Decentralized Agent-based Control of Chilled Water Plants using Wireless Sensor and Actuator Networks

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Abstract— **The resiliency of a ship is dependent upon the resiliency of the various engineering plants that operate the ship. Especially for combatant ships, engineering plants must be reconfigurable when damage occurs to ensure the ship has fight-through capabilities. Furthermore, reduced manning on ships necessitates the automated operation of engineering plants, especially their reconfiguration during times of battle damage. Wireless telemetry has been proposed in lieu of traditional tethered architectures for the monitoring and control of shipboard engineering plants. In this study, wireless nodes capable of sensing and actuation are explored for the automated control of a chilled water plant. A utility oriented agent-based control network is proposed as a scalable and robust approach to the automated configuration of a chilled water plant. To illustrate the performance of the proposed control and reconfiguration architecture, a small-scale chilled water demonstrator is utilized. A network of wireless sensing and actuation nodes are shown to be highly effective in monitoring and reconfiguring the chilled water plant under varying operational conditions to achieve its operational objectives.**

Wireless sensor; decentralized control; shipboard plants; agent-based control; automated reconfiguration

I. Introduction

The U.S. Navy is exploring the use of the all-electric ship (AES) design concept in future naval vessels to render ships more resilient. The AES design concept leverages the electric-drive propulsion system to operate the other naval engineering plants on the ship [1]. The integrated power architecture of the AES design results in many of the ship plants interconnected; this is advantageous with respect to reconfiguring ship plants and the reallocation of shared resources between various ship plants. One set of interconnected ship plants is the electrical distribution plant and chilled water plant. The chilled water plant is vital to the operation of many of the ship's equipment (*e.g.*, radar, pulsed weapon systems) that require cooling during normal operation [2]. The electrical distribution system operates the pumps, valves and sensors that are required for the control of the chilled water plant. To enable higher degrees of automated plant reconfiguration, dense arrays of sensors and actuators are required within the shipboard plants to implement distributed control architectures [3]. Furthermore, to facilitate automated plant reconfiguration in the face of battle damage, computational intelligence must be distributed within the ship plants. This alleviates manning requirements without sacrificing the fight-through capabilities of the ship.

Communication between shipboard plant components is critical for offering coordinated control actions and for the real-time exchange of data. To date, wired communication systems have been used on ships including copper wiring and fiber optic cables [4]. While physical wiring is reliable and secure, it can be challenging to install in ships. Especially as the amount of wiring increases, its installation becomes more expensive and complicated. Wired communication systems can also be vulnerable to failure if the physical wiring is damaged from long-term deterioration or during battle. A potentially more cost-effective approach may be the use of wireless communication in ships. In addition to being cheaper to install, it can also reconfigure its topology if elements of the communication system may fail during battle. The feasibility of shipboard wireless communication has been extensively explored for shipboard monitoring and control systems [5] as well as for hull monitoring systems [6].

In this study, a versatile wireless node that supports the collection of data from plant sensors, actuation of plant actuators, and execution of data interrogation algorithms, is proposed for the monitoring and control of shipboard plants. The *Narada* wireless node is designed to be both low-cost and low-power. A network of *Narada* wireless nodes is explored for the control and reconfiguration of a chilled water plant. To formulate a decentralized control solution ideally suited for the highly distributed sensing, actuation and computing architecture offered by a wirelessly integrated plant, agent-based control solutions based agent utilites are explored. The paper first introduces the wireless sensing and actuation nodes followed by the description of a table-top chilled water demonstrator. Next the decentralized market-based control solution is described accompanied by its performance on the demonstrator system. Finally, the paper concludes with a summary of research key findings and a description of some future research directions.

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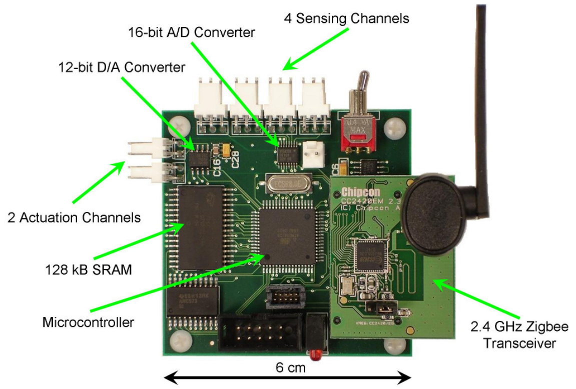

Figure 1. Narada wireless node for shipboard plant monitoring and control.

