Distributed Sensing and Control Architecture for Automotive Factory Automation

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Abstract. In this paper we propose an architecture for distributed intelligent sensing and control (DISC) for automotive factory automation. The architecture is based on a platform-based design approach that breaks the sensing and control problem into increasingly higher levels of abstraction from physical hardware to intelligent sensing and control. The focus of this paper is on the middleware layer that serves as an interface between an upper, agent-based control level and the wireless sensor network. This layer takes advantage the IEC 61499 model for distributed process measurement and control, and in particular, exploits its distributed, modular structure and its close match to wireless sensor systems.

Keywords: industrial automation, wireless sensor networks, IEC 61499.

1 Introduction

While wireless sensor network (WSN) technology has been very successful in military and defence application during the past two decades, it is also rapidly becoming a viable solution for employment at the lowest level of factory automation systems (Pellegrini et al., 2006). Challenges for the applications of distributed sensor systems in manufacturing environments include harsh, uncertain, dynamic shop conditions, as well as integration with new control software approaches to realize the flexibility and responsiveness of the whole system.

In this paper, a WSN architecture is proposed that is intended to exploit the potential of distributed sensor systems to address the challenges faced by today's automotive manufactures: i.e., the combination of increasing stringent customer requirements (e.g. high quality, customizable, low-cost products that can be delivered quickly) and inherent manufacturing system complexity (i.e. these system are by nature, distributed concurrent and stochastic). The primary objective of this work is to develop an efficient shop floor sensing and control system to support real time decision making in automotive factory automation systems.

This project is part of the Canadian AUTO21 Networks of Centres of Excellence: a nation-wide, interdisciplinary research effort that is focused on automotive research. Our contribution to AUTO21 is a collaborative venture between researchers at the University of Windsor, the University of Calgary, and the University of Western

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Ontario and spans the disciplines of micro-sensor design, embedded real-time control, and agent-based systems.

This paper begins with background on the wireless sensor networks in factory automation. Next we describe the overall architecture for our proposed distributed intelligent sensing and control (DISC) system in Section 3. This architecture follows a platform-based design approach that is intended to support collaborative work on each level of control: the physical layer (University of Windsor), the middleware (University of Calgary), and the application layer (University of Western Ontario). For the remainder of the paper we focus on the work at the University of Calgary with an overview of the challenges associated with wireless sensing platforms in Section 4 and a description of the implementation plan in Section 5. The paper concludes with a summary and discussion of future work in Section 6.

2 Background

Conventional factory automation systems rely on a set of hard-wired sensors that are either directly linked to controller I/O devices or are part of a sensor network. These systems are expensive to install and difficult to maintain, and limit future expansion due to an inflexible overall layout.

Wireless integrated network sensors offer a low-cost solution that can cover the entire enterprise. These sensors contain multiple heterogeneous on-board sensors that are networked through wireless links and are deployable in large numbers. This system-wide deployment of sensing devices is referred to as distributed sensing, and the whole infrastructure is called a distributed sensor system.

WSN technology has resulted in a data-rich environment with both temporally and spatially dense information that provides unprecedented opportunities for product quality and productivity improvement.

However, applications of WSNs in manufacturing environments are very different from other applications: e.g., military and defence sensor networks and wireless environmental monitoring systems, where sensors are usually deployed in the open fields or in the ocean. In a typical manufacturing system, various noise and vibration sources as well as diverse electrical and electronic systems, all have significant influence on the performance and efficiency of wireless sensor systems. As a result, smart sensors and communication protocols that have been successfully deployed in other applications will not necessarily work in the harsh, uncertain, dynamic environments typical to automotive manufacturing. Therefore, significant research efforts are required in this area. Additionally, WSN hardware technology alone is not sufficient to address the challenges faced by today's automotive manufacturers: this technology must be integrated with new control software approaches to realize systems that are flexible and responsive to the ever-changing manufacturing environment.

