helps the battery retain a longer interval between charges.

C. *Communications Protocol*

Low-power Wi-Fi and Bluetooth smart modules were proposed as communications protocols for Freshbox. Bluetooth smart was selected ahead of Bluetooth classic v2.1 as the former uses 20 to 100 times less power. Data transfer rates and functionality met with the requirements for Freshbox also.

D. Additional Units

The option of adding an accelerometer was also explored. It was decided to add an accelerometer to the printed circuit board (P.C.B.) but not to activate it until it was required at a later stage.

E. Housing Units

It was initially proposed that the housing for the integrated sensors kit would have dimensions of 150mm x 150mm x 100mm (W x L x H). These dimensions would be reduced as the research progressed and were dependent on the power requirements and the final P.C.B. design as well as the requirement for IP55 rating.

F. Ethylene Sensor

The Consortium partners decided that another feature worth monitoring was Ethylene. To this end, research concluded that an effective method of Ethylene level recording was through the measurement of Methane in the range 0-3%. It was discovered that by measuring Methane gas levels a correlated measurement of Ethylene could be asserted. Further research was completed by IMaR in this respect.

III. SENSORS SELECTION

A. Carbon Dioxide Sensor

SenseAir's BLG CO_2 sensor was chosen as the final unit for Carbon Dioxide measurement. Ease of calibration, long life, low power consumption, well-established communication protocol and ease of P.C.B. integration were all factors that made this the sensor of choice. Additionally, the sensor board comes fitted with temperature and humidity sensors as standard so this reduced the overall P.C.B. footprint. The sensor has a sensitivity in the range of 0-30%.

B. Oxygen Sensor

Ultimately, the Oxygen sensor chosen for the project was not on the original list but was unearthed during a literature investigation of the other sensors [7][8]. The chosen sensor is the XYO Optical Oxygen sensor manufactured by First-Sensor [9]. Its life expectancy is over twice that of any of the previously short-listed devices. Ease of integration with the control unit was another plus factor along with low power consumption, less than 20mA, during sampling. The device is maintenance free over its five-year operating life and has a sensitivity range of 1-25%.

C. Communication Protocol

The integrated sensors kit comprises a microcontroller which communicates with sensors, retrieves data at set intervals and stores them on a memory card for later analysis. The kit has its own power supply in the form of a rechargeable battery. Two communications channels exist on board the P.C.B., one between the microcontroller and the sensors and the other between the microcontroller and an external device such as a smart phone or tablet. Communication with the sensors is set by the manufacturer and is usually one of the common serial communications protocols, Serial Peripheral Interface (SPI) or Inter-Integrated Circuit (I^2C). Sensor to microcontroller communication is controlled by customised microcontroller software via a direct connection between sensor and microcontroller. Power consumption is controlled by the same software by timing the on-time of each sensor.

Communication between microcontroller and external devices is constrained by the need to minimize power consumption. This was the main factor in eliminating Wi-Fi as a communication protocol as it can consume up to thirty times more power than Bluetooth Classic. Bluetooth Low Energy (BLE) was also investigated as it consumes less power than classic Bluetooth but the tradeoff is lower data transfer speeds and a lower communication range. BLE saves a lot of energy by switching to sleep mode when communication is not required. The software required to communicate via BLE was developed and an Android App was also developed to enable the transfer of data from SD card to a BLE enabled external device. The option to transfer data directly from SD card to PC still remains.

D. Additional Units

The design of the P.C.B. allowed for the inclusion of an accelerometer. The accelerometer enables the microcontroller to record impacts of a specific strength as well as any mishandling events above a certain level. These events could bruise and damage the produce and reduce shelf-life. Several accelerometers were examined and tested and software was developed to allow the chosen accelerometer to interrupt the microcontroller to record an event.