II. Wireless Sensing and Actuation Technology

Wireless sensing and actuation nodes represent a powerful new paradigm for the monitoring and control of shipboard plants. In this study, the *Narada* [8] wireless node is adopted for the implementation of the wirelessly integrated plant. The design of the *Narada* node consists of four major subsystems: 1) sensing interface; 2) actuation interface; 3) computational core; 4) wireless interface. The *Narada* sensing interface consists of a 4-channel, 16-bit analog-to-digital converter (Texas Instruments ADS8341) that can sample at rates as high as 100 kHz. Sensors outputs that are not within the 0 to 5V range of the A/D can be preconditioned using external circuitry. To command plant actuators, the node also contains a 2-channel, 12-bit digital-to-analog converter (Texas Instruments DAC7612) that serves as the actuation interface. Similar to the sensing interface, the actuation interface can command interfaced actuators at rates as high as 100 kHz. The output voltage of the actuation interface is 0.0 to 4.095 V. The third subsystem of *Narada* is the computational core. The computational core consists of the Atmel 8-bit ATmega128 microcontroller. The microcontroller controls the sensing and actuation interfaces over a serial peripheral interface (SPI). On-chip, the ATmega128 contains 128 kB of read only memory where software is stored. To provide the computational core with ample memory for data storage, an additional 128 kB of static random access memory (SRAM) is included. Finally, communication between *Narada* nodes is accomplished by the wireless interface. The wireless interface consists of an IEEE 802.15.4 transceiver (Texas Instruments CC2420). This specific radio can communicate at rates as high as 250 kbps with line-of-sight ranges of 50 m or more. A picture of the *Narada* wireless node is presented in Fig. 1.

The impact of wireless sensing and actuation technology goes well beyond being a one-to-one replacement for tethered sensors and actuators. In particular, wireless sensing and actuation nodes include microcontrollers within their design to packetize data for the digital wireless transceiver. Combined with a small amount of on-board memory, the microcontroller can be leveraged as a powerful computing resource for node-based interrogation of measurement data. There are three major reasons why embedded computing is ideal for the automation of shipboard plants [7]. First, local data processing is more energy efficient than communicating raw measurement data. Since the wireless transceiver consumes more power than any other wireless node function, local data processing serves as a substitute for energy consuming communications. Second, data processing at the node can convert a high bandwidth data stream (*i.e.*, raw data) to a low bandwidth stream (*i.e.*, processed results) thereby removing an undue burden on the wireless communication channel. This results in improved reliability of the wireless channel for when communication between plant components is critical. Finally, local data processing is a functional building block of a scalable architecture supporting data processing by automation systems (*e.g.,* feedback control systems). Node-based data processing is required to fully realize the aforementioned goal of plant components being capable of self-assessment and reconfiguration.

Prior work with *Narada* explored use of the node for the monitoring and health assessment (*i.e*., damage detection) of shipboard chilled water plants [9]. Specifically, networks of *Narada* nodes have been implemented as a distributed computing platform consisting of many distributed computational nodes connected by a bandwidth constrained wireless channel. That implementation allowed data interrogation methods that are traditionally implemented in a centralized computing platform (*e.g.,* server) to be divided into smaller computational blocks that are distributed into the network for parallelized execution. An analytical pipe network model of a chilled water plant was implemented within the computational core of the *Narada* nodes. To identify damage to the chilled water plant, a model updating approach was adopted. A novel parallelization of the simulated annealing stochastic search algorithm was proposed and implemented in the *Narada* network to successfully update the chilled water plant model to identify damage existence and location in the plant. Integral to the approach was the implementation of an agent-based method for computational task assignment in the wireless sensor network [9].

