An Integrated Testbed for Advanced Wireless Networked Control Systems Technology

James H. Taylor
Dept. of Electrical & Computer Engineering
University of New Brunswick
Fredericton, N. B., Canada, E3B 5A3
jim.taylor@ieee.org

Jeff Slipp
Petroleum Applications of Wireless Systems
Cape Breton University
Sydney, Nova Scotia, Canada, B1P 6L2,
jeff_slipp@cbu.ca

***Abstract*—Wireless sensor networks (WSNs) have gained widespread acceptance during the last decade, largely due to the greatly increased flexibility, lower costs and scalability that they have been shown to provide. The pace of application in the context of wireless networked control systems (WNCSs) has been somewhat impeded, however, by the reluctance of industry to accept the risks of allowing wireless paths to be incorporated in process control loops. The problem is that there are conflicts between maintaining control loop performance, which can be degraded by many factors, such as low data rates, delays in wireless paths, jitter and electromagnetic interference; and the usual objectives in managing a wireless sensor network, namely freedom to configure the network and to adjust data rates at will, to maximize efficiency and to conserve energy consumption in battery-powered network nodes. In the context of developing advanced controls technology for systems with wireless networks in feedback paths there is a strong need for a test environment that can be used to explore all facets of such systems, including potential problems relating to control loop performance and WSN management.**

We propose to address this requirement by developing a new testbed for research in WNCSs by adding advanced control agents and process simulators from the Intelligent Control and Asset Management or ICAM project to an existing WSN testbed called the Wireless Industrial Sensor Network Testbed for Radio-Harsh Environments or WINTeR. This testbed has been custom developed for oil and gas industrial environments, i.e., it includes features such as electromagnetic interference and complex multipath propagation. The proposed new testbed, hereafter called WINTeR-ICAM, will include the ICAM Supervisor, ICAM Agents and an additional agent to resolve conflicts between maintaining control loop performance and managing the WSN effectively and efficiently, called a WNCS Coordination Agent or WNCSCA. This agent is designed to be part of an intelligent supervisory control system, and to grant the WSN as much latitude in meeting its objectives as possible while maintaining the performance of control loops that incorporate wireless paths, thus adding to the safety and reliability of future WNCSs. Together, the process simulators, ICAM Agents and WINTeR will provide a powerful new environment for research and development of advanced WNCS technology, with WSN hardware and software in the loop; this novel conception is the contribution of this paper.

I. Introduction

During the past two decades, a large amount of research has been done on distributed control systems that incorporate wireless sensor networks, or what are called Wireless Networked Control Systems (WNCSs). That interest can be traced to the many advantages achieved by eliminating the restrictions of traditional point-to-point wired control architectures, such as reduced wiring costs, rapid deployment, flexible installation, fully mobile operation, and improved freedom in placement of controllers, sensors and actuators [1], [2], [3], [4]. In such systems, distributed sensors, controllers and actuators exchange information over a wireless communication network.

New developments in wireless networked control allow engineers to support a number of control applications that were previously difficult to realize or afford. Due to the rapid development of micro-electro-mechanical systems and wireless communication devices, engineers can integrate small sensors, actuators, processors, batteries, and wireless communication devices into what are called wireless sensor and actuator networks, or, more simply, wireless sensor networks (WSNs). The WSN nodes can then be distributed in large numbers to self-organize into networks that serve a wide range of purposes, including off-shore petroleum applications, environmental monitoring, industrial process control and intelligent systems for any application. Improved technology and stricter requirements make the development of WNCSs more difficult, however. Significant problems arise from inflexibility in the imposition of strict requirements on data rates, latency, data loss and jitter to ensure control system performance on one hand [2] [4], and effective protocols for WSN robustness, security and efficiency [1] [3] on the other.

Our primary interest in WNCSs is for the Petroleum Applications of Wireless Systems (PAWS[1]) project, a major research program at Cape Breton University (CBU, the project lead dealing with WSNs [5]), the University of New Brunswick (UNB, focussed on Intelligent Control and Asset Management or ICAM [6], [7], [8]), and the College of the North Atlantic (CNA, which supports a pilot plant for petroleum processing that was modeled by UNB [9]).

