Smart-Fish System for Fresh Fish Cold Chain Transportation – Overall Approach and Selection of Sensor Materials

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***Abstract*—This paper gives and overview of Cold Chain temperature measuring solutions available on a commercial market and introduces an approach of building a smart system for fresh fish transportation, called Smart-Fish. The system measurement ability ranges beyond a temperature measurement. It also features a GPS-based tracking and may be equipped with other types of sensors. A great domain-specific applicability for real-time measures and potentially low production cost stands the system out of crowd of similar solutions. Printed electronics technologies were utilised for temperature sensor, the key element of the system. The paper describes a set of requirements, results of material tests and final selection of material for this element.**

I. Introduction

A concept of Cold Chain Management (CCM) has emerged from Supply Chain Management (SCM) because of a growing demand for a higher quality of easily-perished products and more specific requirements to increase effectiveness of supply chain [1]. Along with medical products, food is one of subjects of cold chain, and fresh fish is one of the most demanding products.

Food industry is very much concerned about saving costs through reducing waist and saving energy with more efficient arranging a food cold chain [2]. Addressing climate change by reducing waist [3],[4] and saving energy [5], and also - obtaining better quality and safety of food [2] is a need of today's society.

In accordance to [6], the global market for food traceability technologies will grow from 10,7 billion USD in 2016 to 15,1 billion USD in 2021 with a Compound Annual Growth Rate (CAGR) of 7,1%. Among the key enabling technologies – barcodes, RFID/RTLS, GPS, infrared technology and biometrics are named, and service segment may include services for technology integration, online traceability, and domain-specific customised services [6].

Support for field operations such as transportation is important since these operations may take a significant time frame of supply chain process. A nature of support develops over years. For example a utilisation of mobile devices by field workers used to be novel, but now it is an essential part of their professional activities [7][8][9]. Cloud computing engine supporting mobile interfaces can bring a variety of advantages, among which are better quality of data processing and presentation, energy efficiency, and other [10].

Temperature conditions are very important to easily-perished products and therefore time/temperature control is crucial in cold chain. Effective tracking of temperature conditions is the most important point to be focused with technical and organisational solutions. [8].

A variety of enabling technologies presented in report [6] are currently utilised by cold chain solutions. Modern printed electronics technologies can bring extra value with their traditional benefits such as physical flexibility, power efficiency and low-cost production [11].

The rest of this paper has the following structure. An overview of Cold Chain temperature measuring solutions is given in Section II. In Section III the Smart-Fish approach for fresh fish transportation is introduced, including some of architecture, hardware and end user interface particularities, and temperature sensor requirements. Section IV describes results of material tests and selection of printed temperature sensor. In Conclusion, a summary of the paper is given along with a review of possible other application areas and a short overview of future work.

II. Overview of Cold Chain Temperature Solutions

A. Temperature indicators

Temperature indicators are simple, lightweight and inexpensive devices that can be used to visually demonstrate the condition a product has been subject to, and enable quick accept or reject decision making on receipt of shipment.

With a colour change indicator or small LCD/LED display (OK/Alarm status) these small devices provide a single visible result, an indication to confirm whether or not the product has exceeded a set value (e.g. a threshold heat or freeze event has occurred) and/or provide an estimate to the cumulative time over which the exposure has occurred (e.g. [12]). They are easy to activate in the field, simple to use and require little or no training or reading software to use. They often take the form of cardboard strips/self-adhesive labels or small devices, to be placed on the product or within a shipment, and able to monitor products individually. Temperature indicators also

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benefit from a long operating/shelf life of around 12-18 months.

The limitations of temperature indicators are that the alarm/colour change processes are irreversible and so they are single use, non-reusable devices. Some of the newer electronic devices may feature multiple alarm limits, however for the majority, once the temperature threshold has been breached, the alarm/colour indicator will be irreversibly set off, even after temperatures have returned to acceptable levels. With chemical indicators, identifying a colour change is subjective and not an exact or accurate temperature reading. For both chemical and electronic indicators, they provide a record of temperature exposure, but do not have any data capture and/or wireless communication functionality.

Key Brands and Products: Chemical: Temptime Corporation (Heat Marker, Freeze Marker, Trans Tracker), 3M Monitor Mark, Sensitech Clear Alert, TimeStrip, FreezeCheck, ColdMark, WarmMark. Electronic: Berlinger (Q Tag, Mini-Tag, Freeze-Tag), Sensitech Tag/Vax/Thermo Alert.

