Advanced Technologies for Command and Control of Combined Sewer Networks

University of Notre Dame's Scope of Work for a Project Entitled
``Metro-Wide Control of Combined Sewer Overflow Events
Using Embedded Network Technology''
A Science and Technology Development and Commercialization Project being submitted by
EmNet LLC to the Indiana 21st Century Technology Fund.

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This project will develop and deploy a metro-wide embedded network for monitoring and controlling combined sewer overflow (CSO) events in the City of South Bend Indiana. The project builds upon the success of the Indiana 21st Century Technology Grant project entitled *Detection and Control of Combined Sewer Overflow Events using Embedded Sensor Network Technology*" (project 512040817). In the summer of 2005, that project demonstrated the feasibility of using embedded networks to control CSO events with the successful deployment of such a network in the city of South Bend Indiana. This new 21st CTF proposal is requesting funds that will enable the project participants to scale-up the effort in a manner that would enable metro-wide control of CSO events using embedded networks. The 21st CTF project is being proposed by EmNet LLC with Notre Dame acting as a subcontractor to EmNet LLC.

Dr. Michael Lemmon and Dr. Jeffrey Talley at the University of Notre Dame's departments of electrical engineering and civil engineering, respectively, will be working on tasks to assure the successful commercialization of CSOnet. Dr. Lemmon will be acting as principal investigator (PI) for Notre Dame's effort. Notre Dame will be working as a subcontractor to EmNet LLC to help it transfer technological innovations developed at Notre Dame into the CSOnet project. A description of the work being performed by Drs. Lemmon and Talley at Notre Dame for this 21st CTF project is provided below.

Notre Dame Task 1: Decentralized Flow Control
(M.D. Lemmon – University of Notre Dame)

This project is attempting to develop scalable real-time controllers for sewer networks. We propose using a *decentralized* control architecture well-suited for implementation on embedded networks. A real-time embedded processor (such as the Chasqui processor) is placed in each manhole of the sewer system. This processor measures the water height (also called *head)* and controls the outflows of water from the manhole. Dr. Lemmon (Univ. of Notre Dame) and his students will develop decentralized control algorithms that are executed by each processor in the network and that automatically adjusts outflows from the nodes to maximize the "power" of the flows in the entire network while minimizing the head height as much as possible (thereby reducing the risk of flooding). The main requirement on our control algorithm is that it be *decentralized* in the sense that a processor's control decisions are only based on information from adjacent processors and the algorithm must be *robust* to modeling error.

Our problem may be more formally stated as optimization problem. In this problem, we let x_i denote the head at the ith node (manhole) in the network and we let q_j denote the flow in the jth link (pipe or conduit) in the network. The node head is related to the link flow rates through the differential equation $\dot{x} = q_0 + D^T q$, where x and q are vectors of the node head and link flows, respectively, and q_0 is a vector of external flows into network nodes. The matrix D is the incidence matrix from the graph formed from the sewer network's nodes and links. We let $U(x,q)$ denote a *utility* function that measures the utility of having a certain set of heads and flows within the sewer system. We can take $U(x,q) = x^T(D^T q - x)$ as a specific example of a utility function that uses the flow *power* $(x^T D^T q)$ as a measure of utility discounted by the head level $(-x^T x)$. The flows through each of the conduits is assumed to be unforced (i.e. no pumping) so that this flow rate is limited by Manning's equation

$$x_i - x_j = \left(\frac{K_i}{A_i} - \frac{K_j}{A_j} \right) q_{ij}^2 + S_{ij}$$

where K_i, K_j, and S_{ij} are loss coefficients, A_i and A_j are cross-sectional flow areas, x_i and x_j are the heads at the upstream and downstream nodes, and q_{ij} is the flow through the link between nodes i and j. With the assumed form of the utility function, the optimization problem we seek to solve has the following form,

$$\begin{array}{ll} \underset{\text{w.r.t } q(t)}{\text{maximize}} & \int_0^\infty x^T \left(D^T q - x \right) dt \\ \text{subject to} & \begin{array}{l} q(t) \le Q(Dx(t)) \\ \dot{x} = q_0 + D^T q \end{array} \end{array}$$

where Q is a function representing the link flow limits imposed by Manning's equation.

