UH-ToSS: A Sensor Networking Testbed with IEEE1451 Compatibility for Space Exploration

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***Abstract*—Smaller, faster, and cheaper sensors resulted from continuing advances in sensor, semiconductor, and communication systems technology makes it possible to have real sensor intensive networks of fixed and mobile devices for use in many in-door and out-door applications. Several sensor network testbeds have been developed, but none of them consider how to incorporate smart sensor capability in the system. In this paper, we describe the design and implementation of a testbed, ToSS (Testbed of Smart Sensors), developed in collaboration with NASA Stennis Space Center for testing and verifying IEEE 1451-compatible sensor systems with network performance monitoring capability for space shuttles and other space exploration relevant tasks.**

Keywords-smart sensor network, IEEE 1451, sensor network testbed, space exploration

I. Smart Sensor Network

The ongoing progress in the semiconductors, sensors, and networking and communication technologies makes it feasible to realize a network of sensors working harmoniously, similar to the chips on a motherboard of a PC. In this respect, the sensors will not be able to reach the level of integration unless they have embedded networking capabilities [1]. Some of these capabilities have been implemented in a proprietary manner in various systems by the sensor networking companies. However, there is a strong push in the industry to harmonize the standards that enable networking and data acquisition of sensors. The need comes from reaching the ultimate goal for networked smart sensors: web access that can enable a distributed decision systems.

The distributed system would be possible by following the path of the networked PCs towards creating the internet: plug-and-play capabilities of PCs paved the way towards making the internet what it has become today. Similarly, sensors with plug-and-play capabilities will enable an autonomous system to be up and running virtually for every kind of sensing application. Transducer Electronic Data Sheets (TEDS) will play an equivalent role to the drivers for PC equipment in realizing this mission.

Communication protocols that integrate the TEDS information into the protocol flow control will deliver the critical differentiated services to the network in order to guarantee an upper bound on the network latency. The control networks will emerge as more dedicated networks with strict latency bounds. Request-response and publish-subscribe types of networking paradigms will exist concurrently in a sensor networking environment [2]. Information fusion that takes into account of a random network delay with an upper bound is critical in sensor networking. Although it is desired to guarantee a deterministic delay, testbeds will enable the analysis of this delay in detail towards preparation for the worst case scenario [3]. In addition to the efforts to create time-synchronized (not only by network events) through IEEE 1588 [4], there are experimental evaluations of potential sensor networks for their synchronization capabilities [5].

The paper presents the design and implementation of a heterogeneous smart sensor network testbed to test and verify IEEE 1451 compatible sensor systems with networking performance monitoring capability. Section II details the networking backbone and high level functionalities of the testbed designed to facilitate the decision support systems for space shuttle and exploration relevant tasks as outlined in previous work [6-11]. Section III lists the main tasks and challenges the authors identified together in designing and implementing such a heterogeneous smart sensor network testbed. Section IV describes the hardware and software architectures of the system and the specific components used in implementing the testbed. The conclusion in Section V envisions how the testbed can be used in real-world applications for space shuttles and space exploration.

II. ToSS Networking Backbone and High Level Functionalities

A. AT&T Networking Backbone

There has been a relatively long history in distributed monitoring and decision support system in control and systems research community [6, 12], and in wired or wireless networking in communication research community. However, the control research community usually is not concerned about network and communication parameters such as details in channel initialization, routing, reconfiguration, and power and topology constraints. Also, the control and decision support systems should be aware of errors caused by networking such as channel errors, delays, and packet losses. Recent research starts to make simple assumption such as error-free communication channels with capacity constraint [13], and research about the robustness of the decision support system to the loss of communication links [14]. The testbed presented here aims to bridge the gap between the two research communities.

When designing and implementing such a testbed for plug-and-play intelligent sensors, we make use of a computer networking testbed as a stand-alone networking backbone with various architectural capabilities. The testbed networking architecture is presented in Figure 1. The infrastructure has state-of-the-art networking gear for wireless access and virtual networking with fiber-optic support. Testbed is composed of a SONET ring with high-end routers as drop-off points. Routers (Cisco 7200 and others) give the MPLS and virtual networking capabilities. Different routing algorithms as well as protocols can be implemented on the testbed. The smart sensor networking data will flow through this testbed as well as other data traffic. The latency during an Ethernet connection with various sensors and actuators will be assessed using networking measurement equipments as well as custom measurement techniques.