B. Temperature Data Loggers

Temperature data loggers are devices that continually record temperature measurements over a period of time (e.g. during transportation). These battery-operated devices, have a considerable data storage capacity and provide accurate temperature and time information, showing exactly when the temperature has fallen outside of a recommended range and for how long. A majority of loggers have a simple integrated USB interface, which when connected to a PC will automatically generate report with all measured data (e.g. [13]). Additional software may be required for downloading and viewing the information.

Temperature data loggers are usually easy to set up and user friendly. Some loggers have pre-configured factory settings, but most offer a degree of personalised user configuration such as altering measuring intervals and multiple alarm settings (e.g. high/low). There are a large variety of temperature data loggers on the market, the less expensive options tend to be single use, but there are reusable devices available. In addition, they vary considerably in size, from small, disposable units and the size of a credit card, to larger, more robust loggers with considerable data storage capacity.

The main limitation to these devices is that data is not available real time, instead only when the shipment has arrived at its destination and data has been downloaded for later analysis. With no visibility or live alert/feedback system in transport, there is an inability to intervene or fix a problem, thus not solving the problem of product spoilage or wastage.

Key Brands and Products: Berlinger (Q Tag), LogTag Recorder, Sensitech Temptale USB, Tiny Tag Transit, TempSen ITAG/Tempod/Alpha, Lascar EasyLog, Elpro Libero CS, Deltratrak Flashlink USB, TSS WebLogger, TSS TempTracer, LOG-IC USB logger, PakSense Xpress PDF.

C. Wireless Radio Temperature Devices

The introduction wireless communication technologies into temperature management has provided the ability to collect and communicate temperature information wirelessly in real time. Wireless tracking system uses radio waves to transfer data from an electronic tag or “smart label” attached to an object, through a reader for the purpose of identifying and tracking the object [14].

The reader and tag must be placed together within the reading range for this wireless data transfer to occur. The reader can take the form of a bespoke hand-held device or fixed unit, or more recently, mobile phones and tablets have been used as a reader. The data can be quickly viewed on your mobile phone or tablet, and emailed directly from the device for review at another location.

There are two main categories wireless temperature devices on the market; compact data logging devices, and the more flexible, credit-card sized smart labels.

RFID Data Loggers

These loggers are small, robust devices designed to be affixed to the inside of a shipment and scanned without opening the container; giving full access to data without sacrificing the integrity of the package contents. They are often enclosed in a rugged, waterproof and dust free casing. RFID data loggers are usually multi-use, have a long battery life of 1-3 years and a large memory size. They are user programmable, including setting time intervals and multiple alarms and some have a LED indication of alarm and record status.

Key Brands and Products: TrackIT RPID, CAEN RFID Easy2Log, FlashLink RF Temperature Logger, Omega Nomad.

Smart Labels

Smart labels provide an innovative temperature tracking solution and are composed of an embedded RFID/NFC/BT and temperature sensor microchip, a flexible battery, a real-time clock to record sensor data at constant intervals and a unique identifier (UID). Following the same principle as the data loggers, the label records and stores temperature and time data; which can then be downloaded wirelessly through NFC or Bluetooth technology, via an application on an NFC/BT-enabled smart phone or tablet.

The main feature of Smart Labels is their size. Lightweight, thin and with an adhesive backing, these labels can be affixed to a variety of packages and surfaces. They are highly durable, often being water resistant and dust proof. Mostly designed to be disposable and single use. Some smart labels have an LED display to signify alarm and recording status.

These temperature monitoring devices offer the ability for detailed and accurate temperature, time and product information to be recorded and automatically transferred to mobile phones/tablets. Aside from attaching the devices to the containers and setting them up; the manual effort of collecting the data is greatly reduced.

One of the main limitations to this system, is that this wireless transfer of data can only occur when the label and the reader are within range of each other. This can occur at any time, in packaging, during transport and when the shipment has reached its destination, but it requires someone to manually place the tag/label and reader within close distance of each other in order to establish a wireless connection. Most of the wireless communication technologies used are for short-length communication (up to 25 cm built on ISO 14443 LF standard and 1–1,5 m built on ISO 15693 HF standard) [15] and so a lot of the products currently on the market require a close connection between the two devices for this data transfer to occur. To this effect, the data capture is not in real time, and most likely the data will be downloaded after the event (e.g. after transport), which restricts the ability to intervene or make any changes to the shipment, if problems or threshold excursions have occurred.

