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Evaluating Sensor Technologies for Gate-Based Object Counting in an Internet of Things Set-up

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Abstract: The increased computational power of modern embedded devices with the widespread development of Internet infrastructure has brought the Internet of Things (IoT) era closest than ever. Recent market researches indicate that IoT product and relevant service suppliers will generate revenue exceeding $300 billion and the interconnected devices will grow to 26 billion [1, 2]. One field that can be benefited from the common advantages of IoT systems, (real time monitoring, large scale deployment etc.) is the Logistics area. In this paper we investigate a common problem in the logistics which is the automating object counting. We concentrate on uniform, disposable products stored on a pile, queue or a stack (e.g., a shelf) and examine a number of different technologies for sensing input and output through a gate to the storage area and how we can integrate them in an IoT environment. We define a set of comparison criteria with practical flavor in order to examine and evaluate twelve different types of sensors [3]. The intention for our study is to form a baseline for anyone needing to implement gate-based input/output control. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Internet of Things, sensor evaluation, gate control, evaluation of sensor technologies

1. Introduction

Counting items is a central part of stock control and has different forms depending on the products stocked and counted [4]. By automating the process of item counting we may introduce many benefits; simplifying the renewal process, eliminating errors, reducing the management cost, minimizing out of stock periods etc. [5].

In this work, we focus on the topic of gate-based, disposable material placed inside a casing and stored in a pile or queue. Within this setting, we examine the case-study of detecting the addition or removal of a product and consequently calculating reliably the number of items in stock. Simplified systems like these are included in the commercial vending machines, and more advanced schemes in mission-critical or safety-critical applications like determining the storage of blood products in a blood bank.

The question this paper deals with is the assessment of all different types of sensors available for automating this process and how these sensors can be interconnected in an IoT Setup. We define several practical criteria that will help chose the correct type of sensor for any given application [6] and we discuss the hardware and software overhead in order to integrate the sensor in an embedded device. Further considerations are network requirements and fault tolerance features that can be implemented.

Under this perspective, the paper is organized as follows. Section 2 describes current techniques in Supply-Chain Management (SCM) and Section 3 records the factors for sensor assessment. Section 4 discusses the different types of sensors giving a brief definition and listing their advantages and disadvantages with reference to the assessment factors. This critique is subsequently summarized and we finish with outlining our case study and listing conclusions and pointers to future work.

2. Related Work

Most of the today's stock control systems use extensive use of Radio-frequency identification (RFID) technology [5, 7] due to the effective way of recording movement of objects within a networked system [8]. In these systems the stock control is achieved automatically by the information system that supports the Supply-Chain Management (SCM) and unauthorized removal of an object is detected by electronic gates that monitor continuously the physical entry points of the area that the system is installed. To add system intelligence, traditional RFID based SCM are integrated with Wireless Sensor Networks (WSN) [4, 6]. These systems incorporate advanced sensing technologies while for the monitoring of the position of an object, we could use localization techniques.

The above practices while being cost effective for large scale deployments they may not be suitable for ad hoc or small scale deployments: They require changes in the existing physical infrastructure and the deployment of sophisticated Information Systems for which the support cost is not insignificant. Furthermore, SCM systems are expensive because of the nature of the sensors (RFID) that are deployed and the extensive features that are available nowadays.

3. Sensor Evaluation Framework

As mentioned above our assessment has a practical orientation and envisages the scenario when products such as cans or bottles are stores on shelves, stacks or piles. The main, driving requirement of our assessment is to be able to count adding or removing objects in a reliable way defined as:

a) Reject false positives, for example the hand of the carrier is not measured as a product.

b) Spot attempts of cheating, for instance trying to extract product from an input-only entrance.

c) Work under environments that can be hazardous (e.g. freezer).

Under this context, we define the assessment factors shown below under which the different types of sensors are evaluated. We consider the two main driving factors that take place in an industry environment business and technology considerations. We decided not to assign weights to these criteria in order to leave the decision making open to each case-study.

3.1. Business Considerations

a) Cost: The overall amount that needs to be allocated so as to make the sensor operational. This includes not only the cost of the hardware but possibly any software which must be purchased. The cost is calculated per unit of coverage e.g. a switch can cover a shelf but a camera can cover a room of shelves.

b) Installation procedure: How straightforward or complex is the deployment of the sensor in the correct place and whether or not a redevelopment of several physical parts of the system is required.

c) Proven in industry: Whether the sensor has already been deployed in industrial applications and has satisfactory proven to operate under the rough conditions of a real environment.