III. Chilled Water Plant Testbed System

Chilled water systems in ships are critical for the cooling of equipment that has a propensity to overheat. Equipment that requires cooling on a naval combatant vessel includes electrical generation units, pulsed weapon systems, radar, among others. A small-scale chilled water system has been created at the University of Michigan to highlight the key functional elements of chilled water plants on naval vessels (Fig. 2). The demonstrator incorporates four resistive heating elements bonded to the surface of aluminum blocks to represent thermal loads the chilled water system is designed to thermally regulate. To cool these two loads, each aluminum block (10 x 5 x 2.5 cm^3) has two cylindrical holes machined 10 cm long and with diameters of 1.25 cm. Aluminum block T1 and T2 are soldered together while blocks T3 and T4 are also soldered. Two pumps are installed in the system with each pump capable of cooling both thermal loads through the use of automated valves and a network of pipes (flexible tubing 1.25 cm in diameter). The cooling system is divided in two major halves (*i.e.,* port and starboard halves) that are designed with a high degree of functional redundancy and interconnectedness. This

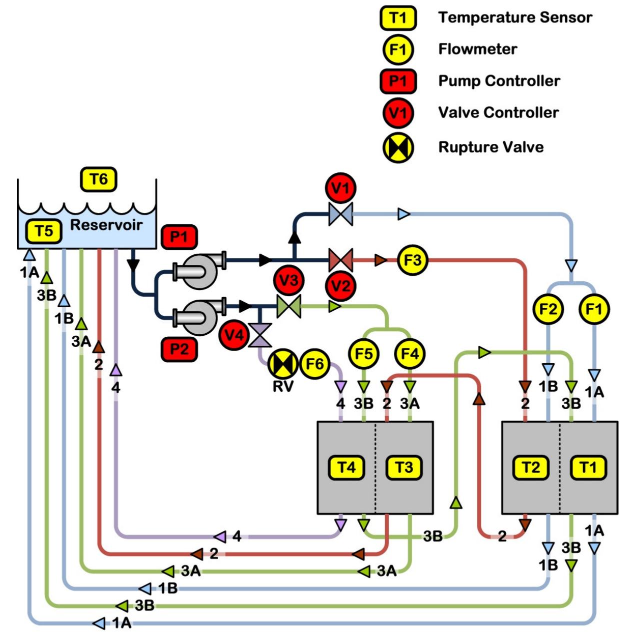

Figure 2. Architectural overview of the chilled water plant demonstrator.

allows the chilled water system to continue to meet its operational objectives even if damage was to occur on one side of the ship (port versus starboard sides).

The chilled water system has two pumps denoted as P1 and P2 in Fig. 2. The pumps selected are Greylor PQ-12 DC gear pumps capable of maximum flow rates of 37 mL/s when powered by a 12 V DC source. The output flow rate can be varied by duty-cycle application of the pump voltage source. Two *Narada* wireless nodes are used to control the pumps with each node controlling the pump power source (a 12 V DC source) using an electrical switching circuit. Specifically, a Vishay 4N35 optocoupler is used by each *Narada* to duty cycle the pump using a pulse width modulation (PWM) signal generated by the *Narada* actuation interface.

The output of each pump is connected to two output channels controlled by valves (denoted as V1 and V2 for P1 and V3 and V4 for P2 in Fig. 2). The STC 2W025-1/4 solenoid valves utilized to route chilled water throughout the tabletop demonstrator require a 12V supply to provide 20W of power in order to open a pipe for flow. Because the *Narada* node itself is not capable of providing sufficient voltage and current to operate the valve, an Omron G2R-1-E-DC12 relay is used to apply a 12 V signal from a DC power supply. This 12V power supply is electrically isolated from the *Narada* actuation interface through the use of a Vishay 4N35 optocoupler.

To measure the flow in the chilled water plant, six flowmeters (DigiFlow DFS-2W) are installed throughout the pipe network. The flowmeters output 60,000 pulses per liter; this requires a high-speed sensing interface that can provide a high-resolution measurement of flow. To reduce the required sampling rate, two ripple counters (ON Semiconductor MC74HC390A) are used in series to reduce the effective pulse rate of the flowmeter to 600 pulses per liter. The output of the second of the two ripple counters is interfaced to a *Narada* node where the signal is recorded. Embedded software in the *Narada* node calculates the flow rate by counting the number of pulses within a fixed time period.

