

# Distributed Diagnostics and Dynamic Reconfiguration Using Autonomous Agents

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## 1.1. Introduction

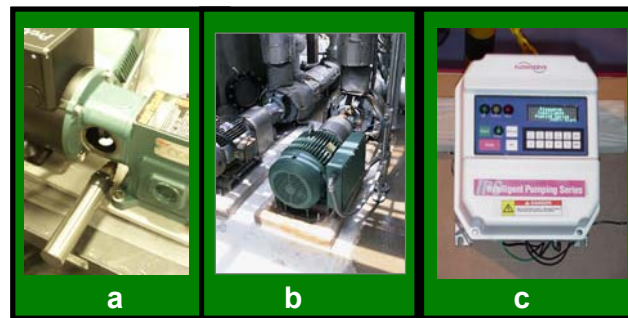
Technological, economic, and cultural changes that are driving the deployment of distributed intelligent devices across a broad range of industrial, commercial, commercial, and military systems. Sensors and actuators that previously provided a single function are being replaced with smart devices that are programmable, perform multiple functions and provide realtime operating information. For example a motor speed controller that historically maintained a setpoint motor speed may now include embedded logic for local closed-loop control, dynamically alter speed in response to changing pump conditions, provide real-time diagnostics, and optimize performance [Discenzo, Rusnak et al. 2002]. The automation of increasingly complex, critical, coupled systems can place a severe demand on centralized automation systems. A framework for managing this complexity employing intelligent agents has been demonstrated for automation systems such as package handling, material processing, and water distribution. The agent infrastructure may be extended to provide for distributed collaborative diagnostics of novel faults. Following fault detection, agents then collaborate to identify and implement a loss mitigation strategy, recovery strategy,

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and eventually, provide a transition back to full functionality when the faulty element is repaired.

### 1.2. Background

Intelligent instrumentation for process industries was introduced approximately 25 years ago. While some improvements in process control throughput and process variability along with a reduction in maintenance and calibration efforts have been reported, it is clear most of these devices are not meeting their potential to improve plant reliability and economic performance [Wallace, Peluso 2002].



**Figure 1. Intelligent Wireless Oil Sensor (a), Self-diagnosing Intelligent Motor (b), and VFD with Embedded Pump Diagnostics & Control (c)**

Intelligent instrumentation often includes features such as embedded diagnostics, communications, and even calibration, and control activities typically performed in a programmable logic controller (PLC) or other distributed control system. The scope of intelligent instrumentation includes sensors [Discenzo, Loparo, Kendig, Theroux 2003][Discenzo, Loparo, Chung, Twarowski 2001], actuators [Discenzo, Marik, Maturana, Loparo 2001][Discenzo, Unsworth, Loparo, Marcy 2000], and speed controllers, for example [Discenzo & Rusnak 2002], as shown in Figure 1. These devices may provide remote computation and control capabilities for flow, pH, level, or concentration level for example. In addition to providing unique capabilities for remote setup, calibration, and diagnostics, an unprecedented amount of device and process data is now available. The amount of data potentially available can easily overwhelm a centralized PLC or central controller for even a modest industrial process.

Parallel to the developments in intelligent instrumentation, in 1996 the HMS (Holonc Manufacturing Systems) program was launched. This program had a major effort focused on distributed systems operation and distributed control such as could be implemented with distributed intelligent devices [Deen 2003]. A significant result from this effort was the development of a formalism for encapsulating, reusing, and deploying intelligent elements in a multi-level automation hierarchy. The standards based architecture is embodied in function blocks and is defined in the International Electrotechnical Commission (IEC) 61499 series of standards [Christensen & Deen (ed) 2003]. The HMS activity consisted of collaborating team members from around the

world and served to bring to light many of the issues critical to the success of complex distributed systems composed of autonomous cooperating units.