Initially, off-the-shelf IEEE 1451 compatible smart sensors will be connected to the backbone through wired and wireless connectors while the factory specifications are being shared by the gateway. Eventually, the testbed will emerge as an autonomous network of sensors with automated TEDS management and a central intelligence unit with ISHM functionalities (Integrated System Health Management).

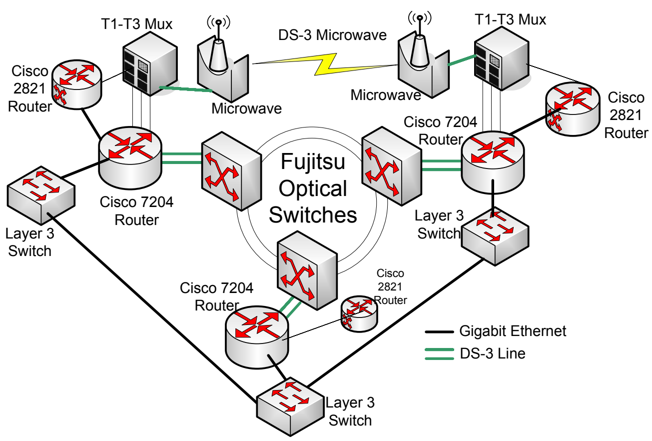

Figure. 1. Networking infrastructure backbone for ToSS.

B. ISHM Technologies and Corresponding Functions

Integrated System Health Management (ISHM) is one of the core competencies at John C. Stennis Space Center of NASA. ISHM technologies are crucial to the development of space vehicles, space/Moon/Mars platforms, robotic vehicles, and ground testing/operation Systems-of-Systems (SoS) [15]. The smart sensor system testbed developed here will contribute to, facilitate, and affect the evaluation, validation, and verification of the ISHM technologies identified such as anomaly database, DIaK (Data, Information, and Knowledge) management for effective reasoning and decision making, one chip intelligent sensors, networking technologies for distributed intelligent elements, qualitative models/descriptions of physical phenomena, intelligent wired/wireless sensors, engine diagnostic technologies, smart system components, and knowledge systems.

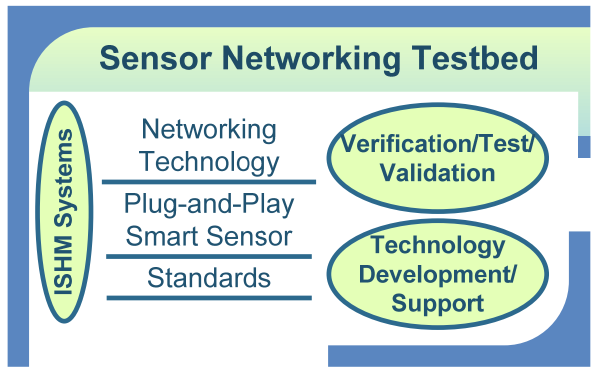

Figure. 2. High level functions of ToSS

The first-of-its-kind testbed, UH-ToSS, will provide up-to-date data and knowledge base on the high level functionalities as shown in Figure 2. This includes verification, testing, validation, as well as technology development and support for networking technology, plug-and-play smart sensors, and standards used for ISHM systems.

III. MAIN TASKS AND CHALLENGES

As presented in [16], a control loop takes into account of the network delay as shown in Figure 3. The control networking performance analysis will include the protocol and standards parameters such as TEDS information delivery and updates, reconfiguration and calibration needs of smart sensors, and response timing in the network. The on-the-fly calibration and reconfiguration requirements will become as important as the data transfer with minimal and bounded latency.