Developing a distributed control system over a WSN is a challenging task because it is necessary to satisfy pressing requirements from both fields, communication networks and control systems. The dynamic performance of a closed-loop system with wireless links (sensor-to-controller, controller-to-actuator) is one of the most important concerns for industrial control systems. Although modest data rates, network delays

[1]The PAWS project is supported by the Government of Canada, through the Atlantic Innovation Fund (AIF).

and packet losses may generally be acceptable in communication networks, there are strict limits as to what can be accepted in the case of closed-loop control over wireless networks. In WNCSs the network design objectives must include optimizing control performance, or at least maintaining stability-related constraints such as maximum acceptable percent overshoot. On the other hand, from the WSN perspective it is desirable to conserve node battery power and to have complete flexibility to configure the network to promote the efficient use of resources; therefore, lower data rates and more delay may be accepted to achieve these goals. Thus, there are distinct tradeoffs between network communications and control system performance.

We are addressing these impediments to WNCS research by (1) extending the Wireless Industrial Sensor Network Testbed for Radio-Harsh Environments (WINTeR [10]), (2) installing process models [9], [11] for use in testing and refining our WSN technology, (3) extending the WNCS Coordination Agent (WNCSCA) to address the conflicting requirements of the WSN on one hand and process control loops on the other, and (4) installing ICAM agents for linearized model identification, data reconciliation, and fault detection, isolation and accommodation. WINTeR permits testing and demonstrating WNCS in a realistic setting, with WSN hardware and software in the loop, where data rates, path delays, electromagnetic interference and network loading can be included in a controlled and repeatable manner. The main responsibilities of the current WNCSCA are *path delay* and *data rate management*, both of which have a major impact on controller performance over the WSN and on the energy consumption of the WSN nodes. Node energy conservation is often a critical issue in WSNs for node and network life, as the nodes are usually powered by batteries, and in many cases the replacement of these power sources is difficult, inconvenient, and/or expensive. Our WNCSCA coordinates with ICAM and the routing layer, through the WSN Gateway, to allow as much network optimization, flexibility and efficiency as possible based on the safety requirements of the WNCS.

The body of this presentation is as follows: First, we provide an overview of the WINTeR testbed [10], and then we outline our agent-based supervisory control system called ICAM [6], [7], [8]. Then, we present the concept and design of the WNCSCA and describe the current effort to integrate ICAM and its Agents with WINTeR. The capabilities of the integrated system are then enumerated, and an example is given to illustrate a typical planned use of the combined testbed. Finally, we conclude by summarizing the current plan for developing this new test facility and potential future work.

II. WINTeR WSN Testbed

WINTeR is an open-access, multi-user experimental facility that supports the development and evaluation of WSNs for radio-harsh environments (RHEs). This testbed supports the development and evaluation of emerging WSN technologies, including physical layer developments, propagation modeling, new protocols for WSN management and security, the validation of wireless solutions for industrial processes, and cross-layer optimization. A schematic depiction of the WINTeR testbed is shown in figure 1.