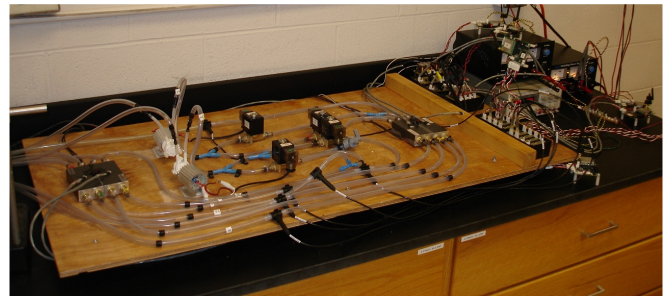

Figure 3. Fully constructed chilled water demonstrator system.

The temperature of each aluminum block is monitored using National Semiconductor LM35DT solid-state temperature sensors interfaced directly to *Narada* nodes. The temperature sensors have a sensitivity of 10 mV per degree Celsius and operate between 0 and 100 °C. The four temperature sensors are denoted as T1 through T4 in Fig. 2. Two additional temperature sensors are deployed in the system: one in the reservoir from which the chill water is derived (denoted as T5), and the other in the vicinity of the demonstrator (denoted as T6) to measure the ambient air temperature. Fig. 3 is a picture of the completed demonstrator.

IV. DECENTRALIZED CONTROL ARCHITECTURE

The agent-based approach to controlling a shipboard chilled water system, which has been studied by others [10], is fused with a wireless sensor network topology in this paper. An agent-based system can be defined as any system in which multiple intelligent agents (*i.e.*, wireless *Narada* nodes) interact directly with each other and with the environment (*i.e.*, pumps, valves, flow meters, temperature sensors). In a multi-agent environment, agents each have an incomplete view of its environment and acts according to its own knowledge and set of rules. Multi-agent systems (MAS) have been successfully applied to a large number of real world problems, including structural monitoring, resource allocation [11], online trading [12], environmental monitoring [13], disaster response, and personnel distribution [14].

When applied within a network of wireless devices, an agent-based environment allows us to distribute computational or control tasks across a large number of wireless nodes in a parallel fashion. As such, problems associated with power efficiency, data loss, and finite communication ranges can be minimized while providing a powerful framework for the autonomous, in-network processing of sensor data and the control of physical systems. Because each node in an agent-based wireless network has the opportunity to play an equal part in any computational task (assuming they are within communication range), an agent-based framework plays directly to the strength of a WSN: its prolific intelligent nodes.

A centralized controller can be implemented to optimally control the temperature of the four thermal loads. As a hybrid system that is defined by both continuous dynamics (*e.g.*, fluid flow, heat conduction) and discrete changes in the system state (*e.g.*, changes in the network configuration by opening and closing valves), the controller must consider both the continuous time dynamics and discrete changes in the system state. Toward this end, a controller can exhaustively search every configuration of pump duty cycle and valve configuration to determine which configuration has the most beneficial impact on the thermal load temperature while consuming the least energy. This model-predictive approach to centralized control is capable of assigning valve configurations and pump speeds to the demonstrator's various components such that each of the demonstrator's heat sources is kept under a critical danger temperature while using as little pump power as possible. The weakness of this approach is that it requires a large amount of computation, even in the case of the rather simplistic demonstrator described herein. For example, the chilled water demonstrator is defined by a space of almost 1000 possible system configurations from which an optimal pump and valve assignment must be found that maximizes the utility computed by (1) over the prediction horizon. When implemented in larger shipboard systems or within a low power wireless network, this approach would quickly lose scalability.