E. Sensor Housing

A critical component of the integrated sensors kit, the housing unit, had to meet several requirements.

secure and restrict movement of the P.C.B. and power supply.

provide air egress because of the localized air temperature difference caused by the electronic components.

for sampling purposes, sufficient air ingress was required.

provide IP55 protection rating for the complete system.

radio wave transparency at 2.45GHz for external communication.

Several prototypes were printed in-house at IMaR. These were useful for testing different sized P.C.B.s and battery pack combinations. Because of the varying climatic conditions experienced during the transportation of fresh produce, prevention of moisture ingress was high on the list of requirements for the housing. Moisture ingress could ultimately damage the delicate electronics in the sensors kit. IP55 protection rating does allow for a certain amount of water ingress but not enough to cause any lasting damage. An IP56 rated housing was sourced and the inclusion of an air vent reduced the final rating to IP55. The overall dimensions, including the air vent, are 160mm x 120mm x 80mm (L x W x H).

F. Ethylene Sensor

The original requirements of the integrated sensors kit included the addition of an Ethylene sensor. Upon investigation, it was discovered that the optimum method of determining Ethylene concentration in an environment was by measuring the

Methane level. Three potential Methane sensors were identified, all manufactured by Dynament [10]. Having a range between 0 and 30,000, these sensors were not sensitive enough to be useable in the project. Several more sensors were investigated but all proved ineligible for different reasons. Ultimately, the Consortium partners unanimously decided to remove the requirement for Ethylene sensing from the project.

IV. PROTOTYPE DEVELOPMENT

The first prototype to be tested utilised a Waspmote sensor board, a readymade device that can accommodate a variety of sensors [11]. It was configured to monitor and record temperature and humidity. Data was stored on an SD card and the only means of data transfer was by physically removing the card from the Waspmote and inserting it into a PC or other card reader.

Fig. 1. Waspmote 2 in 3-D printed housing

Oxy1 was developed using prototyping board and sensed O_2, temperature and humidity without any storage facility.

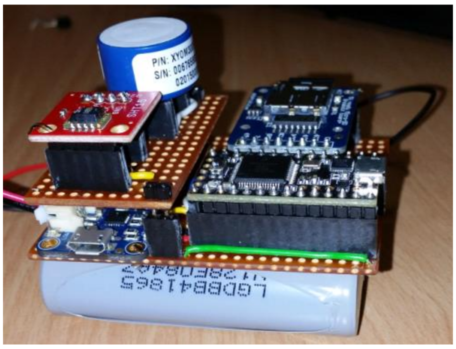


Fig. 2. Oxy1with O_2, temperature and humidity sensors

The next iteration of the prototype, named Oxy2, used the Teensy 3.2 microcontroller. It was configured to communicate with an array of sensors; CO_2, O_2, temperature and humidity. Data was stored on SD card. External communication was via Bluetooth Classic. It was primarily developed to meet a deadline for live testing of fruit in a Freshbox.

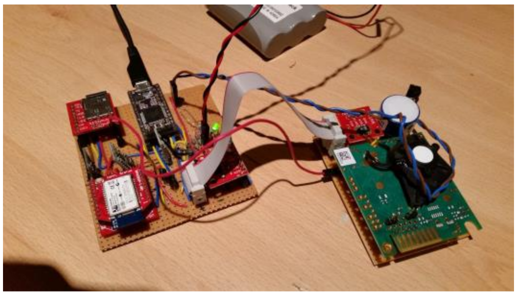


Fig. 3. Oxy2 tested with separate board for sensors

An issue with the relative humidity sensor was addressed in the succeeding prototype, Oxy3.

Oxy4 focused on deploying the BLE protocol for external communication and also the use of a more powerful power supply, 10,000 mAh.

Fig. 4. Oxy4 etched P.C.B., populated with sensors and secured in housing.

Prototype, Oxy5, included an accelerometer. Because of incompatibilities with the Teensy several accelerometers had to be assessed. The final device has been added to the P.C.B. but it had to be switched off because of oversensitivity to impact.

