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Multi-Agent Control System for a Municipal Water System

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Abstract. The control system for a municipal water system needs to meet the criteria of maintaining continuity and reliability in the water supply for satisfying the consumer demand while saving the energy costs and maintaining the quality of water. In this paper, we propose an intelligent agent system for a municipal water system. This work shows the benefits of using the agent-based approach in handling different scenarios including the uncertain behavior of the system. A distributed control strategy is implemented and promising results are evaluated in a simulation of a water distribution system.

Key-Words: - Agents, distributed control, intelligence, quality, planning, scheduling, demand, cost

1 Introduction

Water distribution systems play a vitally important role in preserving and providing a desirable life quality to the public. Water supply, operation cost, and water quality are herein studied with greater attention due to their importance and complexity. There are three key issues in this area: (1) Demand, (2) Energy costs, and (3) Water quality.

In the past, much of the effort in the design of water distribution systems had emphasis on the aspect of least cost. Today, there has been a growing awareness that it is equally important to have a public water distribution system possessing high service reliability and also water quality.

Demand is a critical aspect affecting the control of these systems. Knowledge of the current and future demand will determine how much water is needed in the tanks and at what time. This in turn provides a time-based control strategy that meets the predicted demand while achieving the cost and quality objectives. There are many ways to predict the demand [1]. A method is to predict the demand using the historical data for the specific period [2].

Energy costs are important aspects affecting the operation of a water system. Optimizing the operation of a pump system in a municipal water system can reduce energy costs and also realize other economic and operational benefits. Theoretical and empirical studies of pump scheduling in various water supply systems suggest that 10% of the annual energy and related costs may be saved by optimizing pump operation [3]. Out of the several techniques deployed for optimizing this scheduling process, the most commonly seen from literature are the genetic algorithms [1][4][5][6] with single objective for minimizing the cost of pumping and with multiple objectives for minimizing the number of pump switches. The latter technique reduces the maintenance cost along with the cost of pumping. Use of dynamic programming for optimizing the pump scheduling claims to reduce the energy costs by 12.5% when compared to a base-level control design [7]. Several other techniques like simulated annealing [8] and fuzzy logic [9] can also be found in literature. In all these techniques, the pump operation is pre-scheduled ahead of time and any unpredicted change and/or perturbation make the network prone to a non-reconfigurable damage.

Water quality is affected by the time a parcel of water is retained in a storage tank. New water entering a tank from a reservoir is assumed to have age zero. The cumulative age of the water is a factor that helps define the quality of the water. The aging of water in a tank is primarily a function of water demand, system operating strategy, and the system topology. The average retention time is found to be 1.3 days and the maximum is 3 days [10]. Mixing (or turnover) can be used to decrease the water age.

From the survey, all the key issues mentioned above are found to be managed by a single centralized controller. However, relying on a single intelligent controller causes a survivability problem in case of damage to the controller itself**.** This poses the need for a more efficient, safe and reliable technique for controlling the system while enabling reconfiguration to respond to unpredicted changes. Classical control systems based on feedback techniques generally cannot manage computational complexity, nonlinearity and uncertainty. Complex problems like this can be resolved by using distributed agents, as they can handle combinatorial complexity in real time [11]**.** Agents can schedule the pump operations for short intervals of time unlike other optimizing techniques that pre-schedule ahead of time. This makes the agent-based system a very attractive technique. We propose an agent-based distributed control system for monitoring and controlling a municipal water-supply system to ensure optimal control while reducing energy costs.

2 Problem Statement

To demonstrate the benefits of using the agent-based control for water distribution networks, we choose to develop a scale-down model of a municipal water system (MWS). In this model, we establish distributed agent and control behaviors to operate the system [12]. This model includes:

- Water: Service or product with a defined flow and quality requirement.
- Tanks: A cylindrical vessel.
- Pumps: Links that impart energy to a fluid thereby raising its hydraulic head.
- Pipes: Links that transport water from one point in the network to another.
- Valves: Links that limit the pressure or flow at a specific point in the network.
- Reservoirs: Large water deposit which can be natural or artificial.
- Controllers: Hardware and software components to control and monitor the system.
- Sensors: Instrumentation that extracts data from the physical system (sensors).
- Consumers: System end points or boundaries with service requirements.

