Timing Analysis of Real-Time Networked RFID Systems

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Abstract

Radio Frequency Identification (RFID) is an automatic identification (Auto-ID) technology which allows remote interrogation of ID data on RFID tags using radio frequency (RF) as a means of wireless communication between tagged objects and RFID readers. This paper studies whether so called "networked RFID" systems can meet the timing constraints set by real-time industrial control applications. It outlines key research issues, examines timing analysis of networked RFID control systems and introduces a gate switch control application used in an experimental conveyor system as a case study.

1. Introduction

The real-time availability of RFID data is critical for many RFID applications such as manufacturing automation systems. In a manufacturing automation system, the process control system will usually require real-time RFID and sensor data to make control decisions, and will then execute the decisions in real-time to control the physical process flow, in order to meet certain hard timing constraints. While *stand alone* RFID technology can provide important identity and location information for tagged items [7], low-cost *networked* RFID has recently been popular with manufacturing, retailing and supply chain industries as an enabling technology for goods tracking and inventory management. A networked RFID solution links product identity information from a tag to other information stored on networked databases [8].

2. Related work

Although RFID is much publicized nowadays, little has been published about the use of RFID in the real-time domain. A few application papers, such as the one by Bornhovd *et al.* [1], and industrial RFID white papers, such as the one by Brooks Automation [2], have claimed real-time visibility of supply chains or real-time data acquisitions, but the term *real-time* mentioned in those papers only means timely or fast, but does not refer to meeting individual task timing constraints. To differentiate the meaning of real-time RFID in various contexts from real-time systems perspective, we refer to the former cases as *timely RFID*. In this paper, we look at RFID from a *real-time systems* perspective which is defined as an information processing system which has control over external environments, respond to external stimuli and affects the functioning of the external environments within a finite and specified period of time. The information processing time constraints are usually derived from the dynamics of the physical objects or processes under control in the external environment.

3. Real-Time networked RFID control system

3.1. Networked RFID

A *networked RFID system* generally comprises the following elements [8]: (1) a unique standard identification number assigned to a particular item, which is called *electronic product code (EPC)*; (2) a low cost identity tag that is attached to the item with a chip capable of storing—at a *minimum*—the unique identification number. The tag is capable of communicating this number electronically. (3) networked RFID *readers* and data processing systems that are capable of collecting signals from multiple tags at high speed (100s per second) and of pre-processing this data in order to eliminate duplications, redundancies and misreads; and, (4) One or more networked databases that store the product information and enable information exchange.

3.2. Real-time control system

A typical real-time control loop includes sensors which provide information about the operations, the control algorithms which calculate the control actions, and the actuators which are used to influence the operations, as it is embedded in Figure 1.

3.3. Real-Time networked RFID control system

By integrating networked RFID with a real-time control system, a *real-time networked RFID control system* (see Figure 1) is a real-time control system which captures ID data from RFID tags in real-time and controls the operations of tagged items or processes in real-time. The decision-making process can get access to ID data from tags, local and remote RFID databases through network, for example, EPC (Electronic Product Code) network, which will allow the decision-making process to be dynamically optimized with real-time data.

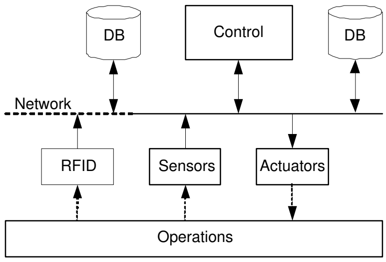

Figure 1. Real-time networked RFID control system

4. Real-time RFID issues

When networked RFID technology is integrated to real-time control systems, to ensure real-time operability of the system, it must meet any timing constraints imposed by the environment. Most commonly, the timing constraint is that the control information flow must be faster than physical flow, therefore, we are interested to know:

1. What is the *system timing constraint* set by the environment?
2. How can the system meet those timing constraints?

4.1. System timing constraint

The first question given above is reasonably straightforward to answer; the timing constraint is the deadline set for the information processing systems by the controlled processes or physical systems, which is rather explicit. Deadlines in real-time systems are usually introduced to specify quality of service (QoS) or control the operation of physical systems.