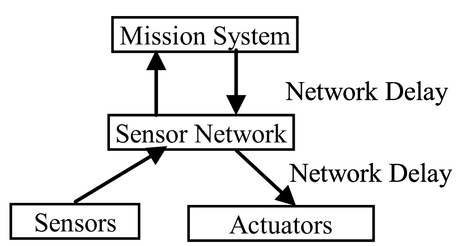

Figure. 3. Control Network Response Loop

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Based on the high level functionalities identified, the tested is designed with NASA engineers to complement the functionalities of the ISHM system for the following tasks:

- Off-the-shelf plug-and-play sensor verification, testing, and evaluation: The standards on sensor networking have been harmonizing the access methods for the sensors to the networks. These standards and the available sensors in the marketplace will be cross-matched and verified using the testbed. The process will help industry in validating the requirements lists for developing smart IEEE 1451 compatible sensors.
- Implementation metrics and requirements for monitoring and evaluation of capabilities in a Systems of Systems (SoS): The performance of the network will be monitored using the real-time control parameters. The testbed will provide networking performance monitoring and evaluation capability based on following indices: network latency, throughput, synchronization, and deterministic and random behaviors.
- Assessment of the flexibility and integrability of different sensor systems. The standards of sensor interfacing will be tested and verified for SoS deployment over this testbed. Assessment methods and test scenarios will be developed in order to have a uniform performance evaluation and specification validation of standardized issues in sensor networks.

The testbed will provide a mechanism to assess networking architectures, smart sensor capabilities, and standardization procedures. It consists of a high-end internet backbone and off-the-shelf IEEE 1451 compatible smart components. We identified following challenges for developing and implementing such a testbed:

1) Networking and Web Access:

a. Research and experimentation of possible candidate architectures to determine the challenges of plug-and-play sensors operating in an intelligently controlled computer network.

b. Experimentation with deterministic and best effort protocols (e.g. TCP/IP, UDP and RTP) and study their effect on ancillary and real-time application scheduling.

2) Smart Sensor Interfacing: Health management computer system and sensor interaction (sensor communication and development standards) and TEDS definitions for sensors in the network.

3) Standardization Procedures:

a. Possible networking architectures with web access will adhere to the emerging IEEE 1451 sensor interfacing standards.

b. TEDS distribution and sensor data readings will follow the IEEE 1451 standards.

TABLE I. IEEE 1451 SMART SENSOR STANDARD SUMMARY

Standard #	Description	Status
IEEE 1451.0	Encourages compatibility among other 1451 standards and eases the development of new 1451 standards using new physical layers	not issued yet – last update was in 2003
IEEE 1451.1	This section of the standard covers Network Capable Application Processor (NCAP) Information Model	Published - 1997
IEEE 1451.2	This section of the standard covers transducer to microprocessor communication protocols and Transducer Electronic Data Sheet (TEDS) formats	Awaiting revision of 1997 version
IEEE 1451.3	This section of the standard covers Digital Communication and Transducer Electronic Data Sheet (TEDS) Formats for Distributed Multidrop Systems	Approved - 2003, awaiting publishing
IEEE 1451.4	This section of the standard covers Mixed-Mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats	Published - 2004
IEEE 1451.5	This section of the standard specifies information that will enable 1451 compliant sensors and devices to communicate wirelessly, eliminating the monetary and time costs of installing cables to acquisition points. The IEEE is currently working on three different standards, 802.11, Bluetooth and Zigbee.	Awaiting approval
IEEE 1451.6	This is the information required for the CAN (consolidated auto network) bus.	Awaiting approval

IV. IEEE 1451 COMPATIABLE SMART SENSOR SYSTEMS SURVEY

In compliance with NASA's mission and operational standard, the testbed is designed to evaluate, verify, and validate smart sensor systems following IEEE 1451 standards. Table I summarizes the current IEEE 1451 standards that are relevant to the design and implementation of the testbed. By supporting IEEE 1451 smart sensor standard, ToSS will provide an open framework to simulate and model behaviors of distributed monitoring and control systems based on wired and wireless smart sensor network with different networking parameters configurations and various networking error scenarios.

Besides the high-end internet backbone, the testbed being developed consists of wired and wireless networking and communication devices, and various off-the-shelf IEEE 1451 compatible smart sensor components. There are numerous companies that have been developing, manufacturing, and selling sensors and sensor systems for industry. We finished an extensive study on available sensors and sensor systems/platforms with networking capability. Table II summarizes the results of our investigation by listing available (smart) sensor and sensor systems of 32 vendors, the general description of the system, whether or not it is IEEE 1451 compatible, and the type of communication it supports. This is a limited set of companies in a dynamic market. The goal is to identify the set of heterogeneous off-the-shelf plug-and-play sensor systems that will be connected to the networking backbone of the testbed described in section II. The vendors that have IEEE 1451 compatible sensor systems/platforms are highlighted using bold font.