Key Brands and Products: Avery Dennison TT Sensor Plus, UID Tempevent, Paladin ID Smart Label Temperature Log-ger, Flexstr8 Smart Temperature Label, Identiv uTrust Sense Temperature Tracker, KSW Microtec Variosens, LOG-IC NFC Logger, DELTA Microelectronics THOR, PakSense UltraNFC Labels, TAG Sensors, Thinfilm Temperature Threshold Indicator.

D. Real-time cloud-based temperature and location monitoring devices

These devices use cellular connectivity to securely transfer temperature, time and location data in real-time to cloud-based storage software (e.g. as in [16]). In range of a wireless network, these data logger devices collect and transfer data wirelessly, using cellular networks (GSM, GPRS, 2G, 3G, 4G), to cloud based applications. Integrated GPS receivers provide information on location tracking. Outside of a wireless network, loggers continue to record and save their measurements, automatically downloading them upon arrival with a wireless network.

The recorded data can be accessed remotely, at any time via a web-based or mobile application. The cloud software offers huge potential for reporting and data interpretation functionality. These robust devices provide the opportunity for a huge wealth of information to be collected, from shipment creation (unique ID), trip information (departure and arrival times, location), and condition (e.g. environmental, handling, door opening). There are a wide variety of different sensors available, offering valuable information such as humidity, light, shock, and tamper evidence.

The benefit of being in real time, is that any problems such as temperature excursions, are picked up quickly and there is the opportunity to intervene and correct the problem. Alerts (e.g. text, email) can be set up to automatically indicate when thresholds are about to be exceeded, enabling pro-active intervention. In addition, with the GPS tracking facility, there is advanced information about where the product is located and when it will arrive at its destination. These automated systems decrease the amount of manual activities required for the tracking and monitoring of temperature-sensitive products.

There are two main types of real-time system. Stand-alone compact devices; and separate systems which include individual sensors and an access box which communicates the data from and to the sensors via cellular networks.

Stand-alone devices

Small, battery operated devices, which are easy to integrate into any shipment and encompass tracking and data log-ging functionalities.

Key Brands and Products: Sensitech VizComm Geo, Sensitech VizComm Geo Eagle, Paksense Autosense real time log-ger, Roambee, Sendum PT300, Locus Traxx SmartTraxx GO, Sensaware 2000 (Fedex), Marken Sentry, Nimble Toucan N5, DeltaTrak Flashlink Real Time logger,

Sensor and Access Box Systems

These systems consist of separate sensor devices which wirelessly communicate with an access box. The access box is a reader device which securely communicates data to a web/mobile application using cellular networks. The access box modem combines cellular and GPS communication functions, and is often a fixed device, being positioned at the destination/distribution depot, or within the transport vehicle itself (dashboard). Multi-sensor systems are more efficient in measuring temperature [17], but at the same time are more expensive.

The limiting factor to these systems is that if the sensor and access box are not in location of each other, data will not be updated in real time, only when they are in a suitable range to communicate.

Key Brands and Products: Berlinger Smart Point (communication device Smart Gate), CartaSense U-Sensor, CoolPac GPS Tracking and Wireless Temperature Monitoring, Zenatek Tracking System, Xsense BT9 HiTags and Communications Unit, SenseAnywhere AiroSensor (with access point), Lab Sensor Solutions T Tracks.

III. PROPOSED APPROACH

A. Overall Architecture

An overview of existing cold chain temperature solution brought understanding that future-proof system must be of real-time cloud-based temperature and location monitoring device type [18], competing with performance of temperature sensor, domain-specific applicability of entire system, and low-cost.

As a result of collaborative work of research institutions and business entities from different countries a Smart-Fish system was originated. The architecture of the system is shown in Fig. 1. This is a wireless transmission system and a selection of components, which can collect data from the individual sensors and upload it to a cloud server, which is used to process data and provide end users with GUIs. Some parts of the system are implemented using printed electronics technologies.

System architecture was designed as utilising real-time cloud data collection engine. The system can log temperature data from sensors in real time and send alarms and notifications for the person in charge if the temperature is out of limits. With alarms and real-time data, it is possible to prevent fish spoilage and calculate remaining shelf life of the fish product.

Telecommunication system is low power to ensure at least four days transmission with battery power. Mesh network is required in order that every sensor has the possibility to send data to collector device even if some of the sensors aren't working properly. Low transmission peak power is required because of the printed battery restrictions.