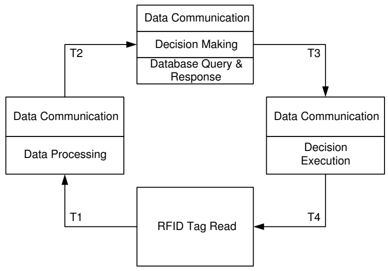

Figure 2. RFID Control System time delay blocks diagram

4.2. An approach for system meeting timing constraint

The second question raised above is not so explicit, but can be answered by decomposing the timing problem into the following sub questions:

1. How can the system be decomposed into different subsystems or processes?
2. What is the timing performance of each subsystem?
3. How can the system overall timing constraint be divided into constraints for each subsystem or process?
4. What is the performance of each subsystem in terms of meeting individual timing constraint?
5. In terms of timing performance of each subsystem or process, how to schedule all the processes in order to design such a system that can meet the system timing constraint?
6. In terms of design, how to specify the timing constraints of system behavior and verify the timing constraints have been met?

The first sub-question can be answered by following control system block diagram rules. The system can be decomposed into the following functional blocks: operations, RFID data acquisition, decision-making, and actuator decision execution. Each functional block can then be decomposed into time delay blocks (see Figure 2): RFID tag read time delay, RFID data processing time delay, network communication time delay, decision-making process time delay, local/remote databases query and response time delay and actuator decision execution time delay. It can also be decomposed into the following three parts: *event streams* (RFID data events) as input to *resources* (computational and communication resources) and processed by *function units* (such as buffer) to allow for composable modular performance analysis of the system [12].

The second sub-question can be answered by formal specifications, program analysis, datasheets, experimental results or practical measurement data. The third sub-question depends on the answer to the second sub-question. Formal specification methods, such as timed automata [3], can be applied. It can also be done in an iterative way by returning to this sub-question after answering the fourth sub-question. Probabilistic as well as worst case execution time (WCET) descriptions of the performance are desirable for firm and hard real-time systems. In a hard real-time system, an operation is considered successful only if it finishes its execution within the specified deadline even in the worst case. While for a soft or firm real-time system, the key measure of system performance is the percentage of all operations that complete within their deadlines.

The fifth sub-question is the most important issue in real-time systems, in which scheduling mechanism and concurrency control protocols should be applied. It can be answered by comparing different scheduling algorithms and concurrency control protocols, with regard to the performance of meeting timing constraints.

The sixth sub-question is about the timed systems modeling and model checking, it can be answered by comparing different modeling approaches. It will need to apply formal methods, such as timed automata, timed Petri nets, process algebra and temporal logic approaches, for specification and verification of real-time systems.

5. Timing analysis of real-time networked RFID control system

5.1. Introduction

In this section, we are going to examine the timing performance of subsystems in the real-time control loop (see Figure 2). T_1 is the RFID tags data acquisition time delay; T_2 is the RFID tags data processing and communication time delay; T_3 is the data communication, decision-making and database query and response time delay; T_4 is the actuator action execution time delay. In a hard RFID real-time control system, if τ is the real-time constraint of the physical system, then $T = \sum_{i=1}^{4} T_i$ should be less than the system real-time constraint τ. In the following subsections, the factors which can influence T_1 and T_2 will be examined in detail; The timing analysis of T_3 and T_4 is widely available in the literature and therefore will not be unfolded. The factors for T_1 are further classified as *contributing factors* and *uncertainties or variations*, in which each time delay component *must* have contributing factors and *may* have uncertainties.

