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C^2SLDS: A WSN-based perishable food shelf-life prediction and LSFO strategy decision support system in cold chain logistics

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ABSTRACT

Temperature monitoring, shelf-life visibility and Least Shelf-life First Out (LSFO) stock strategy are important contents in perishable food cold chain logistics for both cold chain managers and workers in order to reduce quality and economic losses. This paper illustrates a wireless sensor network (WSN) based integrated Cold Chain Shelf Life Decision Support System (C^2SLDS) designed for perishable food product cold chain management. The system is implemented based on the WSN and time temperature indicator (TTI) features. Compared with traditional cold chain management methods used before, the C^2SLDS not only bridges the information gap which exists between different cold chain phase enterprises and provide a seamless information flow along the whole chain but also enables cold chain enterprises to predict perishable food's shelf-life and helps make a smart LSFO strategy to reduce the quality and economic loss. System test and evaluation shows that the infield radio transmission is reliable and the whole system meets most of the users' requirements raised in system analysis.

1. Introduction

Many food products are perishable by nature attributes and require protection from spoilage during their preparation, storage and distribution to give them desired shelf-life (Holley & Patel, 2005). Shelf-life is the time during which a perishable food remains safe, complies with a label declaration of nutritional data and retain desired sensory, chemical, physical and microbiological characteristics when stored under the recommended conditions (IFST, 1993). Temperature is one of the most important parameters of quality control and freshness is almost an exclusive function of time and temperature. Thus the temperature is becoming an important function for perishable food and visibility & traceability is especially important in its cold chains (Zhang, Liu, Mu, Moga, & Zhang, 2009).

In order to ensure freshness, extend shelf-life and enhance perishable food safety and security, cold chain management (CCM) methods are established. In CCM developments and practices, solutions provides temperature monitoring, shelf-life visibility, position visibility and LSFO decision support are required by cold chain managers in the remote and workers infield. TTI and WSN are currently highly researched to fulfill the above demand.

In the cold chain infield aspect, TTI provides the continuously monitor and record the time–temperature history along the whole supply chain in a simple and economical way (Taoukis & Labuza, 1989). For now, there were different kinds of TTI based on chemical (Galagan & Su, 2008; Kreyenschmidt, Christiansen, Hubner, Raab, & Petersen, 2010; Lee & Shin, 2012; Nga et al., 2011), microbiological (Ellouze & Augustin, 2010; Y. A. Kim, Jung, Park, Chung, & Lee, 2012; M. J. Kim, Jung, Park, & Lee, 2012; Vaikousi, Biliaderis, & Koutsoumanis, 2008; Wanihsuksombat, Hongtrakul, & Suppakul, 2010), mechanical (Mehauden, Bakalis, Cox, Fryer, & Simmons, 2008) and enzymatic (Giannakourou, Koutsoumanis, Nychas, & Taoukis, 2005; W. Kim, Choe, & Hong, 2012; Smolander, Alakomi, Ritvanen, Vainionpää, & Ahvenainen, 2004; Yan et al., 2008) principles had been developed and tested in the perishable food supply chain.

For cold chain managers in remote, WSN is a cost-effective sensor and communications technology that allows the distributed data acquisitions and transmission from anywhere to end users, in locations without a previous telecommunication infrastructure (Garcia-Sanchez, Garcia-Sanchez, & Garcia-Haro, 2011). In a 'from farm to fork' style food supply chain, the WSN has been

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applied in many phases include the precision agriculture (Damas, Prados, Gómez, & Olivares, 2001), precision viticulture (Matese, Di Gennaro, Zaldei, Genesio, & Vaccari, 2009; Peres et al., 2011), precision harvest (Yu, Li, Rains, & Hamrita, 2011a, 2011b), greenhouse control (Kolokotsa, Saridakis, Dalamagkidis, Dolianitis, & Kaliakatsos, 2010), grain storage monitoring (Zhao, Yu, & Yuan, 2010), animal behavior monitoring (Butler, Corke, Peterson, & Rus, 2004; Ma, Wang, & Ying, 2011; Nadimi, Blanes-Vidal, Jørgensen, & Christensen, 2011), fish farm (Lloret, Sendra, Garcia, & Lloret, 2011; Qi, Zhang, et al., 2011), cold chain management (Jedermann, Behrens, Westphal, & Lang, 2006; Kacimi, Dhaou, & Beylot, 2009; Lakshmil & Vijayakumar, 2012; Wang, Jabbari, Jedermann, Laur, & Lang, 2010) and entire supply chain management and its traceability (Catarinucci et al., 2011; Chen et al., 2009; Yang, Yang, & Yang, 2011).