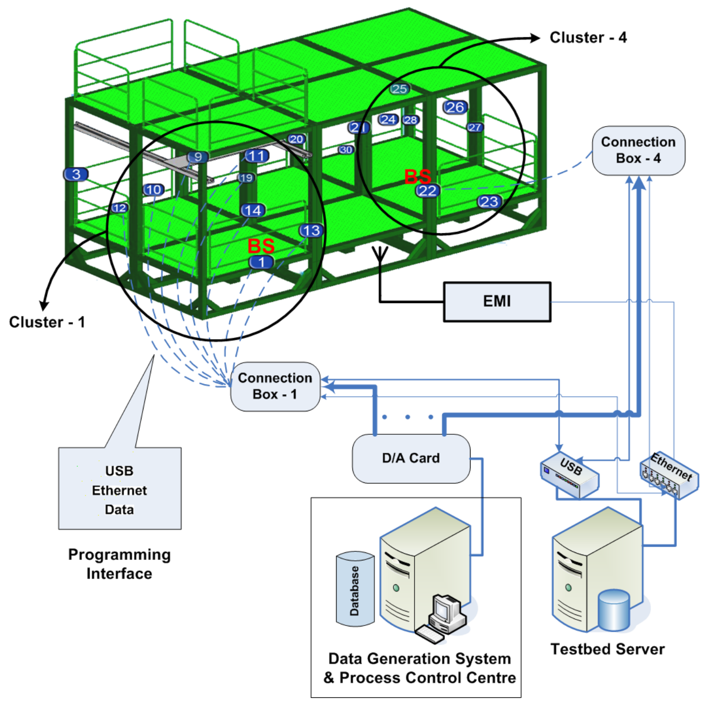

Fig. 1. Schematic of the WINTeR Testbed

This testbed is designed to replicate an industrial WNCS environment in every way possible, and support wide-ranging research activities needed to advance the field. To illustrate the breadth of testing that can be conducted, we provide a list of features of WINTeR, organized roughly in order of importance:

- RHE – The testbed physical environment replicates the extreme multipath conditions that exist in a RHE, as shown in figure 1.
- Remote Accessibility – WINTeR is web accessible, to promote collaboration among geographically dispersed teams.
- Network Management – The testbed supports extensive network management of the motes. This includes programming, status monitoring, and enabling/disabling of the motes.
- Experiment Control – The testbed supports programmable configuration of network and node parameters such as application selection, selection of nodes that will participate and node signal strength.
- Extensibility – The testbed is easily extensible to support a variety of existing and newly emerging mote platforms.
- Scalability – The testbed is scalable, to support testing of many (up to 127) wireless devices.
- Process Simulation – the WINTeR testbed includes two process simulators to provide realistic real-time data streams that mimic real WSN data handling. Both simulators include separate access to process controllers and

sensors, so WNCSs can be studied with wireless paths in the loop.

- Electromagnetic Interference (EMI) - The testbed provides for the generation and control of EMI as it would exist in an industrial environment.
- Repeatability – The testbed supports, to the greatest extent possible, repeatable experiments. However, it is realized that, because of external factors, it is difficult to realize complete repeatability in a wireless testbed.
- Signal Attenuation – The testbed provides control over mote signal strength, to enable testing under varying signal-strength conditions. This includes effects due to changes in distance between wireless devices.
- Instrumentation – The testbed provides instrumentation for generating data and monitoring network performance metrics, such as mote power consumption. As pointed out in an NSF workshop [12] it is impossible to obtain an adequate understanding of the behavior of networks without comprehensive instrumentation. The authors believe this to be particularly true of WSNs.
- Data Logging – The testbed saves data using a rigorous data-logging facility.

We do *not* support simultaneous users, since this would create conditions that would not be repeatable; for example, sharing of wireless bandwidth and injecting EMI would produce conditions that could only be replicated it the same users were conducting the same tests multiple times. We also do not plan to allow for node mobility – while this might be important for some industrial networks, it was decided that it is only a minor issue at this time, especially in petroleum facilities consisting almost entirely of static nodes.

III. The ICAM System

The main functions of the ICAM system, from the control and information technology viewpoint, can be organized in terms of Intelligent Agents, which automate and monitor/diagnose their individual activities as shown in figure 2 and outlined as follows:

- Data reconciliation (signal conditioning): processing raw data to detect and remove outliers ("gross errors") and data dropouts, correct inconsistencies (e.g., material and energy imbalance) and reduce the effects of error sources (e.g., noise); for further technical detail regarding nonlinear dynamic data reconcilation (NDDR) see works of Moreno, Laylabadi and Taylor [13], [14], [15],
- Process understanding: use the processed signals from data reconciliation to assess the current dynamic behavior (e.g., by linearized model identification or LMId to characterize dynamic behavior near the present set-point [16]),
- Data interpretation: derive higher-level information related to the operational status of the facility and the "health" of the system and subsystems (e.g., fault detection, isolation and accommodation, FDIA); for further technical detail see works of Omana and Taylor [16], [17],
- Wireless sensor network liaison: work with the WSN to manage faults (e.g., node failures) and collaborate in WSN energy management under the constraint that operating control loops must perform acceptably; for further technical detail see works of Ibrahim and Taylor [18], [19],
- Process simulation: ICAM has been intensively tested with two process simulators, one a high-order, highly complex model of the CNA pilot plant [9] which models a two-stage petroleum separator and has five control loops, and the other a simpler nonlinear model of a jacketed continuous stirred-tank reactor (JCSTR [11]) with two control loops (level and temperature). The pilot plant simulator is the most challenging test case, and was used to develop and demonstrate NDDR and FDIA in as realistic an environment as possible, and the JCSTR simulator is substantially less computationally intense, so it was chosen and implemented as a process simulator to better allow us to study issues related to the performance of control systems over a WSN.