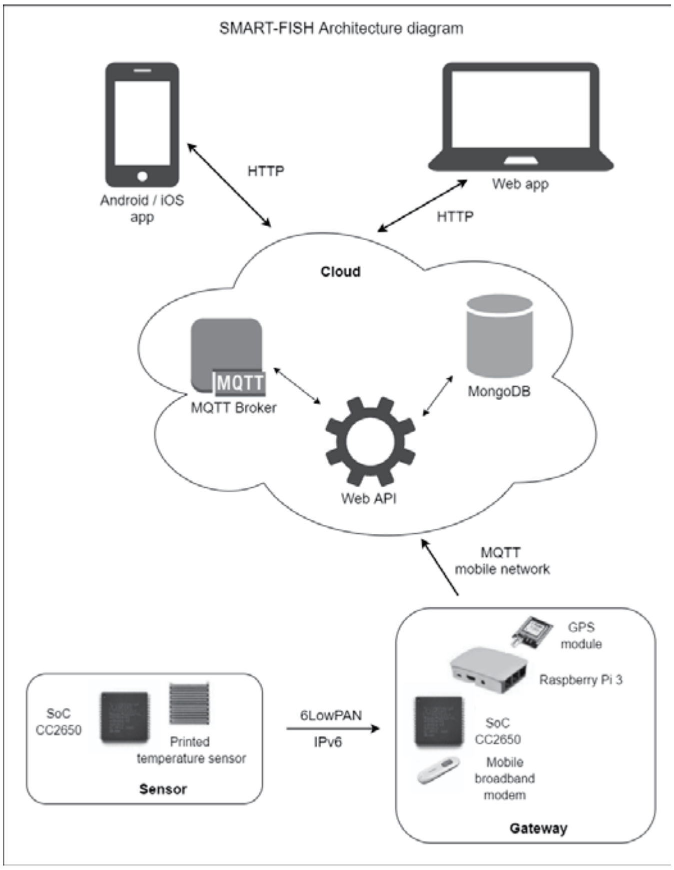

Fig. 1. Smart-Fish System Architecture Diagram

Received raw data is calibrated and stored in cloud. It has been decided to make any necessary data calculations in the cloud to reduce gateway CPU load and power consumption. For cloud database it has been decided to use MongoDB because it is versatile and easily configured to work with different kind of systems and data types, including non-relational.

B. Hardware design

Sensor module, called Smart Label, has a custom design circuit boards that is based on TI CC2650 SoC as Border-Router. The module is also equipped with printed temperature sensors for measuring products temperature. A variety of other sensors may potentially be added (e.g. humidity, light, etc.) to significantly expand functionalities of the system. The form of the module has been designed with involvement of industry experts to achieve the best domain-specific applicability. The Smart Label module is shown in Fig. 2.

Smart Label sensor battery life and energy consumption is critical. Battery life must be at least four days (96 hours) following the industry demand. Sensors should be in sleep-mode all the time, except when it is transmitting data to server. Transmission happens every 15 minutes. When sensor is transmitting the data, energy consumption peak-values must be low enough (~30mW). This is because the Smart-Label system will use printed batteries which have restricted peak-values.

Fig. 2. Smart Label

Gateway module, called Collector, consists of three components: Raspberry Pi 3B, Venus GPS + antenna, and TI CC2650 SoC based Border-Router. The Collector module is shown in Fig. 3.

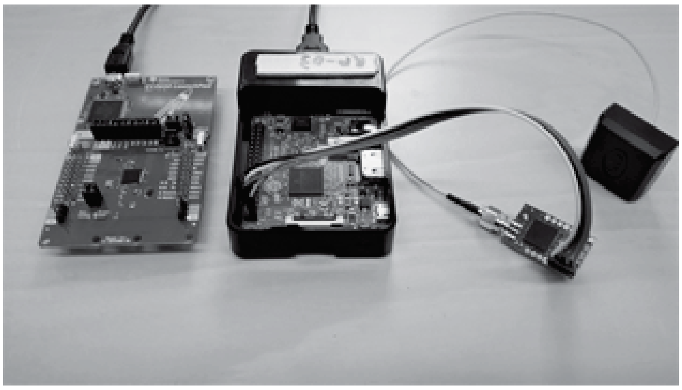

Fig. 3. Collector Gateway

System includes low power short distance 2.4GHz wireless sender that includes printed temperature sensor. Linux based gateway for data collection and mobile network connection. Cloud-based engine for data processing is a server, and a part of the systems is a web server for easy data access. All temperature data is collected every five minutes by gateway and is sent to the cloud with timestamp and GPS information. In case of missing mobile network access data is stored in gateway and sent to the cloud when network access is available.

6LoWPAN IPv6 protocols are used for communication between Smart-Labels and Collector unit. Communication with cloud server is handled with MQTT protocol.