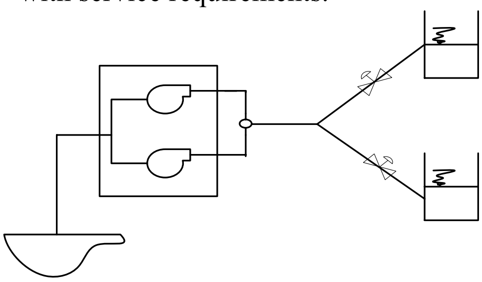

Fig. 1: Baseline Water System

The system has a single pump station (PS) with two pumps. The pump station supplies water to two tanks (TK1 and TK2). The tanks are connected by a T-Junction. Each tank has supply valve associated with it (VL1 and VL2), as shown in Figure 1. There is an inter-tie pipe and valve in between the tanks which is intended to mix the water without pumping.

3 General Architecture of Agents

An agent is a distinct software process that can reason autonomously and which can react to the changes induced upon it by other agents and the environment. Agents cooperate with each other to accomplish system wide goals (e.g., minimization of power use). Each physical device that is coordinated by an agent can be considered as an intelligent node with negotiation capabilities. The intelligence of the system is distributed among multiple controllers by placing standalone or multiple agents inside the controllers. The agents are loosely coupled but their association is cohesive and adaptable [13][14].

A suite of collaborating agents can reduce operating cost and provide increased control flexibility by concurrently looking at constraints, changing system economics and uncertain future demand. These can develop a response using negotiation scenarios by achieving dynamic economics equilibrium. The agents are programmed to evaluate control strategies based on water quality.

Decentralized control has several agents with the same capability, and each agent controls only one small part of the system. Agents communicate with each other using agent language [15] and exchange information about the system status. Distributed agents may self-organize into clusters to insure efficient communications and coordinated operation. So, central failures are avoided and parallelism is increased. However, there is a trade off between parallelism and optimality of the solutions.

We use Matlab/Simulink for the fluid mechanics simulation. Agents are developed using S-functions. The main advantage of using S-functions is that we can build general purpose blocks that can be used many times in the model. This allows for varying parameters with each instance of the block. Simulink makes repeated calls during specific stages of simulation to each routine in the model, directing it to perform tasks such as computing its outputs, updating its discrete states or computing its derivatives.

4 System Analysis

The pumping station takes water from the reservoir (RS) and moves it into the tanks through the T-junction. This junction has two branches moving water from the exit of the pump station to the tanks after crossing the valve in each junction. There is an inter-tie connection between the tanks, where the water flows due to gravity from the higher level tank to the lower level tank controlled by a valve in the tie. This is of use in saving the energy and in maintaining water quality. Each of these components has an agent to control and monitor the simulation. The simulation is used as a test bed to validate the behavior of the algorithms. We select the pump station and tanks as primary agents for developing the algorithms. The pump station agent takes care of the pumps' schedule and energy consumption criteria. The tank agents take care of maintaining the required levels in the tanks. The agents negotiate the water-distribution.

Later, when we formalize the use of agents for the municipal water system, a proper partitioning and number of agents will be established. But for now, the interest is in developing the overall behavior (ontology) of the system and the interaction among the primary agents. Next, we explain how we develop the system ontology for this application. We need to design the schema for the agents to collaboratively evaluate the conditions of the system, make decisions about the operation of the physical components, establish execution plans, and initiate changes in operation.

The pump station agent determines the schedule of the pumps to turn it on or off. The pump station agent generates the schedule and the control function executes it. The pump station's control function commands the simulation to execute the actions affecting the different subsystems. The control actions correspond to Inputs and Outputs (I/O) signals. When both valves associated with the T-junction open, the flow of water is divided into two parts: a parcel of water moving into TK1 and another into TK2. The amount of water in each pipe segment depends on the head that each tank exerts on the T-junction. The heads can be estimated as

$$\%_{INTO\_1} = 1 - \frac{H_1}{H_d} \text{ and } \%_{INTO\_2} = 1 - \frac{H_2}{H_d} \qquad (1)$$

Knowing the flow out of the pumping station (the sum of the flows of the two pumps or one pump only), the water flow is assumed as a percentage distribution of the total flow, as shown in eq.2 and 3:

$$Q_{INTO\_1} = \%_{INTO\_1} * Q_{TOT} \qquad (2)$$

$$Q_{INTO\_2} = \%_{INTO\_2} * Q_{TOT} \qquad (3)$$

The cost of electricity is modeled as a constraint for directing the schedule of the pump to the lowest cost possible. We use the power consumption pattern of the city of Los Angeles, CA, to identify peak and low consumption periods, as shown in Figure 2.