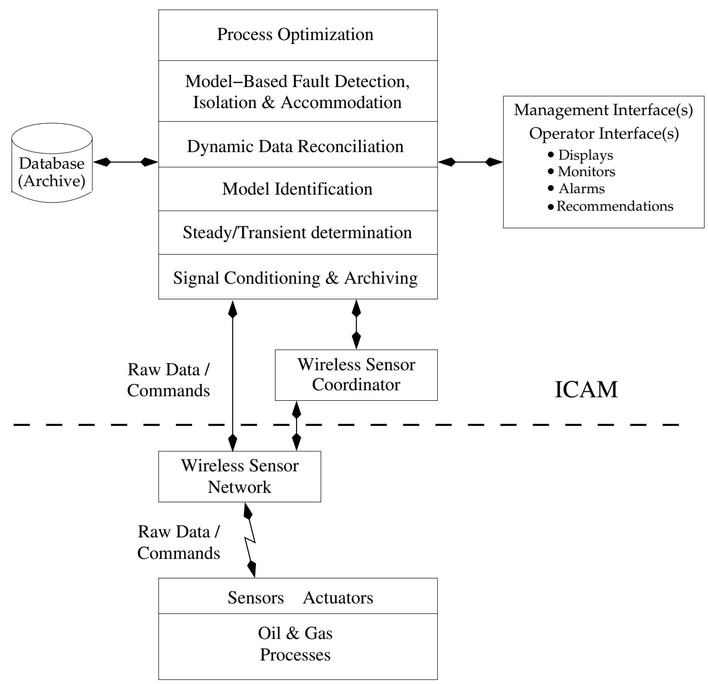

Fig. 2. Schematic of the ICAM Supervisory System

IV. WNCS Coordination Agent

The WNCSCA was conceived as a part of ICAM, to mediate between the ICAM supervisory control system and the Gateway of CBU's WINTeR, which supports implementation and evaluation of WSNs for industrial applications. The interface between the ICAM system and the Gateway of WINTeR is portrayed in figure 3.

During the operation of the ICAM supervisory system, its agents impose different requirements or specifications on the WSN to complete their functions properly. For example, some agents require different data rates from specific sensors and