3.2. Technical Considerations

a) Form Factor: The size of the sensor, a critical parameter in particular applications.

b) Power Consumption: Influences simplicity of installation and use, an important factor when power supply is not available.

c) Reliability: Detecting false positives/negatives e.g. the human hand is not a product moving in or out.

d) Software requirements: Code footprint for software driver and hardware requirements.

e) Hardware requirements: The computational power that is needed in order to support the operation of the sensor. We partition the hardware classes into 3 categories:

- Low: This includes 8-bit microprocessors with small footprint of memory.
- Medium: This includes 16-bit microprocessors with the ability to load a small Operating System (e.g. FreeRTOS) in the system.
- High: Powerful processors able to load an Operating System (e.g. Linux). This category includes a normal PC or an embedded PC (e.g. RaspberryPi).

f) Redundancy: If the sensor or the software can be duplicated in order to take part in a mission-critical system.

g) Network requirements: The communication requirements of the system (wired or wireless), protocol that can support the operation and bandwidth requirements.

4. Materials and Methods

This section examines the twelve different types of sensors that we identified as suitable for gate-based object counting. We outline the way each sensor operates, the industry area that it is mainly used and what are the main advantages and disadvantages.

4.1. Capacitive Sensors

Capacity sensors detect changes in their electric field and estimate proximity [9]. Industrial Style Sensors detect objects passing under/past them. They are widely used in large Form Factors and appear in a number of different packages, suitable mostly for manufacturing lines. They are relatively cheap and can operate under harsh environments, they can be in due course accurate, but their calibration can be very tricky.

Apart from using an off the shelf sensor a custom sensors can be implemented by using 2 I/O pins of a processor that are connected on the same surface [10]. In this scheme we charge the surface using one pin as an output and we measure the response using the other pin.

Generally the software and hardware requirements in using any of the above configurations are very simple, but the energy requirements are high due to the supply of the external sensor or the charging of the capacitive surface.

4.2. Capacitive Array Sensors

Capacitive Arrays are placed on the “floor” side so as to detect an object placed on them. An analogy on how they operate is how a Smart Phone screen detects touch. They are a fairly novel technique and being innovative they are not yet industry proven and therefore risky. Careful design is needed in environments that include water especially for the grounding mechanism. Occupying a whole side, they could be an accurate solution and filter false positives but the installation procedure requires extensive renovation and careful placement of the wires that interconnect the sensors with the processors. The computational power that is needed for these operations can be handled by CPUs in the middle range.

4.3. Inductive Sensors

Inductive sensors are similar to capacitive sensors, and use variations in their magnetic field to determine proximity and subsequently measure distance of metal objects. Industrial variants have the same type of form factors as capacitive sensors and for all intents and purposes, operate the same as Industrial Capacitive Sensors but only detect metal objects.

They are also proven in industry, are accurate, come in robust packaging and large form factors, suitable mostly for manufacturing lines. Most important could only work with products of a metal element like metal caps.

The computational needs (software – hardware) are low.

4.4. Ultrasonic Sensors

Ultrasonic sensors transmit a sound wave (“Ping”) of ultrasonic frequency and measure the time it takes for the wave to return in order to measure distance. They are widely used in both industrial and hobby circles and come in different form factors. A simple everyday day example of the technology is reversing sensors on modern cars.

They are cheap but they lack accuracy in a real industrial environment because they can count employee hands. In order to avoid these faults in the design of the software driver a filtering mechanism must be incorporated and for better results additional sensors must be installed in order to measure from a different angle. The computational needs are quite small even if you connect a large number of sensors in a small CPU.

4.5. Camera based Sensors

A camera can be paired with a smart controller to detect patterns, shapes or colors, to detect objects entering a storage area. The camera could be trained to watch for a distinctive feature of the object, for instance a branding logo, a characteristic shape or a specific color. With the appropriate software processing, cameras could be extremely accurate and can cover a large area.

Yet, they are a complex solution since cameras are an expensive and sensitive component and they would need a more powerful CPU to process images while also being susceptible to environmental changes, such as lighting. The human factor plays a good part; working personnel can block them which means that for a given area more than one camera should be installed. The images from the different angles must be then processed for an aggregated outcome to be reached.