In this study, a decentralized approach to the control and configuration of the chilled water plant is proposed using agent-based interaction within a network of *Narada* wireless sensing units. In this approach, each actuation agent (i.e., *Narada* commanding a valve or pump) makes a localized control decision in a completely decentralized fashion. In other words, each agent selects the state, s, of its own controlled component that will generate the most utility relative to the previous state, s_{past}, of the system. The utility function of the system (U_{system}) is defined:

$$U_{system} = (1-\gamma)\sum_{l=1}^{\#ThermalBlocks}(UT_l) + \gamma\cdot\sum_{j=1}^{\#Pumps}(UE_j) \qquad (1)$$

On the temperature side, the utility of thermal block l, UT_l, is defined by whether or not that thermal block temperature, TM_l, is in a normal, warning ($T_w \leq TM_l \leq T_D$), or danger state ($TM_l > T_D$). In practice these utility values should be application specific and should be defined by the end user of the chilled water system based on the detriment of functioning with temperatures exceeding the warning or danger thresholds. The temperature utility functions used here-in have been chosen to place a minor penalty when block temperatures are within the warning region, and an increasing penalty when within the danger region according to (2).

$$\begin{aligned} UT_l &= (T_W - TM_l)^2, \quad \text{if } T_W \leq TM_l \leq T_D \\ UT_l &= (T_W - TM_l)^2 + (T_D - TM_l)^4, \quad \text{if } TM_l > T_D \\ UT_l &= 0 \quad \text{otherwise} \end{aligned} \qquad (2)$$

On the energy side, the negative utility associated with running a given pump j, UE_j, is defined by the amount of power consumed by that pump when it is running at a given duty cycle, DC_j (where DC_j is between 0 and 100). Pump utility is modeled by a regression analysis of experimental data using a third order polynomial. Note that $UE_j \leq 0$ for all $0 \leq DC_j \leq 100$.

$$\begin{aligned} UE_j = -1.38x10^{-5}\cdot(DC_j)^3 - 6.23x10^{-4}\cdot(DC_j)^2 - \\ 2.54x10^{-2}\cdot(DC_j) \end{aligned} \qquad (3)$$

In Eq. (1), γ is a weighting factor between zero and one that shifts emphasis between temperature reduction and energy consumption by the system pumps.

The main simplification between the agent-based and centralized approaches is that the agent-based environment only searches new states that can be reached incrementally from the previous state. Thus, at each time step, valve agents will evaluate the derived utility of the previous system state with both their valve open and with their valve closed. Similarly, pump agents will evaluate the derived utility of the previous system state with their integer valued duty cycle increased by 10, decreased by 10, and left the same. This approach to decentralization not only decreases the number of system configurations searched at each time step from 961 to 14, but it distributes this workload across the system's 2 pump agents and 4 valve agents, meaning that each agent is only required to search a maximum of 3 different configurations. As such, this approach is significantly more scalable than using an optimal centralized controller.

A. *Agent-Based Control Algorithm:*

Utilizing the Narada's on board clock, the agent-based model-predictive control network optimizes the control action once every control time step. During each control step a localized control decision is made and performed by each valve and pump agent. The steps of this algorithm are described in detail below:

Step 1. Complete information about the current system state, $s_{current}$, and the current state actions, $a_{current}$, is shared amongst all nodes in the network. These vectors of information can be written as:

$$s_{current} = \langle TM1, TM2, TM3, TM4 \rangle \qquad (4)$$

and

$$a_{current} = \langle V1, V2, V3, V4, DC1, DC2 \rangle \qquad (5)$$

where TMi is the measured temperature of block i, Vj is the current valve state of valve j, and DCk denotes the current integer valued duty cycle assigned to pump k.

Step 2. Each valve agent j creates two potential future state action configurations, one equivalent to $a_{current}$, and one with the opposite value of Vj (*e.g.,* open to close, or close to open).

Step 3. Each pump agent k creates three potential future state action configurations, one equivalent to $a_{current}$, one with a value of DCk - 10, and one with a value of DCk + 10. No DCk values greater than 100 or less than 0 are considered.

Step 4. Each actuation agent, *e.g.* pump and valve agents, will estimate the temperature of each thermal block *i*, *TMi*, at the next time step using each of the state configurations generated in Step 2 or 3. The predicted temperature of the block is based on fluid models that model the temperature of the thermal load as a function of flow rate, ambient temperature, and the temperature of the adjacent block.