Integrated sensors kit version 1.2 was the final iteration of prototype and was developed into a fully functional P.C.B. ready to be deployed in the field.

Fig. 5. Integrated sensors kit v 1.2 P.C.B. in housing

Fig. 6. Integrated sensors kits ready to be deployed

V. ANDROID APP DEVELOPMENT

The integrated sensors kit was designed so that sensor records could be transferred via BLE to an Android device via a customised app. The app was developed using MIT's appinventor2 open source software. It can be installed on BLE enabled Android devices. The app scans for integrated sensors kits within range. The user is prompted to choose a kit from a list and transfer the data to the device. Data must be uploaded to a cloud-based database for future analysis. The app manages this transfer once the user selects a file. Itinerary details, matching the data in the chosen file, must be added by the user. Each parameter may be viewed on a chart per itinerary.

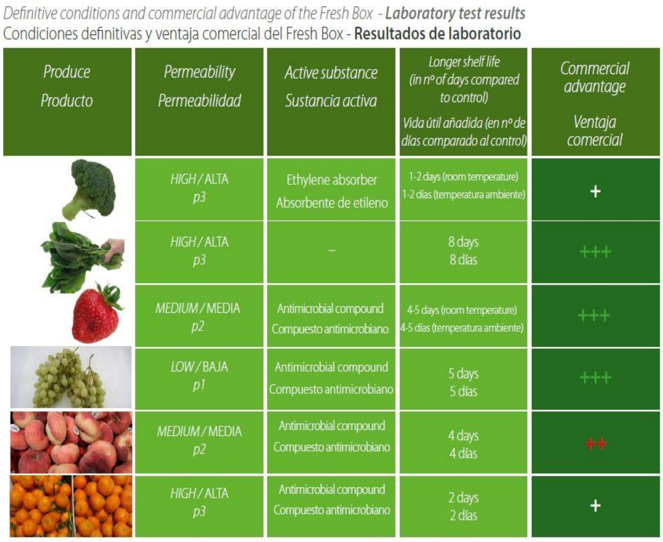
Fig. 7. Parametric data per itinerary

VI. RESULTS

Data analysis was conducted by PCTAD in Zaragoza, Spain. Having selected a number of fruits and vegetables, laboratory testing of the produce was completed prior to transportation testing. These tests were undertaken between April and December 2015 and primarily focussed on absorption of gases. Fig. 8 below illustrates some of the laboratory test results. Significant shelf life extensions were observed.

Transportation tests were carried out between May and December 2016. Fresh produce was transported in Freshboxes via climate controlled trucks between Zaragoza, Spain and Düsseldorf, Germany. Each truck made a return trip to Spain carrying a different fruit or vegetable. A sensorskit was transported in a Freshbox with each consignment. After each itinerary the data was stored on pc and analysed. From the analysis the only produce that did not exhibit a commercial advantage, having been transported in the manner described, was spinach. Fig. 9 illustrates the transportation test results.

A final report is due to be published in August 2017 and a more in-depth analysis of the results and a final technical evaluation will be included.