5.2. RFID tag reading (T_1)

The factors which can influence the read latency of RFID tags are summarized:

- Contributing factors: reader anti-collision mechanism, tag anti-collision mechanism, frequency, air interface

Reader anti-collision mechanism refers to multi-access procedures. TDMA is the common procedure used for RFID systems by far, ALOHA is a kind of TDMA [6]. Tag anti-collision mechanism, such as sleeper in tag chips, for example, after one data transmission, the chip sleeps for 100ms(MCRF355 [9]), which can be regarded as tag TDMA. So that explains why the reads per second with one tag is less than with more tags. Frequency usually refers to HF (13.56MHZ) or UHF (915MHZ or 868MHZ), which allow different bit rate from tag to reader. This can partially explain why UHF systems can have 130 reads per second and HF systems can only have 20$\sim$40 reads per second, although the main reasons are among the first two factors. Air interface specifies the waveforms of the different symbols used in both the interrogator to tag signalling and tag to interrogator signalling, and the rules for building commands, but it does not include the commands themselves. It does include the coding of the tag replies.

- Uncertainties: other physical factors, including the orientation of the tag and reader, the distance between the tag and the reader, the inductive field strength or electromagnetic wave strength.

These uncertainties are not considered here as major factors, as these factors can be avoided by optimizing the physical environment settings. Readers who are interested in these factors are referred to Mallinson [7] for the influence of these physical factors.

5.3. RFID data processing (T_2)

Data processing functionalities are usually integrated in RFID readers to maximally reduce the output RFID data event streams. There are two subsystems specified by [4]: read subsystem and event subsystem, readers *must* have read subsystem and *should* have event subsystem. The functions provided by event subsystem can also be provided by application software or RFID middleware, such as Savant [5].

- Contributing factors: filters

The RFID data must be filtered, since a single tag can be read many times, duplicate reads usually need to be deserted. Different filtering procedures [1] and reader protocols [4] will have different timing performance.

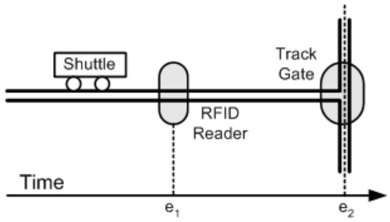

Figure 3. Networked real-time RFID in gate switch control system

- Uncertainties: buffers, aggregation, senders, and writers

Some readers keep a log of the tag reads in a buffer. Application softwares may request RFID tag reads from this buffer. Aggregation can add business meaning to event streams, item level RFID tag reads can be aggregated into case level events; it can be used to compose multiple incoming events into one higher-level event, such as aggregating a series of RFID reads of a single tag to generate an event of tag arrival and departure. Senders can transform the internal data structure to the output format and send them to registered recipients. Writers are used to or change data on a tag or control an actuator.

6. Case study:gate switch control system

The gate switch control system (see Figure 3) in Cambridge Auto-ID Lab simulates the materials flow control in a conveyor transport system in manufacturing. The gate controls the routing of materials which were carried in shuttles, when shuttle passes RFID reader, the reader reads the identity information of the product on the shuttle then passes along to the decision-making system to decide which way the gate should switch to. The RFID reader concerned is a Checkpoint^{TM} 13.56 MHZ Performa Slimline reader. Raw information from the tag readers is filtered by Savant from OAT systems. Readers are referred to [11] for more details about the experiment environment.

6.1. System timing constraint

The gate switch action should be done before the shuttle approaches the gate.Therefore, it is required that the total time delay T is less than the time interval τ when the shuttle moves from the location of the reader to the location of the gate. If the gate switching action can be done in T_4 second, and if the distance from event 1 to event 2 is l meters, the speed of the shuttle is v m/s, so τ is equal to l/v seconds. The real-time requirement for the system is that the information processing time $T_{ip} = \sum_{i=1}^{3} T_i$ should be less than $\tau - T_4 = l/v - T_4$ seconds.

6.2. Preliminary analysis of the timing performance

A preliminary analysis of the timing performance of this system by measurements leads to the following:

- $t_1 \in [2.2ms, 3.0ms]$, $T_{1WCET} = 3.0ms$ per tag read.
- $\tau - t_4 < T_{ip}$, it is not a real-time system.

In addition, $v_{max} = \min(v_{rtmax}, v_{readermax})$, the maximum allowable RFID tags moving speed v_{max} in a real-time conveyor transport system can be determined by the minimum of $v_{rtmax} = l/(\sum_{i=1}^{4} T_i)_{WCET}$ and the RFID reader allowable maximum tags moving speed $v_{readermax}$ [10].

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