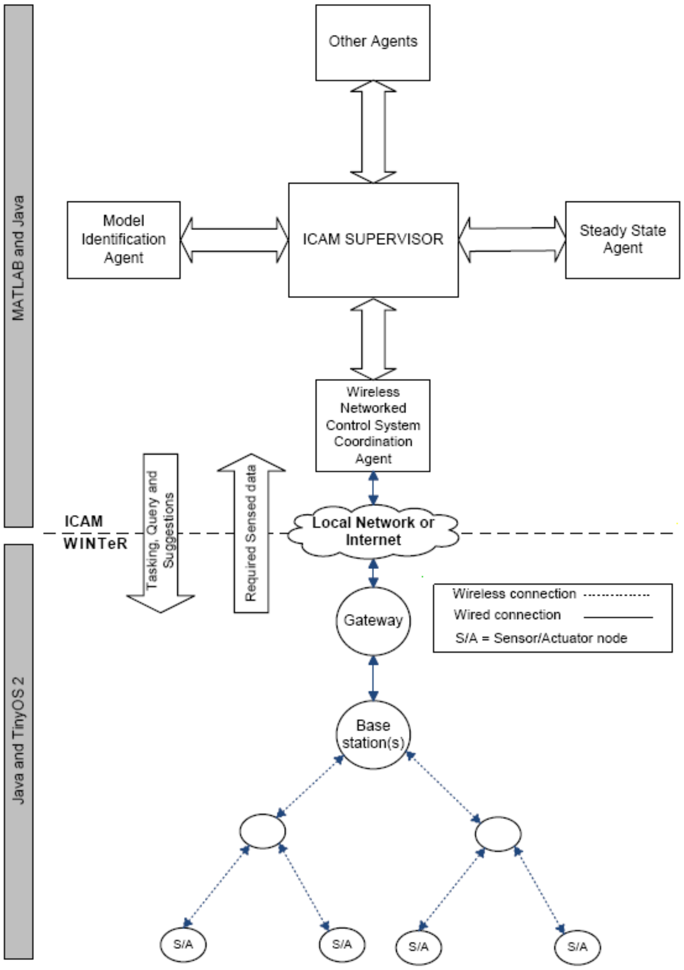

Fig. 3. Schematic of ICAM, the WNCSCA and WINTeR

actuators in specific regimes, such as start-up, set-point change and steady-state for supervising and monitoring the plant. During start-up, the initial process variable transients must decay under closed-loop control, so appropriate data rate and path delay constraints must be imposed to achieve acceptable performance. Once the process reaches the desired steady-state set-point the LMId Agent may perturb the plant with small-amplitude pseudo-random signals (to excite all of the dynamic modes in the plant), gather data and apply its model identification algorithm [16], perhaps using different data rates than those needed to deal with transients. After that, the process may remain settled in steady state, in which case loops can be opened[2] and data rates substantially reduced so ICAM can monitor the process; as long as there are no disturbances or set-point changes slow sampling can continue and the WSN can manage its configuration and data rates freely and meet its objectives accordingly. In many industrial systems a process may be in steady state for long periods of time, with infrequent set-point changes requiring closed-loop control, so this strategy will allow the WSN to be managed in a more optimal way much of the time.

In summary, the various modes of operation require tighter or looser constraints on data rates and path delays; the WNCSCA mediates between ICAM and the WSN to allow both the control system and the WSN to meet their objectives as flexibly and completely as possible. The WNCSCA communication scheme is described in [20]; in [18] the effective method and algorithms are presented and demonstrated for determining the maximum allowable packet delays and minimum data rates that the WSN may utilize without excessively degrading the performance of control loops operating over the WSN when loops are closed. Specifically, we define *design percent overshoot* (% OS) as desirable performance and *acceptable* % OS as the limit enforced by the WNCSCA; for example, the case presented in [18] corresponds to design % OS = 10, acceptable % OS = 30, which represents a case where fast response is more important than overshoot. More conservatively, one may use design % OS = 0, acceptable % OS = 10. The WNCSCA uses a nonlinear process simulator in an effective and efficient way to determine the safety limits for acceptable % OS. This method maintains acceptable closed-loop performance in this sense.

V. Full Integration of ICAM and WINTeR

Figure 4 portrays our plan for the full integration of ICAM and WINTeR. The ICAM Agents are being installed on WINTeR, as shown in this schematic. We are preparing to run scenarios similar to the following 30-minute exercise, which illustrates the anticipated use of WINTeR-ICAM for research on advanced WNCS technology:

1) Start all components of WINTeR-ICAM, including the CNA pilot plant simulator, and initialize the run. Assume we want to study the effectiveness of the ICAM FDIA Agent in a situation where closed-loop control is done over a WSN; thus a sensor fault is set to occur after the first 20 minutes of the scenario.
2) Based on the set points and initial conditions specified, the process simulator starts, under closed-loop control to handle initial transients.
3) The Nonlinear Dynamic Data Reconcilation Agent immediately starts to use it's nonlinear process model to condition the process data, as explained above.
4) The Steady-state/Transient Determination (SSTD) Agent (not shown in figure 4) declares that the process variables are in steady state after 127 sec. of operation.
5) The LMId Agent begins model identification; after an additional 900 sec. of operation a good model has been found and validated; this is made available to the FDIA Agent so fault detection, isolation and accommodation can begin.
6) A moderate level of electromagnetic interference starts at $t = $ 7:00, causing sporadic data drop-out; since these lost data points are isolated (do not occur successively) the data is corrected by the NDDR Agent by extrapolating from the previous values.

[2] Opening control loops momentarily to handle data drop-outs was suggested in [2]; our strategy of opening control loops during steady-state operation to alleviate strict control-related WSN constraints is, we believe, new.