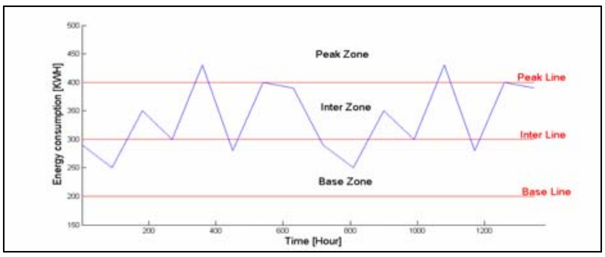

Fig. 2: City Energy Consumption

With this information, it is possible to provide the pump station agent with information about favorable times to run the pumps. The main idea is based on the concept that using the pumps during a high consumption time, the cost will be higher than using the same device during a low consumption time. The consumption curve is divided into three zones: Base, Inter, and Peak [16]. Each zone has its own cost coefficients. These three values increase when the time zone is more expensive (Peak Zone). The main idea is to run the pumps when the energy consumption is low, avoiding high costs.

4.1 Agent Function

The first step is to calculate how much water is needed by the tanks in the near future for an interval of time. A prevision period represents the prediction interval that includes the actual demand plus future demand. Knowing the predicted level, a set of rules is generated to control the level in the tank:

$$(Predicted\_Level_{n'} - Level\_Trigger) > 0 \Rightarrow PumpOn = 0$$

$$(Predicted\_Level_{n'} - Level\_Trigger) = 0 \Rightarrow PumpOn = 1$$

$$(Predicted\_Level_{n'} - Level\_Trigger) < 0 \Rightarrow PumpOn = 1$$

where *n'* is the time range of the predicted interval.

- Rule 1: PumpOn = 0. This rule indicates that the tank contains enough water and that there is no need for additional pumping.
- Rule 2: PumpOn = 1 (a). This rule says that the level of water is low and that pumping is needed to recover the safety buffer.
- Rule 3: PumpOn = 1 (b). This rule tells that the demand was more than the previous prediction and that water is needed now.

Let $T_{Prevision}$ be the time for the schedule. The agent calculates the water demand for the prevision period for each tank by using small intervals within the prevision time:

$$HowMuchWaterToPump = \begin{pmatrix} Level\_Trigger - Predicted\_Level \\ + Level\_Trigger * Percentage \end{pmatrix}$$

In this way, we know how much water the whole system requires for the prevision time. The parameter *level_trigger* changes when the zone of the energy consumption changes. When the period of the day is cheaper (Base zone), the *level_trigger* is high. When the period of the day becomes more expensive, the level trigger decreases. It is to guarantee enough water in the tanks while reducing the activity of the pumps. Knowing the amount of water, we can know the time required to pump with only one pump and with two pumps for each tank. Let $time_1$ be the time needed to give the water to TK1 and $time_2$ for TK2.

$$T_P = \max(time_1, time_2)$$

T_p represents the total pumping time for the prevision period. T_p is smaller with two pumps than one. If the two pumps have the same characteristics, the time required for pumping is reduced by 50%. From the energy consumption curve (Figure 2), the pump station agent determines the intersection between the Base and Inter zones. The cost curve helps to calculate a *BaseMax* section. Let T_{P1} be the time needed to give the amount of water required with only one pump. The following rules apply:

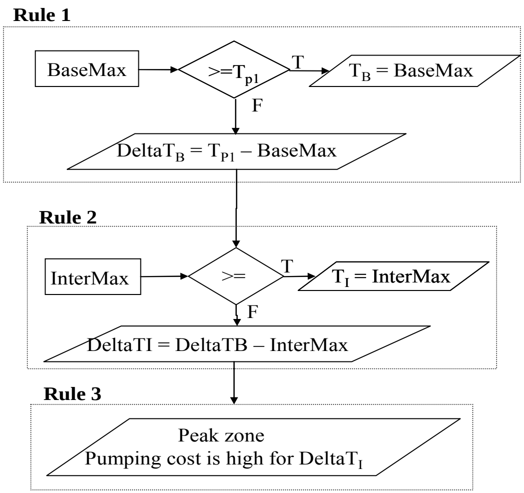

Fig. 3: Flow chart with rules for Pump Station Agent

With the rules in Figure 3, the pump station agent calculates the total power (Kwh) consumption. Let PR_1 be the power rate for pump1:

$$KWH_B = T_B * PR_1$$
$$KWH_I = T_I * PR_1$$
$$KWH_P = T_P * PR_1 \quad (4)$$

With the maximum demand in Kilowatts (KW_{max}), the total cost is calculated:

$$Cost_{1PUMP} = KW_{max} * DCC + KWH * ECC + KWH * ECAC$$

With the algorithm above, the cost for the activity of two pumps ($Cost_{2PUMPS}$) is calculated. If $Cost_{1PUMP} \leq Cost_{2PUMPS}$, then, one pump is less expensive. Else, it is cheaper to use two pumps. This evaluation produces the schedule of the pumps. Since the tanks have different demands, the notion of pumping time, provides enough allowance to transmit water to the tanks. The opening and closing of the supply valves need to be scheduled. They open when the pumping is active. The predicted level is calculated taking into account the actual level at the beginning of the prevision and the estimation of water to be pumped into the tanks.