3 System Architecture

This paper focuses on the first steps towards the development of efficient shop floor wireless sensing technologies to support real time decision making in automotive factory automation systems: i.e., the system architecture. To achieve this goal, a platform based design approach for WSNs proposed by Bonivento and Cailoni (2006) is adopted and modified for system design and functional analysis.

Platform based design is a meet-in-the-middle approach where the top-down refinement of a design specification meets with bottom-up characterizations of possible alternative implementations, which encourages each team member to contribute to the project from their own perspective. In the end, the design space exploration is performed based on estimates of the performance of candidate solutions so that the overall design process is considerably speed up as re-designs are avoided and design re-use is favoured. Based on this, the integration of different task modules within the whole project can be accomplished efficiently.

Our architecture for distributed intelligent sensing and control for automotive factory automation is illustrated in Figure 1.

The WSN platform consists of three abstracted layers: the Sensor Network Service Platform (SNSP), the Sensor Network Ad-hoc Protocol Platform (SNAPP), and the Sensor Network Implementation Platform (SNIP). At the physical device level, the investigation of low power wireless sensors for installation on rotating parts within typical automotive manufacturing environment forms another key research area of this project. The overall system requirements, such as throughput, latency, reliability, security, adaptability, affordability and energy consumption, will be satisfied through the functional integration of different task modules. Descriptions of the four task modules at different levels of the proposed distributed intelligent sensing and control (DISC) system are as follows.

The Sensor Network Service Platform (SNSP) layer is the upper application interface for our WSN system. It defines services available to the user, which include functionalities of sensing, control and actuation. The SNSP can be thought of as the interface to the DISC as it serves as a purely functional description for the system: i.e., the detailed application specific network implementation is not dealt at this level.

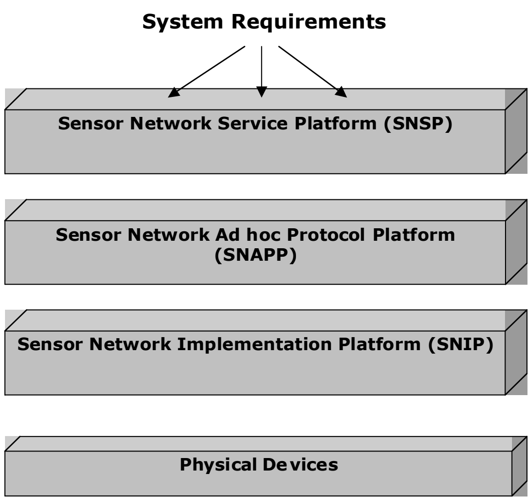

Fig. 1. Distributed intelligent sensing and control system architecture

The SNSP decomposes and refines the interaction among controllers by providing services, such as query, command, timing/synchronization, location, and concept repository.

The Sensor Network Ad-hoc Protocol Platform (SNAPP) defines the software architecture for the physically distributed sensor nodes and maps the functional specification from SNSP level onto sensor nodes. For the proposed DISC system, intelligent software agents will play an important role in this area. In particular, agent clustering and mediation approaches (Shen and Norrie, 1999) will be used to address topology changes of the ad hoc WSN; agent-based distributed decision making mechanisms will be developed and applied for collaborative signal and information processing. An example of this approach is described in (Shen et al., 2005).

The SNAPP will be supported by a library of MAC and routing protocols. These protocols are "parameterized protocols", and the parameters of system working points can be obtained as the solution of a constrained optimization problem, where the constraints are derived from system requirements and characteristics of physical nodes.

The Sensor Network Implementation Platform (SNIP) functions as a middleware to build up a network of interconnected physical nodes that implement the logical function of the application. At this level, both wireless communication standards for networks and sensors need to be considered. SNIP acts as a bottom layer of the software to directly interface with physical sensors. To achieve real-time sensing and control, reconfigurability, as one of the key requirements of distributed sensing networks, will be the research focus for this task module. The challenges associated with the SNIP layer and its preliminary architecture will be described in more detail in sections 4 and 5 respectively.