C. User Interface

End user GUIs are developed as browser-based and mobile Android/iOS applications. They use HTTP protocol to communicate with the cloud server.

The domain-specific applicability of the Smart Fish system in field operations such as Cold Chain transportation brings certain requirements for mobile interfaces and their functionality [7],[8],[9].

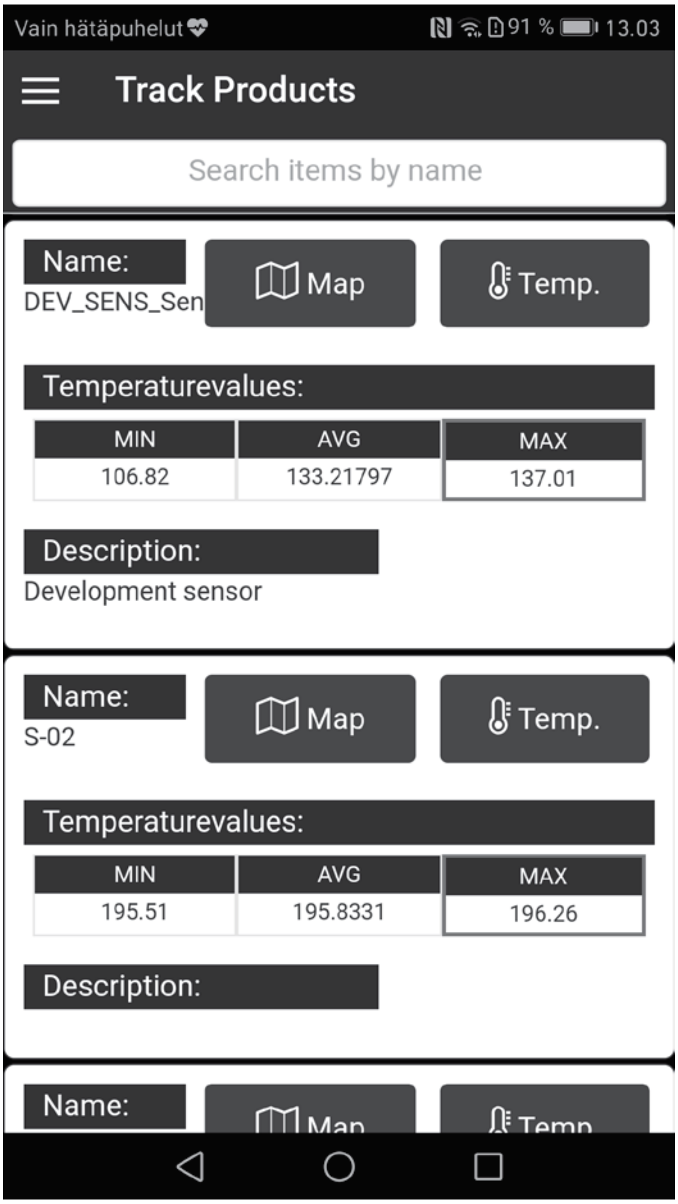

Fig. 4. Smart-Fish Mobile Interface: Tracking

A traceability of food [19][20][21] has a direct positive effect on a performance of Cold Chain and sequentially – quality of food. The importance of location tracking along with a temperature tracking, which is a primary purpose of the Smart-Fish system, have been reflected by design of end user interfaces (Fig. 4).