Many of the issues critical to the success of distributed intelligence for control were pursued within the framework of autonomous agents. Intelligent agent development continues to pursue a biological analogy to realize the important benefits provided by a “bottom-up” approach [Walthrop 1992] where the collection of simple interacting behaviors can define the behavior of a complex dynamic system [Bonabeau, Doriga, Theraulaz 1999].

The dialog for inter-agent communications has been refined by many companies worldwide and a common agent dialog is specified in an open standard defined by FIPA (Foundation for Intelligent Physical Agents) [FIPA]. Intelligent agent tools, architectures, dialogs, and cooperation strategies were developed and demonstrated in pilot applications in parallel to the HMS development program described above [Jennings & Woolridge 1998].

### 1.3. Water Distribution Systems

The controlled distribution of water is a critical requirement for many shipboard, industrial, and commercial processes and for municipal water systems across the country. The criteria for water distribution may include insuring adequate flow while maintaining appropriate water temperature such as in a chilled water system or maintaining adequate water chemistry and clarity such as in a municipal water distribution system. Water distribution systems are often decentralized and failure may occur at any time in virtually any component(s). The failure of a water distribution system may have severe implications including personnel safety and health, and potential failure of a military mission.

The pilot system for testing agents for the navy is based on the Reduced Scale Advanced Development (RSAD) model of the Auxiliary Machinery Controls and Automation Branch (NSWCCD Code 825), Carderock division, in Philadelphia, as shown in Figure 2a. This system is used for evaluation of advanced auxiliary machinery concepts. The RSAD model is a reconfigurable fluid system test platform with embedded

component-level intelligent distributed controls. The RSAD has an integrated control architecture which includes commercially available control and display hardware components.

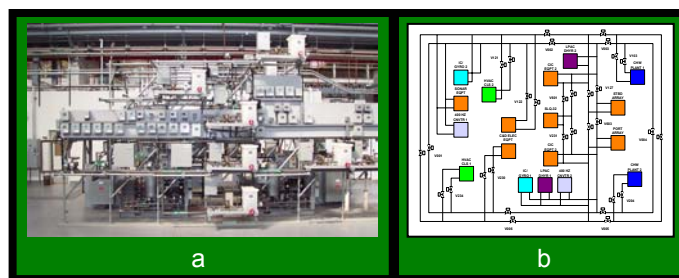
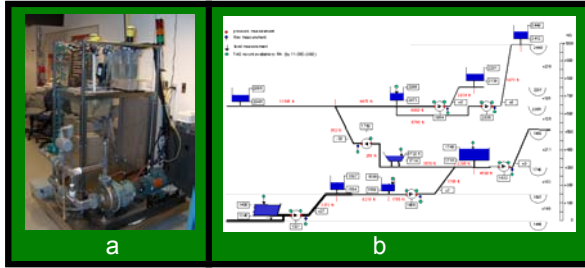


Figure 2. Laboratory Chilled Water System (a), and Chilled Water System Schematic (b)

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The RSAD architecture includes the plumbing, controls, communications, and electrical components that mimic operations aboard a ship and in different operating regimes (e.g. cruise, battle, etc.). The RSAD model is presently configured as the DDG-51 chilled water system as diagrammed in Figure 2b.

Another testbed for validating the performance of distributed agents is a municipal water distribution system (MWDS). A schematic showing a representative MWDS is shown below in Figure 3. A laboratory pump loop consisting of multiple connected reservoirs, pumps, and water degradation modules is shown in Figure 3a and a schematic representation is shown in Figure 3b.



**Figure 3. Laboratory Model of a MWDS (a), and an example MWDS System Schematic (b)**

Intelligent agents have been demonstrated to provide unique capabilities for control and dynamic reconfiguration for critical military chilled water systems [Discenzo, Maturana, Staron, et al. 2004] and for municipal water distribution systems [Gianetti, Maturana, Discenzo 2005]. These results have been recently extended to leverage the development of advanced diagnostics and prognostics capabilities. In particular, system faults and incipient failures may be detected or inferred through the collaboration of distributed intelligent agents. Fault detection may be performed with limited instrumentation or suspect faulty components identified that contain no sensors.