However, TTI's limitation is obvious that the shelf-life information and temperature history can't be recognized by a computer or send back to the cold chain monitoring system by telecommunication so it fails to meet the cold chain stakeholders' demands in real time monitoring and LSFO stock strategy. On the contrary, WSN cannot provide instant shelf-life information to cold chain infield workers. The characteristics of TTI and WSN are complementary as Table 1 figures out each strength and weakness.

Since none of the separated technology has the capability to fulfill the CCM management requirement of infield-remote bilateral temperature, shelf-life and position information transparent during the whole perishable food cold chain logistics, this paper intends to demonstrate a WSN based integrated Cold Chain Shelf Life Decision Support System (C^2SLDS) which is a combination of WSN and TTI's advantages, cost-effective and enables to be rapid adopted in different kinds of perishable food cold chain such as aquatics, vegetables, fruits and meat.

A brief research background introduction is presented in this section. System analysis and design are demonstrated in Section 2. The 3rd section discusses about the WSN-based TTI nodes (WTTI), ARM-based Gateway System (AGS) design and implementation. Section 4 illustrates the PC-based LSFO Decision Support System (LDSS) design and its shelf-life prediction process. Section 5 tests and evaluates the whole system. The discussion and conclusion about this research are listed last.

2. C^2SLDS system analysis and architecture design

2.1. The survey design and analysis

The research target cold chain is a tilapia supply chain from Hainan province to Beijing, China. This chain consisted with harvest, process, storage and transportation phases and 5 enterprises involved. The tilapias are caught from aquaculture ponds in Haikou, Hainan province and processed in a processing plant local. They are then stored temporarily and shipped to Tianjin Port from Haikou Port. Once arrived at Tianjin, the tilapias are going to finish their final approach to Beijing by road transportation. The total time lasts of the cold chain logistics is approximately 296 h (17,753 min, including 29 minutes' processing, 2904 minutes' temporary storage and 14,820 minutes' shipping and road transportation).

The methods adopted to get the user's requirement of the C^2SLDS are observation and interviews along this chain. The whole supply chain of the above tilapias' harvest, process, storage and transportation were included in the observation. The observation continued for 13 days in order to fully get the routine management means of the target cold chain and enterprises.

Interviews were conducted to find out the system requirements which consisted of the functional requirement and the system module division. An interviewee list which includes cold chain managers and infield cold chain workers was formed in Beijing with the support of the target enterprises. People on the list were asked to describe the work routine, how did they record temperature information during the supply chain, how did they get the shelf-life information of their product, whether they have known LSFO strategy or whether they have used it and so forth. In particular, the cold chain managers and cold chain workers were asked about their most concerned functions of the C^2SLDS respectively. The interview continued for 5 days and totally 7 managers and 23 workers were invited to participate in the survey. The basic version of the system requirements structure was formed based on the interviews.

Table 1
Technical characteristics comparison of TTI and WSN.

Technology	Strength	Weakness	Cost
TTI	Instant shelf life visibility	Computer readable Remote real time monitoring	Low
WSN	Computer readable Real time temperature monitoring Position service	Instant shelf life visibility	High

2.2. Users' requirement of the C^2SLDS

Users' requirement based on the survey and the system analysis are concluded and demonstrated via the following tables. Table 2 shows the cold chain managers' requirement while Table 3 provides the infield cold chain workers'.

2.3. System architecture

In order to transmit messages between the cold chain operation sites and Internet and reduce the expense of the wireless network, this research developed 3-layer architecture which consists of WTTI, AGS and LDSS. The following sections describe the structure and purpose of each layer respectively.

Table 2
Cold chain managers' requirements for C^2SLDS.

Requirement ID	The C^2SLDS should:	Requirement type
Req1	Be a system that enables the cold chain managers to get the perishable food products' real time temperature in the remote monitoring center.	Functional
Req2	Be a system that enables the cold chain managers to get the perishable food products' shelf-life information in the remote monitoring centers.	Functional
Req3	Be a system that enables the cold chain managers to get the perishable food products' real time position in the remote monitoring center.	Functional
Req4	Achieve a whole process cold chain monitoring which can help managers to ignore the information gap between different phrases.	Functional
Req5	Be a system that enables the cold chain managers to make smart decisions to reduce the perishable food product quality losses during cold chain logistic based on the shelf-life.	Functional
Req6	Be a system that its user interface is friendly, easy to operate.	Nonfunctional