TABLE II. SENSORS AND SENSOR SYSTEMS VENDORS WITH A LIMITED SUMMARY ON THEIR 1451 INVOLVEMENT

Vendor Name	Description	Communication
AeroComm	Input RS232, ZigBee Compliant Transceivers	ZigBee Compliant
Adalet Wireless	Proprietary Network	Ethernet Access Point, no ZigBee
All Sensors	Specialty in Pressure Sensors	RS232, USB Interface, No TEDS
Apogee Technology Inc.	Wireless Transceivers	Bluetooth Compliant
ARC	Sells Sensors and Instrumentation	
ArchRock	NI User Interface Software, using Crossbows, Nod Platforms, ZigBee	ZigBee Compliant
Atlas	Plug & Play Service	Atlas
Coronis Systems	Uses proprietary standard, cooperation with Wavenis	
Cronis	Cooperation with Wavenis	Bluetooth Compliant
Ember	Radio Communications Boards, Networking Modules	ZigBee Compliant
Esensors Inc.	IEEE 1451 Compliant	TEDS Compliant
Freescale	RF Transceiver Chips	ZigBee Compliant
Frontline	ZigBee Sniffer	ZigBee Compliant
Helicomm	IP Link Modules, IEEE 8051 based Embedded Networking	ZigBee Compliant
Honeywell	Rugged Sensors	TEDS Compliant
Innovative Wireless Technologies	12 Units (nodes) Gateway Included	Proprietary Network
Jennic	Sensors Included in Kit	ZigBee Compliant
LasCar Electronics	Datalogger USB Memory Stick for Sensors	Miscellaneous
Meshgate		
Microstrain	Sensor Intregrable RF Transceiver Chips	ZigBee Compliant
Max Stream	Chip Manufacturer	ZigBee Compliant
National Instruments	TEDS Information, virtual TEDS	TEDS Compliant

Vendor Name	Description	Communication
Oceana Sensors	Remote Controlling Interface, Software available	Uses Bluetooth to communicate with Industrial Computer
S3C Incorporation	Wireless Network Pressure Sensor, Sensors and Networking at same time	ZigBee Compliant
Smart Sensor Systems	IEEE 1451 Compliant	
Solitica	Chorus Sensor Control Hub	
Talon Inc.	Cooperation with Renesas	ZigBee Compliant
Texas Instruments	Intelligent Instrumentation	Ethernet Compliant
USB ZigBee Dongle	ZigBee Sniffer	ZigBee Compliant
(WINA) Wireless Industrial Networking Alliance	Mission - harmonization of the standards	Wireless Networks
Z-Link	Transceivers	ZigBee Compliant
ZMD	Wireless Kits	ZigBee Compliant

V. SYSTEM HARDWARE AND SOFTWARE ARCHITECTURE

Adopting IEEE 1451 smart sensor standards compatible sensor systems and platforms, the ToSS will provide an open framework to simulate and model behaviors of distributed monitoring and control systems based on wired and wireless smart sensor network with different networking parameters configurations and various networking error scenarios. The first version of the testbed has components for the following categories.

1) State-of-the-art wireless sensor system development kits;

2) Wireless access point with virtual private network assignments to various sensor clusters;

3) Sensors with plug-and-play capabilities;

4) Main gateways to request information from sensors as well as to assign tasks to actuators;

5) Remote data acquisition interfacing to all of the equipment for remote monitoring and www access/hosting;

6) Sensor TEDS development software (e.g., Esensors, Inc); and

7) Interface with intelligent control and decision support system such as G2 by Gensym, Inc.

VI. CONCLUSION AND FUTURE WORK

Networked sensor systems with standard plug-and-play capabilities are attracting a lot of attention in the research and industry community. Specifically, IEEE 1451 standard is perceived to introduce smart sensors with plug-and-play capabilities. There is a need to develop a testbed to evaluate different architectures and protocols in IEEE-1451 enabled sensors. This testbed will play a big role in meeting this need and help quantize different performance metrics. Future work will include implementation, data collection and analysis of heterogeneous technologies in the testbed and methods to evaluate the performance of smart sensor systems.