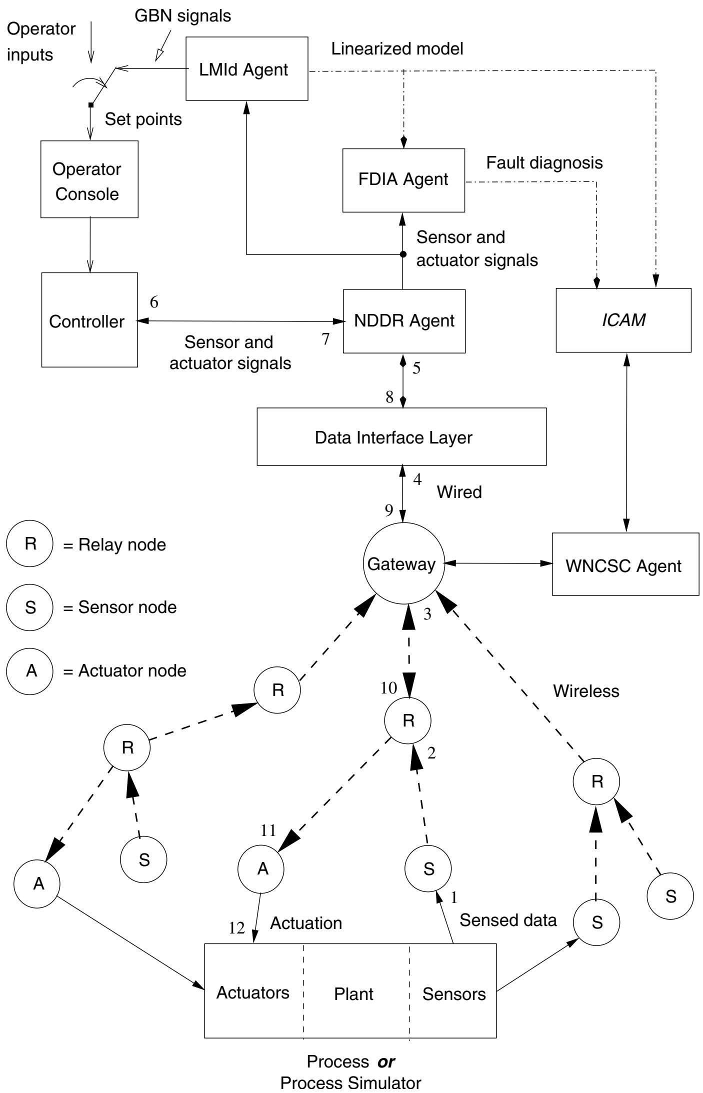

Fig. 4. Integration of WINTeR, ICAM and process.

7) The SSTD Agent again signals that the process variables are in steady state, so the WNCSC Agent can tell ICAM to open the loops and drop back to process monitoring at a substantially lower data rate.
8) A set-point change is ordered by the operator at $t =$ 18:30 min.; the WNCSC Agent immediately orders ICAM to close the loops and tells the WSN Gateway to use the required faster data rate.
9) The sensor fault occurs when $t = 20$ min.; it is detected at $t =$ 20:00:25 and isolated at $t =$ 20:03, so the WNCSC Agent immediately orders ICAM to open the corresponding loop.
10) The fault size is determined at $t =$ 21:19 and accommodation is started immediately thereafter, correcting the fault by "subtracting it out" from the sensed value; the WNCSC Agent immediately tells ICAM to close that loop, in case transients have occurred during the FDIA process.
11) One of the WSN nodes in a control-signal path of the WSN fails at $t =$ 23:00; the WNCSC Agent is notified and it orders ICAM to open the corresponding loop and alarm the operator. The WSN Gateway proposes a new network reconfiguration that the WNCSC Agent rejects because the path delays in the loop are excessive; the WSN Gateway proposes a second configuration that has acceptable path delays; based on this the WNCSC Agent determines the minimum acceptable data rates to maintain acceptable closed-loop performance.
12) The WNCSC Agent determines that the WSN can again support closed-loop control of the loop at $t =$ 23:37; it notifies ICAM to close that loop to control any transients that may have occurred due to disturbances, and tells the WSN Gateway to use acceptable data rates for closed-loop control.
13) At $t =$ 25:42 in the scenario the SSTD Agent again signals that the process variables are in steady state, so the WNCSC Agent can tell ICAM to open the loops and drop back to process monitoring at a substantially lower data rate.
14) The above WINTeR-ICAM scenario completes at $t = 30$ min.