### 1.4. Fault Detection, Isolation, and Remediation

The agents can detect the presence of a leak in the piping system, locate the leak, and seal it off using a reduced set of conventional flow and pressure sensors. These functions are performed automatically (i.e., without operator interaction) and performed quickly. The algorithm for distributed leak detection is described in the next section.

#### 1.4.1. Leak Detection

On a ship, there are redundant suppliers of chilled water called automated chiller plants (ACPs). On the RSAD, there are two, along with 15 heat generating loads (for example, radar, communications equipment, and weapons systems) that require cooling to maintain them within their operational temperature range. Each ACP has both pressure and flow sensors, and for that reason the majority of the algorithm is implemented within the ACPs. Conductance,  $C$ , is defined as:

$$C = \text{flow} / \text{pressure} \quad (1)$$

Conductance is an indication of the piping system geometry through which water is currently flowing. Therefore, given a steady-state condition in which an ACP is

supplying some set of loads with water, and without a disruption or configuration change to the system (i.e., a new load receiving water, a current water-receiving load giving up its water, or a leak), conductance should remain constant. Because of various noise sources, however, the values for  $C$  cluster around a nominal value  $C_{nom}$ . We can estimate  $C_{nom}$  by taking samples of  $C$  and averaging, so that

$$C_{ave} = \frac{1}{N} \sum_{i=1}^N C_i \approx C_{nom} \quad (2)$$

Since the ACP knows when a new load is coming online to receive water or when a load decides to stop receiving water, the ACP temporarily suspends sampling to allow the piping system to re-achieve steady state. Thus any dramatic increase in conductance (flow increasing and/or pressure dropping) indicates a leak somewhere in that part of the piping system currently in use.

Since any unique set of loads receiving water results in a unique geometry of water paths, each set can generate a unique value of  $C$ . The values for conductance therefore depend upon:

1. the number of loads receiving water
2. the particular set of loads receiving water
3. the paths currently in use to supply the water

Let  $L_{max}$  be the maximum number of loads to which an ACP can simultaneously supply water. Considering only the number of loads receiving water, an ACP needs to remember  $(L_{max} + 1)$  sets of samples, i.e., there are only  $(L_{max} + 1)$  unique geometries ever “seen” by the ACP, since it can serve anywhere from zero to  $L_{max}$  loads. Experiments conducted on a simulation of the RSAD system indicated that number-of-loads alone is not sufficient. There are considerable changes in the value of conductance resulting from a different set of loads, even of the same cardinality. Thus it was necessary to consider the actual set of loads receiving water.

Given a total of  $L_{tot}$  loads in the overall system, the number of unique geometries,  $G$ , now discernible by an ACP is

$$G = \sum_{i=0}^{L_{max}} \binom{L_{tot}}{i} \quad (3)$$

where  $\binom{}{}$  indicate combinations. For the RSAD,  $L_{tot} = 15$  and  $L_{max} = 7$ , resulting in 16383 unique geometries.

Thus each set of  $N$  samples in our implementation is keyed by the list of loads receiving water. Since we are continuously sampling, we keep a rolling set of the last  $N$  samples.

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As stated previously, the sampling to determine  $C_{ave}$  is temporarily suspended for a few seconds after a valve or valves opening or closing (to add a load or remove a load) to avoid pressure and flow transients. Besides the sample mean  $C_{ave}$ , we compute for each set the sample variance and standard deviation,  $\sigma_{est}$  .. We detect a possible leak by computing the distance (in standard deviations) between the current sample and the computed mean,  $C_{ave}$ .

$$\begin{aligned} C_i - C_{ave} &\geq R\sigma_{est} && \text{possible leak} \\ &< R\sigma_{est} && \text{no leak} \end{aligned} \quad (4)$$

If the current sample is significantly larger than  $C_{ave}$ , a possible leak has been detected. Otherwise, sampling continues until there is another configuration change. Table 1 shows the descriptions and the values used for the tunable parameters of the algorithm.