4.6. Switch Technologies

The usage of simple mechanical switches positioned in a way that they switch and count objects as they enter or exit the storage area. They are scalable; you can place one in each entry/exit or an array of switches to reduce the chance of false switching and infer direction and the feature of redundancy in the system.

An interesting aspect is a rotary encoder to detect direction as well as actuation. Switches are reliable and simple, proven in industry and a very cheap solution. Since they require power only when activated, they consume minimum power. Although they cannot differentiate between object and detect false positives if placed in clever way they can minimize such occurrences. They are easy to install and replace. The CPUs that will interface the switches can have low processing power making them ideal solution for WSN nodes.

4.7. Magnetic Switches

These can be described as small, mechanical switches encapsulated in a small glass or plastic enclosure, activated by changes in the magnetic field. They are more reliable and space efficient to the simple mechanical switches and are used in industrial applications. They are cheap, however could be fragile especially the ones with the glass enclosure. From the computational perspective they have exactly the same advantages with the mechanical switches.

4.8. Hall-effect Switches

They come in the form of integrated circuits, also activated by changes in a magnetic field. They are smaller and more sensitive than the magnetic switches and therefore can achieve better performance. They are available in analog and digital form providing higher resolution and can detect not only presence but also distance and speed (through change). Also proven in industry, they add a degree of complexity compared to other solution since they are an electronic component with power and enclosure requirements.

4.9. Optical Sensors

There are various types of optical sensors, two of which are applicable in our domain of interest. The first are Interrupt Beam type sensors, where the transmitting beam and receiving sensor are placed opposite each other. When the object passes the beam the interrupted beam would cause a switch.

The other choice are reflected Beam type Sensors, where the transmitter and receiver are next to each other and the changed angle of the reflected beam is detected when an object passes through it.

Optical sensors have no mechanical parts, so virtually there is no wear. They have many industrial variants that are well proven and can be easily simplified to a light source and photodiode. They may have very small form factors. Their performance though, may be erratic not be able to detect different opacities or false positives.

4.10. Strain Gauge

Load cells are a practical application of Strain Gauges. Ultimately, they measure weight; they consist of an array of piezoelectric materials that generate a voltage proportional to the stress applied. There exist three types worth considering:

a) Bending Beam;
b) Shear Beam;
c) Pancake Cell.

This solution would be the most accurate representation of how many objects are in a storage area if these objects have uniform weight. Since it counts objects individually, it would have the least number of false positives. They are in cheap price if bending or shear beam but they need to be customized for different products. The measured values though have low sensitivity in low temperatures and humidity and self-temperature compensated techniques should be used to avoid this problem. Usually an analog input from the CPU is need which means that low end processors can be used for this range of sensors.

4.11. Barcodes

A barcode is an optical machine-readable representation of data relating to the object to which it is attached. Originally barcodes systematically represented data by varying the widths and spacing of parallel lines, and may be referred to as linear or one-dimensional (1D) [11]. In order to use barcode sensors extensive rework must happen to the mechanical part of the system in order the items to leave from a particular exit and with a certain orientation so that the sensor would be able to identify them correctly. The shape of the object that needs to be counted plays a significant role, rectangular objects are easier to be counted while rounded objects (e.g. bottles) can create big problems in the system because they rotate during the loading-unloading from the shelf. The implementation of the sensors is not a trivial issue but middle range microcontrollers have the necessary processing power to cope with the algorithm of the barcode decoding [12].

Another solution is to buy an off-the-shelf barcode reader and interface through the serial port with a low end microcontroller. This approach reduces significant the development cost since the integration is quite trivial.

4.12. QR Codes

A QR code [13] consists of black modules (square dots) arranged in a square grid on a white background, which can be read by an imaging device (such as a camera) and processed using Reed–Solomon error correction until the image can be appropriately interpreted; data is then extracted from patterns present in both horizontal and vertical components of the image [12]. The need for a camera in order to capture the image makes the technique expensive, while the algorithms in order to decode the QR code are quite sophisticated [14]. The same issue with the shape of the object that we described in the Barcode section exists here as well.

5. Case Study

This research is currently investigating the applicability of the above solutions using as a case-study shelves in which objects embedded in a cylinder shaped boxes are stored. Placing them inside a cylinder box ensures uniformity and eases stock control. Moreover it is a shape that is compatible with switches, capacitive arrays, QR code and optical sensors.