VI. Integration Project Status

The ICAM Agents are being readied for installation on WINTeR. They will be reimplemented in C as function blocks (under standard IEC 61499 [21]) for use in industrial process control applications, and then interfaced with each other and the WSN Gateway; until this work is complete we will use MATLAB® versions of the ICAM Agents interfaced using TCP. This protocol has been implemented in java as a MATLAB® process interface, and testing has shown that the numerous ICAM real-time agents can exchange data reliably and at a good data rate. The JCSTR and pilot plant models, which were originally monolithic MATLAB® functions, have been split into a continuous-time process and a two- or five-loop discrete-time controller, respectively, so they can be installed as two separate units connected over the WSN, as shown in figure 4. The process simulators do not need to be reimplemented in C, as they are not key elements of the WINTeR-ICAM testbed; rather, they may be regarded as signal generators. The ICAM Supervisor is presently being reimplemented in a simpler way using the G2 expert system shell; its operation will also initially be mocked up in a manual fashion using MATLAB® scripts before the supervisor is ready.

The WSN configuration management protocol is currently under development, so in initial testing of the WINTeR-ICAM testbed this function will be performed manually. We plan to implement a new Delay and Rate Sensitive Routing Object (DRSRO) for use in ISA100.11a networks [22], based on WirelessHART, an open-standard wireless networking technology developed by the HART Communication Foundation; it was approved by the IEC in April 2010 as the first international standard for wireless, IEC 62591 [23]. After the basic WINTeR-ICAM testbed is operational we plan to add security (cryptography, [24]) and intrusion detection [25]. We anticipate being prepared to run scenarios such as that presented above using mocked-up components by the end of 2010; the configuration protocol and ICAM expert system should be operational in Summer 2011 for more realistic testing, refinement and demonstration, then the reimplemented ICAM Agents and additional Smart Agents will be installed as they become available.

VII. Summary and Conclusion

The WINTeR-ICAM testbed will be an extremely valuable facility for developing advanced WNCS technology, with minimal risk. The wireless issues involved in WNCS systems will be realistically implemented as "hardware and software in the loop", so robust methods for dealing with latency, data rates, jitter and electromagnetic interference can be developed, tested and refined with rigor. Advanced controls technology can also be implemented, tested and evaluated, as our initial efforts with NDDR, FDIA and WNCSC will demonstrate. Other researchers will be welcome to use the WINTeR-ICAM testbed, so there should be substantial synergy achieved in the near future, as various research groups exchange their experiences and ideas. We are looking forward to exciting and fruitful opportunities for future work in WNCS development.

Acknowledgment: We gratefully recognize all the effort put into the PAWS project over the last eight years. **To the CBU team** – Mr. James Nicholson, Mr. Martin Murillo, Mr. Nagesh Polu, Mr. Mohsen Marami, Dr. Shuiping Luo, Dr. Richard Ma and Mr. Babar Shehzad – **and to the UNB team** – Dr. Atalla Sayda, Dr. Maira Omana, Mr. Mazyar Laylabadi, Ms. Pilar Moreno, Mr. Hazem Ibrahim and Mr. Zhenyu (Scott) Bao – **many thanks for the years of enthusiasm, hard work and creativity.**

References

[1] C. Fischione, K. H. Johansson, F. Graziosi, and F. Santucci. Distributed cooperative processing and control over wireless sensor networks. *Proc. International Conference on Wireless Communications and Mobile Computing*, July 2006.

[2] P. Kawka and A. Alleyne. Stability and feedback control of wireless networked systems. *Proc. American Control Conference*, June 2005.

[3] X. Liu and A. Goldsmith. Wireless network design for distributed control. *Proc. 43rd* IEEE *Conference on Decision and Control*, December 2004.