4 Challenges Associated with Distributed Sensing and Control Platforms

According to the system structure described in Section 3, the tasks of three WSN platform modules of our distributed sensing and control system focus mainly on software/middleware. All three of these layers are closely interconnected. It is intended that the integration of these three layers will provide a new control approach to realize systems that are flexible and responsible to the ever-changing manufacturing environment.

In today's market, nearly all wireless sensor vendors' software can provide some level of node configuration, offer information on the state of each node, display real-time wireless sensor data on a graph for monitoring purposes, and even provide an interface that allows the user to set up basic data logging, making it possible to export data to a spreadsheet for offline analysis (Hobbs, 2006). Although these software tools are fairly intuitive, they typically have fixed capabilities and lack several key features to support real-time decision making in automotive factory automation systems. As a result, novel programming paradigms and new technologies are required for our distributed sensing and control platforms.

More specifically, the proposed Distributed Intelligent Sensing and Control (DISC) platform for factory automation will focus on three key challenges:

1. self-organization,
2. embedded node intelligence, and
3. low-power operation.

4.1 Self-organization

DISC self-organization can be thought of as dynamic reconfiguration (Brennan et al., 2008) of the system nodes. In other words, the DISC system must be capable of accommodating changes to sensor node configuration automatically, as the system operates. Examples of sensor node reconfiguration may include the addition of new sensor node, reassignment of existing sensor nodes, or the removal of obsolete sensor nodes.

Ad hoc wireless sensor networks rely on a fully distributed architecture where there is no central controller (Stankovic, 2003). All operations (access control to the radio medium, routing, etc.) are data centric and application-oriented. Explicit node addressing via ID or IP is unfavourable since random node distribution and mobility impedes assignment of node addresses to the position of a measurement. As a paradigm shift, the network topology needs to be constructed in real-time and updated in a self-configuring fashion periodically as sensors fail or move and new sensors are deployed (Deb et al., 2001).

4.2 Embedded Node Intelligence

Given the processing limitations of WSN technology, one must be realistic about the DISC system's ability to support embedded node intelligence. More specifically, although it is unrealistic to expect extant wireless sensor nodes to support software agents with high-level reasoning capabilities, it is reasonable to exploit the node's hardware and software platform to enhance the node's intelligence in areas such as signal processing, alarm monitoring, and node diagnostics.

Current wireless sensors are passive nodes that simply pass the data they are hard-coded to provide back to the user. Few have built-in intelligence for data analysis or automated power management. For example, a node might be embedded in a large machine to monitor vibration levels. Although it can acquire a large amount of raw data, it may need to send only pass/fail information to the host, indicating whether the machine is within acceptable limits (Hobbs, 2006). Intelligent nodes are essential for the higher level monitoring and control, and can further improve the intelligence of the whole system.

Embedding intelligence into sensor nodes has the advantage of redistributing some of the overall processing load from the upper-level controllers to the sensor system. More importantly, for the purposes of our DISC system, it supports the platform-based design approach to dynamic reconfiguration and ultimately, intelligent reconfiguration at the higher agent levels. In other words, by shielding the upper layers from the hardware implementation details, the lower-level SNIP layer provides a common interface to the WSN. For example, at the SNSP level, one is not concerned whether a new sensor is a Type X or a Type Y vibration sensor (requiring configuration X or configuration Y respectively): only that the new sensor is a vibration sensor.

4.3 Low Power Operation

Closely related to the processing limitations of WSN technology is the low power operation limitation of these systems. Normally sensor networks run on small batteries and often need to operate for a long time: power conservation is a key issue at all layers in sensor networks. Besides the effort put at the physical device level, recent studies have shown that radio communication is the dominant consumer of energy in sensor networks (Hill et al., 2000). As a result, implementing a low-power task scheduling, communication protocols are all important for energy conservation.