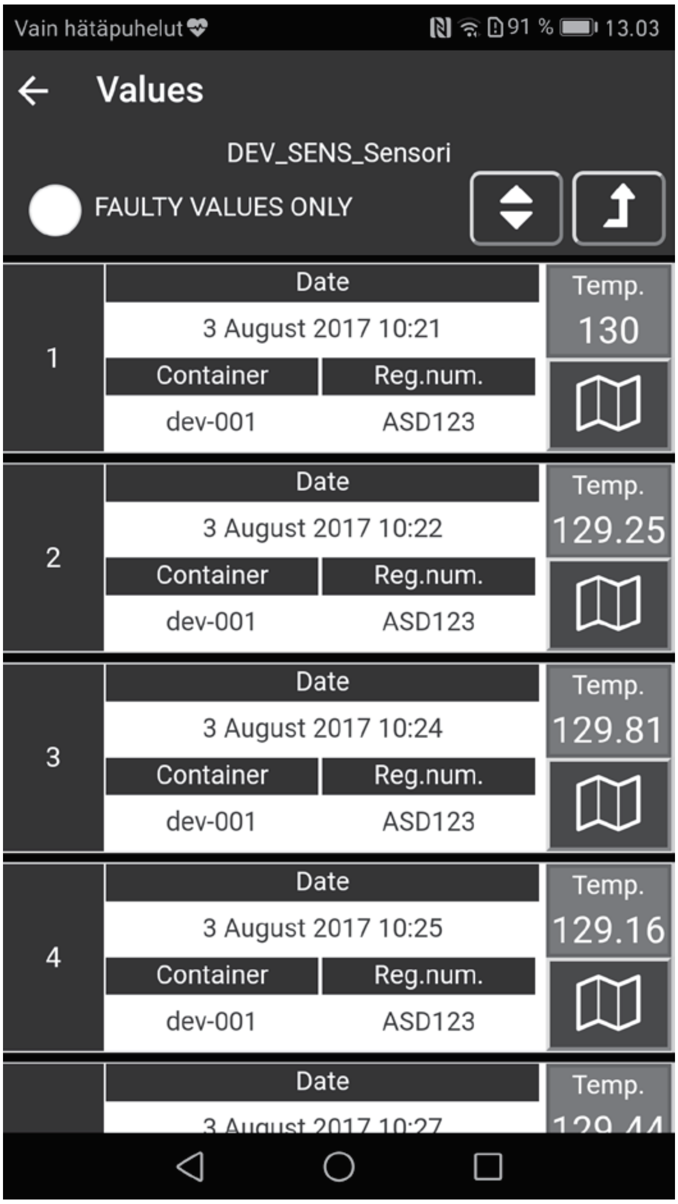

Fig. 5. Smart-Fish Mobile Interface: Review of Measured Values

The Track Products screen brings information about measured range of temperatures for every Smart Label, and alarms in case of fault. The fault is a situation when the result of temperature measurement exceeds an allowed range. It is possible to review results of measurements (Fig. 5), sort the view, and limit to faulty results only.

D. Temperature Sensor

The Smart-Label temperature sensor is a key element of Smart Fish system to be used for monitoring temperature in fish and other cold supply chains. This particular use case means that the environment where the product is placed is relatively harsh and definitely sets special requirements for the temperature sensor [18].

Sensor requirements are collected from representors of cold chain and fishing industries. The summary of requirements is shown in Table 1. These give important information for both, the developers to design a system satisfying the requirements and the testers to verify that the system satisfies requirements.

Each requirement is uniquely numbered for identification purposes and prioritized according to priority definitions.

TABLE I. SMART-FISH SENSOR TECHNICAL REQUIREMENTS

Req.no.	Requirement	Priority
001	The sensor should be able to measure temperature changes	1
002	Temperature measurement range is -1°C to 10°C	1
003	Temperature measurement accuracy ± 0,5 °C or better	1
004	Sensor can tolerate (survive) ambient temperatures from -20…+35 °C	1
005	Sensor can tolerate salty environment	1
006	Sensors are printed (and mass manufacturable)	1
007	Sensors are flexible (not rigid), min. bending radius 20 mm	1
008	Sensor should withstand repeatable bending at bending radius of 20 mm, 15 bending per minute, for total of 1000 cycles	1
009	Sensor should withstand high force impacts (mechanical stress)	1
010	Sensor must be able to connect to SF Label measurement system (microcontroller)	1
011	Sensor should tolerate water and high humidity	1
012	Sensor materials should be biocompatible	3
013	Sensor operating voltage should not exceed 3 V	2
014	Sensor should enable SF Label battery life time is at least 48 hours	1
015	Sensor can survive in freezer for 48 hours	1
016	Sensor lifetime at least 96 hours	1
017	Sensor shelf life at least 6 months	2
018	Sensor size max. 70 mm x 30 mm x 0,25 mm	1
019	Sensor should withstand UV	2
020	Sensor should withstand static electricity discharge	2
021	Sensor should not be a major cost for the SF Label. Label should cost less than 10x “normal” labels (target around 20 cents (€))	1

Priority Definitions in the table are intended to work as a guideline to prioritize requirements.

- Priority 1: The requirement is a “must have” as outlined by specific need and/or policy/law.
- Priority 2: The requirement is needed for improved functionality, and the fulfilment of the requirements that will create immediate benefits.
- Priority 3: The requirement is a “nice to have” which may bring new functionality.

IV. TEMPERATURE SENSOR MATERIAL TESTING

Total of 19 different types of materials were tested for their suitability to be used as a printed temperature sensor (thermistor). Some materials were used several times by changing something in the manufacturing process or using different substrate. Total number of different samples was 23.