Step 5. Each actuation agent will calculate the estimated utility of each of its own proposed configurations using Eq. (1). The agent will then put itself in the configuration that will locally maximize the global utility. Note that if a valve does not see a significant utility difference between an open and closed position, it will default to the open position, giving its associated pump the opportunity to affect downstream temperatures by altering flowrate. If however both valves downstream of a pump are closed, the pump is automatically shut off for the duration of the control step.

V. RESULTS

Shipboard chilled water networks are inherently nonlinear systems. As such, defining tight bounds on controller performance are infeasible for systems even as simple as the chilled water demonstrator presented in this study. Controller performance is instead determined through simulation of the controlled system exposed to loads analogous to real world events. The agent-based controller presented herein is benchmarked against the aforementioned centralized exhaustive search controller and a simple constant duty cycle controller.

The cooling loads on shipboard chilled water systems can be classified into two categories. Persistent loads such as turbines, motors, and transformers are active the majority of the time and impose on the system relatively constant loads. Intermittent loads such as pulsed weapons systems strain the system over a short duration with a relatively large load. Considering these two classes of loads, a loading pattern was developed to validate the performance of the controllers. Thermal loads *T1* and *T2* are classified persistent 70 W loads that engage ten seconds into the test and remains on for the remainder of the 1000 second test. Thermal loads *T3* and *T4*, emulate a 70W intermittent load that pulses on for 120s starting at t=130s and reengages at t=490s with a duration of 240 s.

The controllers can compute the projected response of the system based on the differential equations describing the flow of heat in and out of the thermal loads. Each thermal block, *i*, may transfer heat with: its surroundings, Q_{air}, the water flowing through pipe, *k*, $Q_{W,k}$, and to the attached adjacent block, *j*, $Q_{i,j}$. The change in the block's temperature is related to the rate of change of energy through the block, the block mass, *m*, and the block specific heat, c_p:

$$\dot{Q}_{air} + \sum_{k=1}^{K} \dot{Q}_{W,k} + \sum_{j=1}^{J} \dot{Q}_{i,j} = m \cdot c_p \cdot \dot{T}_i \tag{6}$$

Newton's law of cooling relates heat flow through a block to the block's temperature and the temperature of its surroundings. The heat flow to the air is characterized by the heat transfer coefficient hA_{air} and the air temperature T_{air} in Eq. (7). Similarly the water temperature in pipe *k*, $T_{W,k}$, and $hA_{W,k}$, lead to Eq. (8), and the adjacent block temperature, T_j, and $hA_{i,j}$, lead to Eq. (9).

$$\dot{Q}_{air} = -(hA_{air})(T_i - T_{air}) \tag{7}$$

$$\dot{Q}_{W,k} = -(hA_{W,k})(T_i - T_{W,k}) \tag{8}$$

$$\dot{Q}_{i,j} = -(hA_{i,j})(T_i - T_j) \tag{9}$$

The combination of (6), (7), (8) and (9) for each block encompasses a full description of the dynamics of the chilled water demonstrator. The model parameters, hA_{air}, $hA_{W,k}$, and $hA_{i,j}$, are identified by least squares regression analysis using experimental data.

With a full system model in hand, the controlled system can be simulated when excited by the aforementioned dual class loading scenario. The simulated ambient air and water temperatures are 20°C, and the warning and danger temperatures are 39°C and 49°C respectively. In order to generate a valid comparison between the centralized exhaustive search controller and the incremental agent-based controller, the value of γ was fixed for both to a value of 0.5. This choice of γ equates to an equal weighting between the thermal and energy utilities.