For the proposed DISC system, power consumption will be a key constraint of our system design. Although increased node intelligence will likely result in higher power consumption at the node (i.e., increased processor load), this should be offset by decreased node communication requirements. In particular, node-level signal processing will reduce the amount of raw data that will be transmitted from the sensor node to the upper, controller levels of the DISC system.

The three key challenges described in this section figure prominently in the design of a DISC system. Of course, these design considerations must be addressed in addition to the typical challenges associated with WSN implementations. In particular, security, predictability, real time performance, and integration with the rest of the enterprise need to be taken in to consideration as well for wireless sensor network platform design.

5 The Sensor Network Implementation Platform

In this section, we look more closely at the implementation of the SNIP (sensor network implementation platform) level of the DISC. As noted previously, the SNIP acts as a middleware between the agent-based software at the SNAPP level and the physical sensor nodes. In other words, the SNIP provides an interface between upper level software agents and lower level physical devices that abstracts the implementation details at the device level to support intelligent control at the level of the agent system. As a result, embedded intelligence and interface design are key concerns at the SNIP level.

The SNIP level's tight link to physical devices and the DISC system's requirement for a distributed software model are, consequently, a very good match to the IEC 61499 model for distributed process measurement and control (IEC, 2005). As well, recent work on real-time reconfiguration services for function block based systems (Zoitl, 2006) should support the ultimate software/hardware implementation at this level.

Some early research efforts utilizing function blocks include reconfiguration of real-time distributed systems (Brennan et al., 2002), holonic control (Wang et al., 2001), function block oriented engineering support systems (Thramboulidis and Tranoris, 2001), Web-based engineering and maintenance of distributed control systems (Schwab et al., 2005), and OOONEIDA initiative where function block can serve as a cornerstone for further development of the automation object concept due to its characteristics of portability and reusability (Vyatkin and Christensen, 2005).

5.1 WSN Sensor Nodes

Before we look at the relationship between the SNIP and the IEC 61499 model, we will first look more closely at the basic structure of a sensor node. As illustrated in Figure 2, a physical sensor node is a collection of physical resources, such as clocks

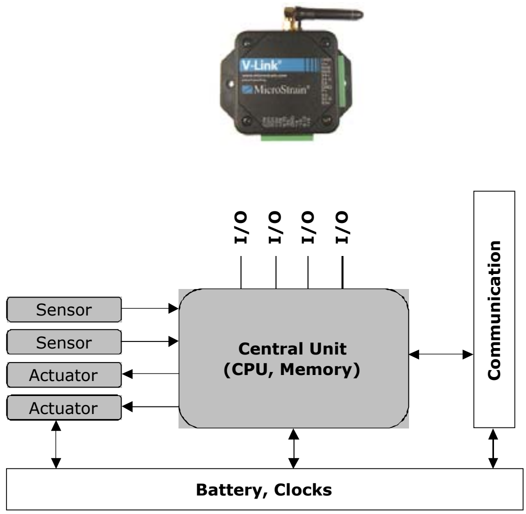

Fig. 2. Basic structure of a sensor node

and battery resources; processing units, memory, communication and I/O devices; sensor and actuator devices.

This figure also shows an example of a typical commercial sensor node: i.e., a V-Link® Wireless Voltage Node (MicroStrain, 2008). This particular sensor node utilizes the IEEE 802.15.4 open communication standard and supports simultaneous streaming from multiple nodes. Its onboard memory stores up to 1 x 106 measurements, and its 3-volt sensor excitation supports most analogue sensors.

5.2 The DISC and IEC 61499

As noted, given the IEC 61499 model's focus on embedded and distributed control (Vyatkin, 2007; Zoitl, 2006), it provides a natural mapping to our proposed DISC system. More specifically, there is a direct mapping between IEC 61499 devices and WSN sensor nodes as illustrated in Figure 3.