Suitability is set by fulfilling the project requirements shown in the table I. Materials were printed onto thin (50 – 350 µm) PI, PET or paper substrate using table top screen printing, dispensing, inkjetting and Roll-to-Roll gravure manufacturing techniques. The materials were acquired and received from several different manufacturers.

All of the materials are commercially available and they were used unmodified. Only the substrate surface energy was modified when needed. The performance of the materials was evaluated in an environmental test chamber using the temperature range specified in the project (Table I).

Out of 23 samples tested it was found that only one material was performing well enough in the environmental tests. The material performance is suitable to be used as a temperature sensor material in the required temperature range of -1 to +10°C (Table I). Change in material resistance over the specified temperature range is relatively large (~10%) which enables the accuracy requirements to be met. Nominal value in ohms is in the range of 10k…100k, which is suitable for measurement system used in the project and doesn´t unnecessary add the loading of the system.

Some of the tested materials have even bigger change in resistance calculated in percent, but the starting value is excessively low to be used. For example, most of the silver pastes have nominal resistances around a couple of ohms which makes the resistance change hard to measure with the Smart-Fish system. All the tested materials and results of measurements are shown in Table II. In the Table II sample number is the identification of the sample, description column shows the functional part of the material used as well as the formation. Manufacturing process of the sample is shown on the 3rd column. ITO PET was acquired ready made. Rest of the columns show the range of the measured resistances (Ω, kΩ, MΩ) and the change in resistance values from -2°C to +12°C in ohms and percent.

TABLE II. PRINTED TEMPERATURE SENSOR – TESTED MATERIALS

Sample ID	Description of the material	Manufacturing process	Range	Resistance change Ω -2…+12	Resistance change % -2…+12
1	Silver paste	screen	Ω	0,0	0,0
2	Carbon paste	screen	kΩ	43,0	4,3
3	Carbon paste	screen	100Ω	4,8	1,4
4	Carbon paste	screen	100Ω	2,0	0,5
5	Silver paste	screen	Ω	0,0	0,0
6	Silver ink	inkjet	Ω	-0,1	-14,3
7	Carbon paste	screen	kΩ	60,0	3,7
8	Silver paste	dispensing	Ω	0,1	10,0
9	Silver Flexographic Ink	gravure	Ω	0,1	2,9
10	ITO PET		Ω	1,2	1,3
11	Carbon Coating	gravure	kΩ	80,0	1,2
12	Conductive ink	gravure	100Ω	72,9	33,2
13	Carbon paste	gravure	kΩ	-1652,0	-33,0
14	Carbon paste	gravure	kΩ	-50,0	-1,2
15	Carbon paste	gravure	10kΩ	410,0	1,9
16	Conductive ink	inkjet	Ω	0,2	3,8
17	Carbon + Ag/AgCl	screen	Ω	0,0	0,0
18	Silver paste	screen	Ω	0,0	0,0
19	Silver paste	screen	Ω	0,1	1,9
20	ATO dispersion	paint	MΩ	-1300000	-3,4
21	Carbon filled Si ink	Screen (wet to wet)	kΩ	55	3,5
22	Carbon filled Si ink	Screen (wet to dry)	10kΩ	1460	12,6
23	Carbon filled Si ink	Screen one layer	100kΩ	7900	9,5

First prototypes of Smart-Fish temperature sensors are screen printed on 250 µm Valox FR1 PET substrate using the selected carbon blend paste. For light mechanical and environmental protection, the sensors are covered with a thin transparent dielectric layer. However, the dielectric layer does not provide a perfect insulation against conductive materials such as water. An extra layer of insulation should be used in case of possibility of conductive materials to be in contact with the sensor and also for better mechanical protection.

Several different layouts were tested to find the optimal performance of the component as well as optimal manufacturability. Examples of test component layouts are shown in Fig. 6.

Optimal performance would require the component to be sensitive to temperature change, but not to other ambient conditions such as humidity etc. Resistance value should be within reasonable range and the physical size of the component should be suitable to enable easier mass manufacturing using printed technologies, but nevertheless enable small amount of material needed to manufacture it.

Size of the tested component layouts were from 6 x 6 mm to 25 x 30 mm, while some of the layouts used finger structure and some not. Optimizing the layout furthermore would still require more testing.