REFERENCES

[1] T. Abdelzaher, J. Stankovic, S. Son, B. Blum, T. He, A. Wood, Chenyang Lu, "A Communication Architecture and Programming Abstractions for Real-Time Embedded Sensor Networks," IEEE Proc. of the 23rd International Conference on Distributed Computing Systems Workshops, 2003.

[2] R. D. Schneeman, "Implementing a standards-based distributed measurement and control application on the internet," US Dept. of Commerce, NIST Sensor Integration Group, Technical Report, June 1999.

[3] R. Hammett, M. Ferry, "A testbed for the development, demonstration and testing of information fusion systems," IEEE Proc. of the 7th International Conference on Information Fusion, 2005.

[4] A. Moldovansky, "Application of IEEE 1588 in industrial automation and motion control systems," Rockwell Automation, Presentation in the IEEE 1588 Workshop Tutorial, October 10, 2005.

[5] W. S. Conner, J. Chhabra, M. Yarvis, and L. Krishnamurthy, "Experimental evaluation of topology control and synchronization for in-building sensor network applications," Journal of Mobile Networks and Applications, vol. 10, pp. 545-562, 2005.

[6] John Schmalzel, Fernando Figueroa, Jon Morris, Shreekanth Mandayam, and Robi Polikar, "An Architecture for Intelligent Systems Based on Smart Sensors," IEEE Transactions on Instrumentation and Measurement, Vol. 54, No. 4, Agust 2005, pp. 1612-1616.

[7] F. Figueroa and J. Schmalzel, "Rocket Testing and Integrated System Health Management", Chapter in the book Condition Monitoring and Control for Intelligent Manufacturing (Eds. L. Wang and R. Gao), pp. 373-392, Springer Series in Advanced Manufacturing, Springer Verlag, UK, 2006.

[8] Fernando Figueroa, Randy Holland, John Schmalzel, Dan Duncavage, Rick Alena, Alan Crocker, "ISHM Implementation for Constellation Systems," 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 9-12, 2006, Sacramento Convention Center, Sacramento, CA.

[9] Fernando Figueroa, John Schmalzel, Jon Morris, Ajay Mahajan, Don Nickles, David Rauth, Lucas Utterbach, P. Bandhil, "Intelligent Sensors and Components for On-Board Systems," 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 9-12, 2006, Sacramento Convention Center, Sacramento, CA.

[10] Fernando Figueroa, Randy Holland, and David Coote, "NASA Stennis Space Center Integrated System Health Management Test Bed and Development Capabilities," SPIE Defense & Security Symposium, Sensors for Propulsion Measurements Applications (OR13), April 17-21, 2006, Gaylord Palms Resort and Convention Center, Orlando (Kissimmee), FL, USA.

[11] Fernando Figueroa, Randy Holland, John Schmalzel, and Dan Duncavage, "Integrated System Health Management (ISHM): Systematic Capability Implementation," SAS 2006 - 2006 IEEE Sensors Applications Symposium, Houston, Texas, USA, 02-07-2006.

[12] S. C. A. Thomopoulos, R. Viswanathan, and D. K. Bougoulias, "Optimal distributed decision fusion," IEEE Trans. Aerospace Elect. Syst., vol. 25, pp. 761-765, Sept. 1989.

[13] J.N.Tsistsiklis, "Decentralized detection," in Advances in Statistical Processing, Signal Detection, vol. 2, H.V. Poor and J.B. Thomas, Eds. Greenwich, CT:JAI, 1993.

[14] S.C.A. Thomopoulos and L.Zhang, "Distributed decision fusion with network delays and channel errors," Inform. Sci., vol. 66, no. 1, pp. 91-118, Dec., 1992.

[15] Z.B.Tang, K.R.Pattipati, and D.L.Kleinman, "Optimization of distributed detection networks: Part II generalized tree structures," IEEE Trans. Syst., Man and Cybern., vol. 25, pp.21-42, Jan. 1995.

[16] Hong Seong Park, Yong Ho Kim, Dong-Sung Kim, and Wook Hyun Kwon, "A scheduling method for network-based control systems," IEEE Transactions On Control Systems Technology, vol. 10, no. 3, May 2002.