[4] N. Plopyls, P. Kawka, and A. Alleyne. Closed-loop control over wireless networks. IEEE *Control Systems magazine*, June 2004.

[5] I. Johnstone, J. Nicholson, B. Shehzad, and J. Slipp. Experiences from a wireless sensor network deployment in a petroleum environment. *ACM International Wireless Communications and Mobile Computing Conference (IWCMC)*, August 2007.

[6] A. Sayda. *Intelligent Control and Asset Management of Oil and Gas Production Facilities*. PhD thesis, *University of New Brunswick*, May 2008.

[7] A. Sayda and J. H. Taylor. An intelligent multi agent system for integrated control & asset management of petroleum production facilities. *Proc. Flexible Automation and Intelligent Manufacturing (2007 FAIM)*, June 2007.

[8] J. H. Taylor and A. Sayda. Prototype design of a multi-agent system for integrated control and asset management of petroleum production facilities. *Proc. American Control Conference*, June 2008.

[9] A. Sayda and J. H. Taylor. Modeling and control of three-phase gravity separators in oil production facilities. *Proc. American Control Conference*, July 2007.

[10] J. Slipp, C. Ma, M. Murillo, J. Nicholson, N. Polu, and S. Hussain. WINTeR: architecture and applications of a wireless industrial sensor network testbed for radio-harsh environments. *Proc. Communication Networks and Services Research*, January 2008.

[11] J. H. Taylor. Jacketed continuous stirred-tank reactor - models and simulators. *PAWS Internal Memo, available from the author*, November 2009.

[12] NSF Workshop on Network Research Testbeds, Chicago, IL, Oct 2002. Available: http://www.net.cs.umass.edu/testbed_workshop/

[13] R. del P. Moreno. Steady state detection, data reconciliation, and gross error detection: Development for industrial processes. Master's thesis, *University of New Brunswick*, January 2010.

[14] M. Laylabadi and J. H. Taylor, ANDDR with Novel Gross Error Detection and Smart Tracking System, *Proc. 12th IFAC Symposium on Information Control Problems in Manufacturing*, Saint-Etienne, France, 17-19 May 2006.

[15] J. H. Taylor and M. Laylabadi, A Novel Adaptive Nonlinear Dynamic Data Reconciliation and Gross Error Detection Method, *Proc.* IEEE *Conference on Control Applications*, Munich, Germany, 4-6 October 2006.

[16] M. Omana. *Fault Detection, Isolation and Accommodation Using the Generalized Parity Vector Technique*. PhD thesis, *University of New Brunswick*, October 2009.

[17] J. H. Taylor and M. Omana, Fault Detection, Isolation and Accommodation Using the Generalized Parity Vector Technique, *Proc. IFAC World Congress*, Seoul, Korea, 6-11 July 2008.

[18] J. H. Taylor and H. S. Ibrahim. A new, practical approach to maintaining an efficient yet acceptably-performing wireless networked control system. *Proc.* IEEE *Conference of System Science and Engineering*, July 2010.

[19] Hazem S. M. Ibrahim, Wireless Networked Control System Coordination Agent, MScEng thesis, *University of New Brunswick*, March 2010.

[20] J. H. Taylor, H. S. Ibrahim, J. Slipp and J. Nicholson. A Safe Communication Scheme for an Intelligent Wireless Networked Control System Coordination Agent. Accepted for the IEEE *International Conference on Systems, Man, and Cybernetics*, October 2010.

[21] Valeriy Vyatkin, *IEC 61499 Function Blocks for Embedded and Distributed Control Systems Design,* ISA, 2007.

[22] ISA-100.11a-2009 *Wireless systems for industrial automation: Process control and related applications,* ISA, 2009.

[23] IEC 62591 ed. 1.0, *Industrial communication networks - Wireless communication network and communication profiles - Wireless*HART, ISA, 2010.

[24] Q. Wang, T. Zhang, "Sec-SNMP: Policy-Based Security Management for Sensor Networks", in *Proc. International Conference on Security and Cryptography (*SECRYPT*),* 2008.

[25] I. Onat and A. Miri, "An intrusion detection system for wireless sensor networks", *Proc.* IEEE *International Conference on Wireless And Mobile Computing, Networking And Communications (WiMob 2005,* August 2005.