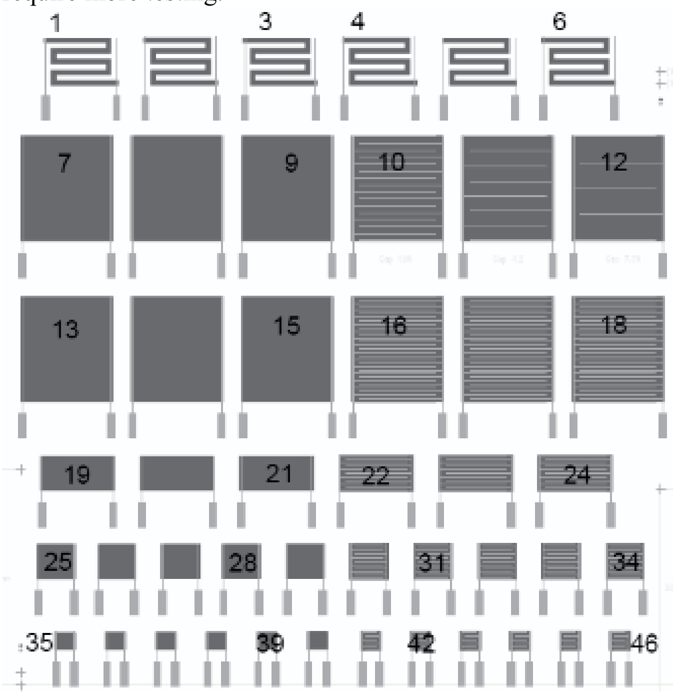

Fig. 6. Printed Temperature Sensor Layout Tests

The printed sensor should not be subjected to heavy mechanical stress, such as low radius bending or the application of a force over small area. Electrical characteristics of the sensor might change permanently if excessive stress is applied.

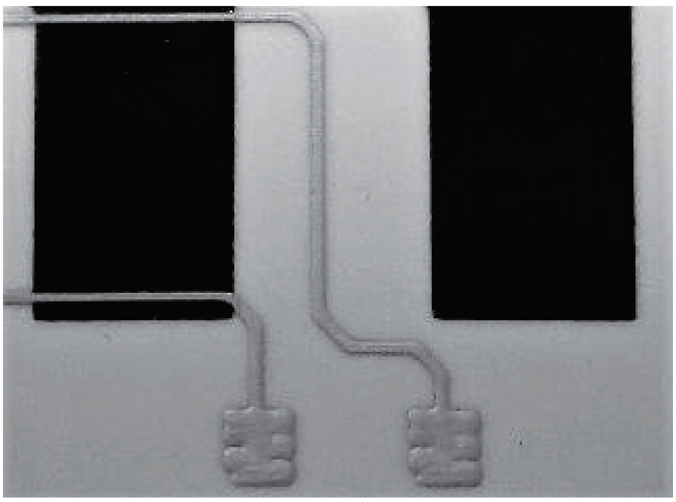

Fig. 7. Smart-Fish temperature sensor v. 0.1 with dispensed silver connecting pads (left) and plain sensor (right)

Nominal resistance of the first batch prototype component measured at 22 °C is ~84 kΩ. Change in resistance between -2 and 12 °C is approximately 600 Ω/°C. Size of the actual sensor area is 10 x 7 mm (Fig. 7).

VI. Conclusion

In this paper an overview of cold chain temperature solutions is given, and architecture of the Smart-Fish system for fresh fish cold chain transportation is introduced. The focus has been on the key element of the system – the printed temperature sensor. A set of requirements, material tests and result of selection are described. The sensor is printed using carbon blend paste with dispensed silver connecting pads. The selected material is the most suitable from the range of those that undergo experiments.

The advantage of the Smart-Fish system is its great domain-specific applicability in real-time data capture facility, which offers the ability for closer control of temperature, to maintain quality properties, allows for more informed decision making and helping to reduce waste. In addition, the ability to operate with other data sources, such as GPS, allows a valuable extension of functionality, for example a product tracking. The overall design and utilisation of printed electronics brought extra expansibility and applicability, and able to reduce an overall cost of an estimated commercial solution – especially in greater volume of products.

This system thereby lends itself to a multitude of different industries and end users. The potential applications for this product include: pharmaceuticals, medical (organ management, blood), clinical trials (biological samples), chemicals and polymers, food and beverage industry (seafood, fruit, frozen, meats), horticulture, live animal transport, cosmetic industry and logistics service providers.

The entire Smart-Fish system will undergo the field experiments and will be a subject of testing for improvement of quality of communications. For example, during the laboratory tests it was found out that current mesh-based solutions use too much power or are too unstable for long term use. The operability may improve with utilisation of Bluetooth 5 or UHF technologies. Bending effects on the printed sensor performance and optimal physical layout are still to be evaluated.

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