**Table 1. Parameters of the Leak Detection Algorithm**

PARAMETER	VALUE	DEFINITION
$G_{remembered}$	15	The number of unique geometries remembered by each ACP. The ACP implements a cache that holds the last 14 geometries encountered, plus 1 dedicated to remember the conductance values when no loads are receiving water.
N	10	The number of conductance samples kept for each geometry.
T	2 sec.	Time between samples of conductance.
$L_{tot}$	15	The total number of loads in the application.
$L_{max}$	7	The maximum number of loads serviceable at one time by any ACP.
R	10	The distance, in units of $\sigma_{est}$ , at which a conductance sample will trigger the leak location algorithm.

### 1.4.2. Locating and Isolating the Leak

Once a possible leak has been detected, the agents collaborate to locate it. Given that an ACP has detected a possible leak, a procedure is initiated to locate the leak or faulty component and isolate it from other system elements that are continuing to operate properly. The process of locating and isolating the leak consist of:

1. The ACP notifies the loads it is servicing that a possible leak has been detected and fault isolation will be initiated.
2. Each load consecutively instructs connected components (e.g. valves) to temporarily close (given that this operation is permitted) and report their status back to the load.

3. A ordered list of component status is compiled by each load and reported back to the ACP.
4. The ACP consolidates the response from each load and if no leak is indicated, proceeds to interrogate the ordered list of components by sequentially closing and opening the suspected component.
5. If no leak is found, the loads are instructed to reset themselves and all valves are instructed to resume normal operation. If a leak is found, affected loads are notified and components (e.g. valves) adjacent to the fault are instructed to close to minimize damage and loss of chilled water.

### **1.4.3. Fault Accommodation and Service Restoration**

The failed segments such as a stuck valve or leaking pipe are effectively isolated from the system and the remaining components are reconfigured to accommodate the demand using existing facilities. Further dynamic reconfiguration may be initiated in response to changing water demand, additional failures, or possibly changes in higher level missions, system economics, or operating context (e.g. shift to battle mode from cruise mode).

When faulty components are restored back to service levels, an associated reconfiguration will occur to reintegrate the additional capacity back into the system. This is scheduled and carried out through the coordinated action of the distributed autonomous agents. This has been routinely demonstrated in multiple chilled water system demonstrators and in a separate package handling simulation.

## **1.5. Conclusions**

Autonomous intelligent agents have been shown to provide valuable capabilities for distributed control and dynamic reconfiguration without the need for centralized control. The capabilities of autonomous agents have been extended by augmenting agent logic to include collaborative reasoning to identify and detect suspected faulty components, process problems, or incipient failures. This additional information provides fault coverage that surpasses the scope of information provided by traditional machinery diagnostics sensors and provides a basis for predictive reconfiguration.

The detection of degraded or worn components may trigger the asymmetric loading of system components or the reconfiguration of system operation to eliminate stress on weakened components. This can serve to avoid an unexpected or catastrophic failure. Limiting or removing stress on weakened components provides a unique capability to preserve useful life in critical components until needed for extreme duty or to complete a critical mission. While important new capabilities for fault detection and remediation has been demonstrated, there remain important open issues such as configuration planning and evaluation, re-configuring systems with incomplete state information, the coordinated re-configuration of coupled systems such as power and water, and establishing an alternative control strategy that remains stable while accommodating a reconfigured system with missing or degraded components.

## 1.6. Summary

The growing deployment of distributed autonomous agents is driven by the parallel developments occurring in low-power smart sensors and actuators, the development of distributed AI (DAI) techniques, the expanded automation of critical, complex systems, and the maturing formalism of collaborative computing systems. These developments may effectively leverage the important work done by the diagnostic and prognostic community to provide superior incipient fault detection and the ability to dynamically establish the remaining life of critical system components. Together these technological developments promise to change the nature of critical complex automation systems in the 21<sup>st</sup> century.

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