This figure shows the bottom three layers of the DISC architecture illustrated in Figure 1. At the sensor node implementation platform (SNIP), sensor nodes are represented by IEC 61499 devices that are linked by a WSN. Embedded node intelligence is supported by IEC 61499 function block applications (FBA).

The key to the mapping lies in the IEC 61499 modular software model. As noted previously, the main SNIP design issues are interface design and embedded intelligence. As a result, the SNIP will utilize a library of device level services – in the form of IEC 61499 service interface function blocks (SIFB) – to support WSN communication and the process interface. Given the typical sensor node structure (illustrated in Figure 2), the process interface will be at the level of the node's central unit: i.e., the sensor interface will be handled by the node's underlying hardware and software.

Sensor node embedded intelligence will be a combination of service interfaces (i.e., where some signal processing and diagnostic services are already provided) and custom function block applications. In the latter case, basic and composite function

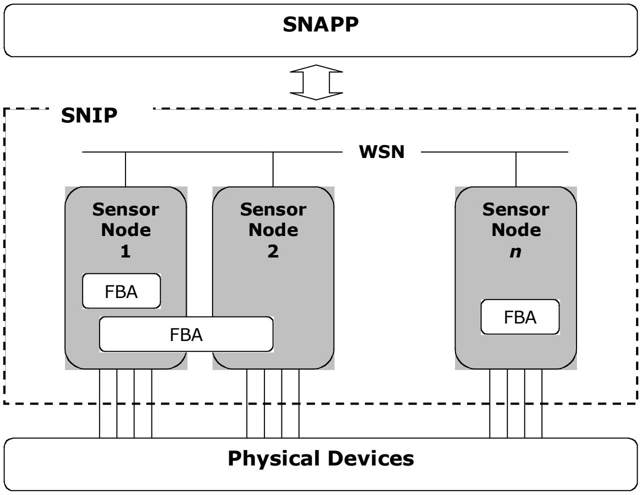

Fig. 3. Mapping between the IEC 61499 and the DISC system

block models can be exploited to develop custom function block applications at the SNIP level.

Given that "embedded intelligence" at this level of the DISC means a masking of the sensor node's implementation details from the agent-level (i.e., the SNAPP) and basic diagnostic services, the function block applications will map to individual sensor nodes (i.e., they will not be distributed across nodes). However, it is conceivable that higher levels on embedded intelligence may be possible at the SNIP that would require distributed function block applications as illustrated in Figure 3. For example, simple fault monitoring an recovery could be dealt with at the SNIP without the need to defer to the agent level. However, a key constraint that will need to be considered will be the power drain that would result from increased inter-node communication.

6 Summary

This paper provides a summary of the basic architecture for a distributed intelligent sensing and control (DISC) system for automotive factory automation. At the University of Calgary, we are focusing on the main issues of sensor network implementation at the middleware level and propose the IEC 61499 model to support sensor node embedded intelligence and distributed sensing and control.

Intelligence at the lowest levels of the DISC is intended to enhance sensor node functionality, performance, reliability, and facilitate sensor node integrated with the entire system (e.g., local analysis and node aggregation). Local data analysis means only parametric data needs to be passed to the upper level system. For example, a node might be embedded in a large machine to monitor vibration levels. Although it can acquire a large amount of raw data, it may need to send only pass/fail information to the host, indicating whether the machine is within acceptable limits (Hobbs, 2006).

While the SNIP layer focuses on the functionality of the application, the SNAPP layer provides the services of sensor discovery and collaborative signal processing. To integrate these two layers, security and real-time issues are involved. Communication interfaces at different levels of function block network build up an information channel between the SNIP and SNAPP levels. The analysis capability and programmability of IEC 61499 function blocks make system simulation, execution and monitoring at higher levels possible, and have the potential to further guarantee the security and real-time requirements of the overall system.

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