4.2 Control Function

The control function activates the pump based on the schedule. Also, the control function has to change the pump activity to avoid problems, e.g., lack of water. So, it generates alarms to notify the pump station agent or tank agents when:

- The predicted level value is different than the actual level and greater than an acceptance threshold
- The level in the tank is near less than a fixed percentage of the maximum level admissible
- The predicted level value is very different from the actual level and the actual level is very close to the level trigger.

The rules above establish the behavior of the agents and the control function.

5 Simulation Results

The simulation model has been calibrated to mimic a real system. Each tank agent changes the prevision time throughout the day to follow the demand and cost periods. Based on the energy consumption curve, the prevision time is set to 12 hours if the current time falls within the Base zone, 6 and 3 hours for the Inter and Peak zone respectively.

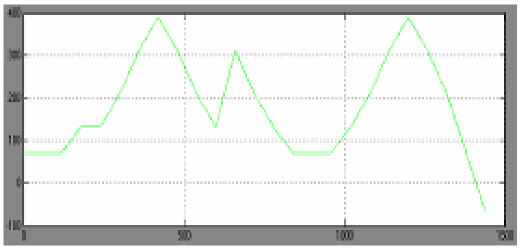

Fig. 4: Demands for Tanks (TK1 and TK2)

The level prediction is based on historical demand for 30 minutes intervals. The pump agent calculates a new schedule when the prevision time is finished and also if an alarm occurs. Figure 4 shows water consumption for the tanks. It shows the actual demand that changes to reflect the consumption periods of an urbanized area of the city.

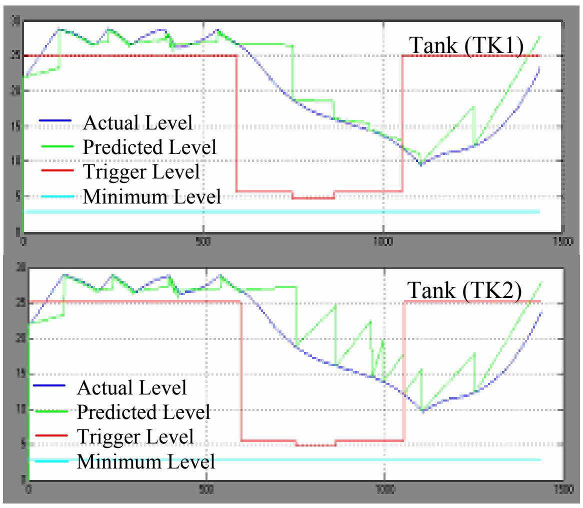

Fig. 5: Levels in Tanks (TK1 and TK2)

Figure 5 represents the results for a 24-hour simulation. The levels for TK1 and TK2 are shown with correction actions. During the Peak zone, the tank agents try to maintain only the required amount of water above the safety buffer (cyan line) to avoid using the pumps. In this manner, the tank agents also contribute with energy savings.

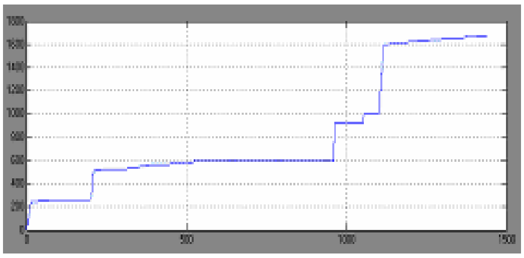

Fig. 6: Cumulative Cost

Figure 6 represents the cost accumulation**.** It can be concluded that it is more expensive to startup a pump during peak period than maintaining it on during and inter periods. This is due to a cost coefficient associated with the pick (pump startup) and steady state consumption.

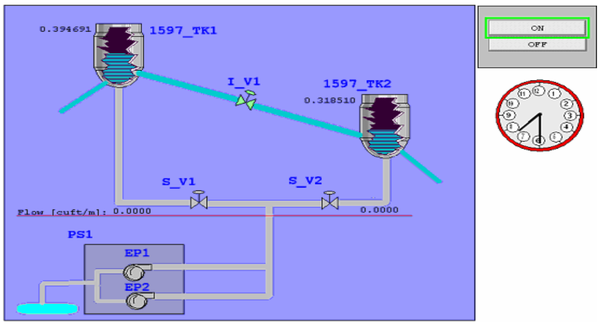

Fig. 7: System using the Inter-tie valve to share water

A GUI model for this system was created in RSView32 package from Rockwell Automation (Figure 7). The solid line connecting the two tanks is the inter-tie pipe which is blue when circulating water and gray when not.