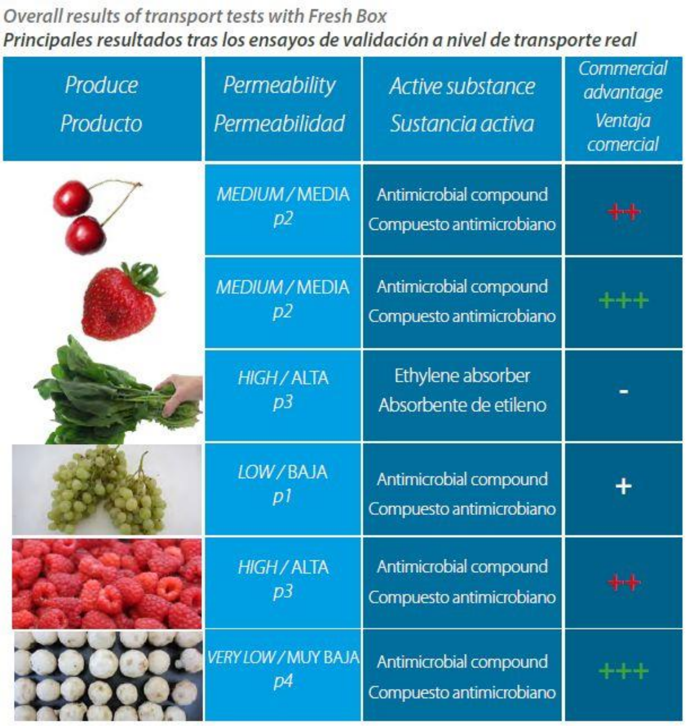


Definitive conditions and commercial advantage of the Fresh Box - **Laboratory test results**
Condiciones definitivas y ventaja comercial del Fresh Box - **Resultados de laboratorio**

Produce / Producto	Permeability / Permeabilidad	Active substance / Sustancia activa	Longer shelf life (in nº of days compared to control) / Vida útil añadida (en nº de días comparado al control)	Commercial advantage / Ventaja comercial
	HIGH / ALTA p3	Ethylene absorber / Absorbente de etileno	1-2 days (room temperature) / 1-2 días (temperatura ambiente)	+
	HIGH / ALTA p3	–	8 days / 8 días	+++
	MEDIUM / MEDIA p2	Antimicrobial compound / Compuesto antimicrobiano	4-5 days (room temperature) / 4-5 días (temperatura ambiente)	+++
	LOW / BAJA p1	Antimicrobial compound / Compuesto antimicrobiano	5 days / 5 días	+++
	MEDIUM / MEDIA p2	Antimicrobial compound / Compuesto antimicrobiano	4 days / 4 días	++
	HIGH / ALTA p3	Antimicrobial compound / Compuesto antimicrobiano	2 days / 2 días	+

Fig. 8. Laboratory test results for selected fruits and vegetables.

Image adapted from http://fresh-box.info/en/project-actions/actions-28.html



Overall results of transport tests with Fresh Box
Principales resultados tras los ensayos de validación a nivel de transporte real

Produce / Producto	Permeability / Permeabilidad	Active substance / Sustancia activa	Commercial advantage / Ventaja comercial
	MEDIUM / MEDIA p2	Antimicrobial compound / Compuesto antimicrobiano	++
	MEDIUM / MEDIA p2	Antimicrobial compound / Compuesto antimicrobiano	+++
	HIGH / ALTA p3	Ethylene absorber / Absorbente de etileno	-
	LOW / BAJA p1	Antimicrobial compound / Compuesto antimicrobiano	+
	HIGH / ALTA p3	Antimicrobial compound / Compuesto antimicrobiano	++
	VERY LOW / MUY BAJA p4	Antimicrobial compound / Compuesto antimicrobiano	+++

Fig. 9. Transportation test results.

Image adapted from http://fresh-box.info/en/project-actions/actions-28.html

VII. Conclusions and Recommendations

The development of a fully integrated sensors kit by IMaR was successfully completed and transported to our partners in Spain. The kits have been deployed in the field and the data has been collected and analysed.

Further developments of the integrated sensor kit could incorporate a cheaper suite of sensors, making the kit more economical for mass production. Once Ethylene sensors of a suitable size and cost become available they can be integrated into the overall design. A new circuit board may be added to the existing P.C.B. to replace the existing accelerometer once more testing of a suitable accelerometer is completed.

Acknowledgments

I would like to thank the staff at IMaR and our Consortium partners Aitiip, PCTAD, Kölla & Co., LaFuente Tomey, S.L., Transfer LBC. Project co-financed by the European Union through the LIFE programme.

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