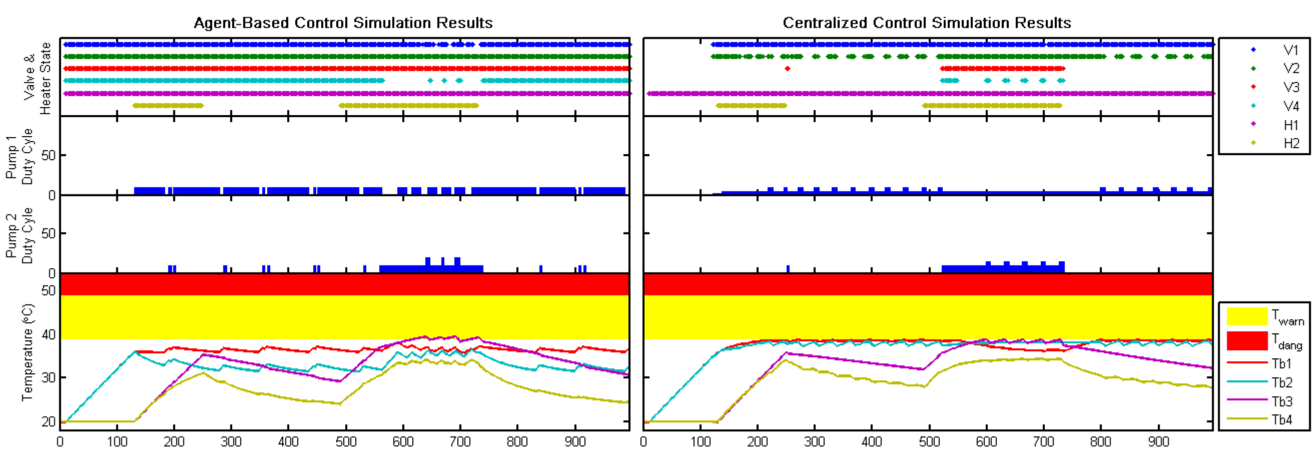

Figure 4. Agent-based control versus centralized control simulation results

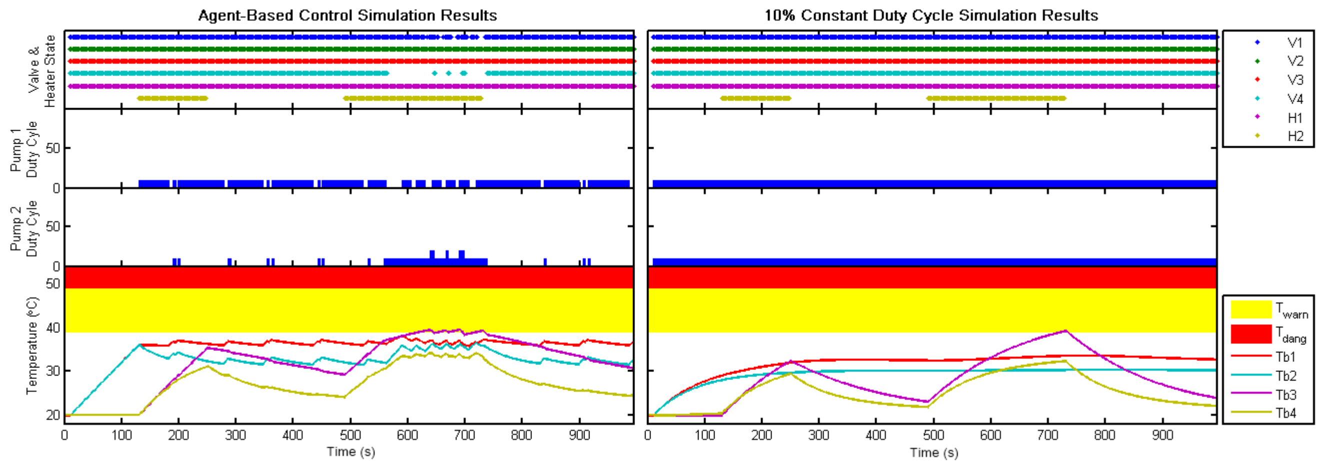

Figure 5. Agent-based control versus 10% constant duty cycle simulation results

Figures 4 and 5 compare the simulated response of the system when controlled by the agent-based controller versus the centralized and 10% constant duty cycle controller respectively. The presence of a dot in the top axes of each figure indicates whether a valve, V1…4, or heater, H1…2, was in the "on" state at that instant in time. The middle-upper and middle-lower indicate the pump duty cycle the controller specified at each time step, and the lower plots indicate the temperature of each block compared to the specified danger (red) and warning (yellow) temperatures.