Different shelves with the twelve sensors are used to measure their reliability, endurance, easiness of installation and sensitivity.

6. Conclusions

Table 1 presents in an organized format our findings which generated the following outcomes:

1. Although some are relative to each other (e.g., QR and Barcode), the number of different available approaches makes evident that even in quite specialized situations, an optimum solution could be achieved exactly because of the sheer quantity of solutions.
2. Cost does not appear to be a forbidding factor for any of the technologies, but the application complexity can grow when advanced technologies are selected (e.g. QR) or careful calibration is needed (especially if the system has multiple sensors).
3. Switch-based approaches seem to be the most suitable when cost and simplicity are the main requirements and have the lowest installation cost due to the minimum requirements for cabling and the reduced power consumption.
4. Sensors are available in three forms, namely, mechanical, magnetic mechanical and half-effect providing different levels of sensitivity.
5. As Internet of Things (IoT) grows in importance, choosing the right technology of sensor to link to the communication module of an IoT device will also be pivotal. Simple solutions have a significant advantage because can be easily integrated in existing wireless IoT solutions (e.g. Redwire with Contiki OS).
6. All of the solutions we have investigated do not have any significant network requirements because the processing take place locally in an embedded platform and just disseminate the results through the network to a gateway. Possible workarounds where the local nodes do not process the information but they transmit it to a central server for further processing have been explored but abandoned because they create a significant communication overhead due to the amount of data that have to be transmitted especially in the camera based sensors.
7. Power consumption and durability plays a major role because the hardware usually is installed in harsh conditions and maintenance is difficult to take place.
8. Software drivers that we implemented, for similar sensor technologies, can be reused with minimum re-development cost.
9. Redundant solutions are difficult to be implemented when the sensors need extensive rewiring and external power due to the limited amount of space on the shelves.
10. Wired and wireless communication means with the gateway was explored but wireless communication is more appropriate due to the lack of any cabling between the sensor and the gateway.
11. Mechanical switches suit better. They perform better in the sense of minimum cases of false positives and false negatives especially when they are used in numbers to verify each other’s triggering.
12. The capacitive arrays also provide accurate measurements however their installation process is longer and need to be refitted for every new shelf.
13. The optical sensors require the usage or development of extra software to filter out hand movements of the hand placing objects in our out of the shelf.
14. The QR and barcode choices need special care from the user to scan the code and from the system to give feedback (e.g., sound).

7. Future Work

In this work we assessed the suitability of twelve different types of sensors for gate input/output control of simple regular-sized items As requirements and their gravity vary on each application, there is no single preferred solution. It is remarkable however how technologies of diverse orientation could be applied to solve a single problem.

Current and future research work involves not only the further specification of the assessment factors but the application of techniques, such as fuzzy logic with sets associating factors and sensors and different fuzzy rules to apply in order to get a qualitative or quantitative marking. This will enable to objectify the suitability of every sensor technology for specific application needs.

Table 1. Synopsis of Sensors and their features.

Sensor	Cost	Install effort	Industry	Power	Form	Robustness	Reliability	Software/ Hardware
Capacitive	L	M-H	Bottling and Manufacturing plants	H	L-M	H	H	L
Capacitive Array	L	H	None	H	L-H	M	Unproven	M
Inductive	L	M-H	Manufacturing Bottling	L	L-M	H	H	L
Ultrasonic	L–M	M	Diverse	M	L-H	L-H	H	L
Optical Interrupt Beam	M-H	M	People Counting Bottling and Manufacturing plants	M	M	H	H	L
Optical Reflected Beam	M-H	M	Bottling and Manufacturing plants	M	M	H	H	L
QR	H	H	Diverse	H	M	L-H	High for certain shapes	H
Camera	H	H	None	H	H	L-H	H	H
Mechanical Switch	L	L	Diverse, Variety of equipment and applications	L	L	L-H	H	L
Magnetic Switch	L	L	Diverse, Variety of equipment and applications	L	L	L-M	H	L
Hall-effect Switch	L	L	Diverse, Variety of equipment and applications	L	L	M-H	H	L
Weight Load Cell	L-H	H	Weighting scales, Mini Bar Fridges	L	L-H	L-H	H	L
Barcode	M	H	Diverse	H	L-M	L-H	High for certain shapes	H

L: Low, M: Medium, H: High

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