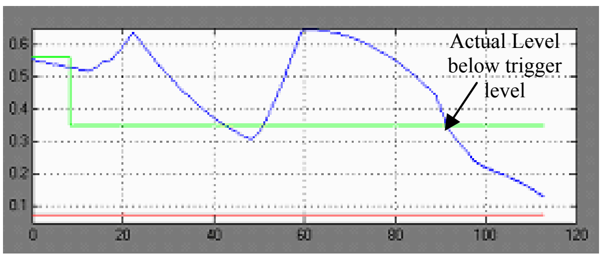

Fig. 8: Level in Tank - TK2

Figure 8 shows the scenario when tank TK2 needs water and tank TK1 has water to share. Tank TK1 is at a higher altitude than tank TK2, and hence water can be moved from TK1 into TK2 by gravity. Instead of asking the pump agent to pump, tank TK1 opens the inter-tie valve to share its water, thus saving energy and also allowing mixing of water.

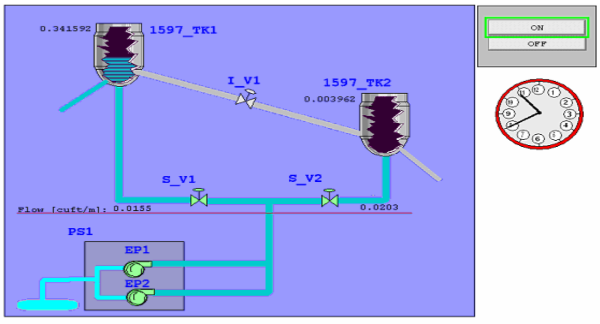

Fig. 9: System recovering from un-modeled disturbance

Figure 9 shows a critical situation with an unexpected steep increase in the demand. This scenario corresponds to an un-modeled disturbance in the system. The agents reconfigure the system by rescheduling the pumps. For instance, the pump station agent decides to activate both pumps to swiftly move water into the tanks to compensate for the variation, but this action is expensive if the pumping occurs during the expensive period

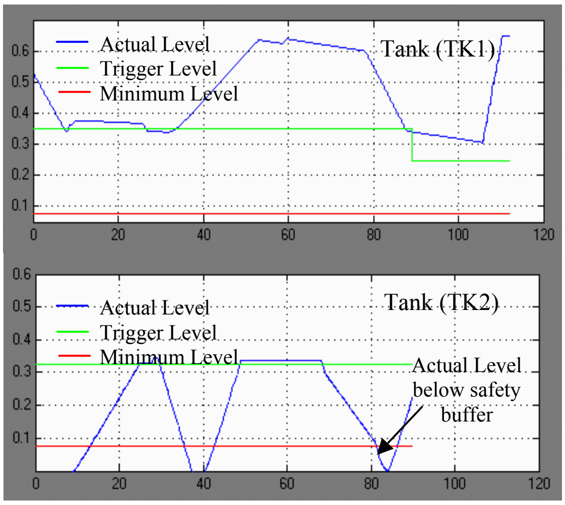

Fig. 10: Levels in Tanks (TK1 and TK2)

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However, it solves an immediate need which has higher priority than cost (e.g., fire). In Figure 10, the level in tank TK2 falls below the safety buffer and so the demand valve closes automatically. This is a control-level response with no agent intervention. This response triggers an event into the tank agent to urgently request for water.

# of Pumps	No Energy Saving	With Energy Saving
1	2260	-
2	4550	-
1 or 2	-	1680

Table 1: Cost of each simulation

In Table 1, the first and second trials correspond to simulations with no energy saving and the third uses energy saving. When the energy saving algorithm is used, the results are very encouraging, with a saving between 26% and 63%.The cost reduced by 26% with respect to the system with only one pump. Moreover, it reduces cost by 63% with respect to the system with two pumps. To increase the saving, the planning interval will need to be increased to schedule the pumps to run during low cost periods and to avoid high cost periods.

6 Remarks

A Municipal Water System model was studied using agents for controlling the physical equipment. A variable set point for the tank levels was found to be important in reducing the energy costs. The multi-agent control appears as a very attractive solution to save energy and to maintain water quality and supply. Future work includes a more complex system with more pumps, pump stations, and inter-tie connectivity to consider more scenarios with the same objective of maintaining secure, reliable and safe water distribution for consumers.

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