VI. Conclusions

The proposed agent based controller performs similarly to the better performing, but more computationally intensive, centralized exhaustive search controller as seen in Table 1. All three controllers adequately protect the system from prolonged exposure to the warning temperature; however the centralized and agent-based solutions utilize more energy as shown in the summary of utilities presented in Table I. The observed differences in thermal utility is negligible between the three simulated responses, however the power consumed increases with decreasing controller computational complexity. The agent-based controller presented herein serves as a balance between centralized and constant controllers. In addition the agent-based controller has the advantage of straight forward implementation on a network of wireless nodes. Future research will take full advantage of the wireless nature of the control architecture and study methods to make the control system more robust to node and system failure than a centralized controller.

Table 1. Summary of Simulated Utilities

	UT_{Total}	UE_{Total}
Centralized Controller	0.00000	23.3
Agent-Based Controller	0.00870	32.2
10% Const. Duty Cycle	0.00056	65.5

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References

[1] B. Wagner, "Powering the fleet: all-electric ship could begin to take shape by 2012," *National Defense*, November 2007.

[2] S. K. Srivastava, D. A. Cartes, *et. al.*, "A control system test bed for demonstration of distributed computational intelligence applied to reconfiguring heterogeneous systems," *IEEE Instrumentation and Measurement Magazine*, vol. 11, no. 1, pp. 30-37, 2007.

[3] E. L. Zivi, "Integrated shipboard power and automation control challenge problem," *IEEE Power Engineering Society Summer Meeting 2002*, pp. 325-330, 2002.

[4] L. Dunnington, H. Stevens, G. Grater, *Integrated Engineering Plant for Future Naval Combatants – Technology Assessment and Demonstration Roadmap.* Technical Report MSD-50-TR-2003/01, Anteon Systems, Fairfax, VA, 2003.

[5] A. J. Seman, K. Toomey, S. Lang, *Reduced Ship-crew Virtual Presence (RSVP) Advanced Technology Demonstration*, Technical Report NSWCCD-T12-2003/02, Machinery Engineering Directorate, Naval Surface Warfare Center, Philadelphia, PA, 2003.

[6] R. A. Swartz, A. T. Zimmerman, J. P. Lynch, J. Rosario, T. Brady, L. Salvino, K. H. Law, "Hybrid wireless hull monitoring system for naval combat vessels," to appear in *Structure and Infrastructure Engineering*, 2011.

[7] J. P. Lynch, R. A. Swartz, A. T. Zimmerman, "Distributed data processing architectures for structural monitoring systems implemented on wireless sensor networks," *Proceedings of the Fourth European Workshop on Structural Health Monitoring,* Krakow, Poland, 2008.

[8] A. Swartz, D. Jung, J. P. Lynch, *et. al.*, "Design of a wireless sensor for scalable distributed in-network computation in a structural health monitoring system," *Proceedings of the 5th International Workshop on Structural Health Monitoring*, Stanford, CA, 2005.

[9] A. T. Zimmerman, J. P. Lynch, "A parallel simulated annealing architecture for model updating in wireless sensor networks," *IEEE Sensors Journal*, vol. 9, no. 11, pp. 1503-1510, 2009.

[10] F. P. Maturana, R. J. Staron, and K. H. Hall, "Methodologies and tools for intelligent agents in distributed control," Intelligent Systems, IEEE, vol. 20, pp. 42-49, 2005.

[11] S. H. Clearwater, Market-based control : a paradigm for distributed resource allocation. Singapore ; River Edge, N.J.: World Scientific, 1996.

[12] K. O'Malley, "Agents and automated online trading," Dr. Dobb's Journal, vol. 26, pp. 23-8, 2001.

[13] I. N. Athanasiadis and P. A. Mitkas, "An agent-based intelligent environmental monitoring system," Management of Environmental Quality, vol. 15, p. 238, 2004.

[14] L. McCauley and S. Franklin, "A large-scale multi-agent system for navy personnel distribution," Connection Science, vol. 14, pp. 371-85, 2002