This is an *optimal control problem* whose solution via Pontryagin's maximum principle [1] yields an optimal flow of the form

$$q_j^* = \begin{cases} d_j x & \text{if } d_j(x-p) \le 0 \\ 0 & \text{otherwise} \end{cases}$$

where d_j is the jth row of the incidence matrix D and where x and p are time-varying functions that satisfy a two-point-boundary value problem (TPBVP). The function x, of course, represents the heads within the network, but the function p (which is also called the *co-state*) can be interpreted as a *price* that the network charges each node for storing water. This control law says that if the head difference exceeds a given level set by the *price*, then we should open up the conduit, otherwise we should shut it. This is a *decentralized* control since decisions are based on heads and prices of nodes adjacent to the current node. The strategy controls the node outflows in a way that maximizes the difference between the head of two adjacent nodes. This leads to a staggered closing and opening of pipes in a way that maximizes the flow power (product of the head difference and flow rate) while trying to control the head level at all network nodes.

The chief challenges faced in this project concern methods for solving the TPBVP determining the price and head levels. We propose doing this using a recently proposed approach to stabilized receding horizon control [2]. Receding horizon (also called model-predictive [3]) control generates a sequence of controls that are optimal over a finite horizon of length T. Using the stabilization technique in [2], we can assure that this sequence asymptotically converges to the solution of the original infinite-horizon optimization problem for any choice of horizon, T.

Since the computational complexity associated with solving the TPBVP decreases with smaller T, the use of the stabilized receding horizon controller allows us to develop a computationally tractable decentralized algorithm solving the preceding optimization problem.

This task will develop decentralized flow control algorithms for CSOnet that will scale up gracefully with network size. We will develop application software for the CSOnet application that will be tested as part of the project's metro-wide demonstration of CSOnet.

Notre Dame Task 2: In-situ Treatment of Wastewater Flows.
(J. Talley – University of Notre Dame)

During wet weather events, wastewater treatment plants (WWTPs) run at full capacity, treating as much wastewater as possible. However, few, if any, CSO communities have WWTPs that can treat all of the combined wastewater in the system. This leaves the communities with three options: release the excess wastewater in the environment, store that water in the combined sewer system (CSS) until the WWTP can handle the additional flow, or treat the stored wastewater to below WWTP standards in situ and then release that water directly into the environment. The first option results in CSO events and the second option requires the WWTP to run at full capacity for an extended period of time at a high cost. We propose adopting the third option of in-situ treatment.

Currently, there is no single in-situ treatment method that provides complete treatment of the wastewater. Some communities have realized the importance of in-situ treatment and have begun partially treating retention basin waters and combined wastewater. The purpose of this study is to develop a new and novel in-situ treatment system for wastewater stored in the combined sewer lines. The treatment is to be automated using EmNet technology and adaptive to the current conditions in the storage area. The treatment focuses primarily on the reduction of TSS (Total Suspended Solids) levels, the BOD (Biochemical Oxygen Demanding compounds, a measure of the amount of BOD that can be biodegraded in 5 days) concentration, and fecal coliform levels.

Preliminary bench studies have been done using hydrogen peroxide (H_2O_2) to treat simulated combined wastewater, which consists of one part dry weather WWTP influent diluted with three parts of distilled water. Hydrogen peroxide was selected because it is a powerful oxidant that readily produces the hydroxyl radical which causes the cells to lyse and may also oxidize organic and inorganic matter [11]. However, the total oxidation of organic carbon requires a large concentration of hydroxyl radicals, which H_2O_2 cannot alone provide [7]. H_2O_2 was also selected because it is readily available, can be safely stored, and degrades to oxygen and water. To stop the reaction, the H_2O_2 can simply be quenched by sodium thiosulfate [6].

Results from some of the preliminary studies show that the addition of H_2O_2 to the wastewater not only prevents the same increase in TSS that occurs in the control, but also decreases the TSS by up to 25% after 6 hours. This data suggests that H_2O_2 may be a promising in-situ treatment method. The H_2O_2 can be more effective and faster acting with higher concentrations, but care must be taken not to increase the concentration too high or else the H_2O_2 can also act as a counter-productive scavenger of free radicals [10].

This task will develop an in-situ treatment system based on the ideas outlined above. There are specific issues with the outlined approach that will need to be addressed during the course of this task.

- Gas Bubble Disease: The dissolution of H_2O_2 to oxygen supersaturates the water with this gas. If this water is released directly into the environment like this, the fish in the receiving waters may develop gas bubble disease (GBD). GBD is a fatal disease in which gas bubbles form in the gills, in the vascular tissue, and behind the eyes of fish, casing suffocation, blocked blood vessels, and blindness [9,8,13]. To prevent GBD, the treated water must have the excess oxygen removed by a degassing tower or by having a series of cascades in the CSS. Conversely, the additional oxygen does prevent the wastewater from becoming septic and aids in odor control.

- BOD oxidization: The current system is unable to reduce BOD to acceptable levels and also requires a long retention time of 6 h. These problems may be solved by combining the H_2O_2 treatment with UV radiation. The UV radiation drastically improves the disassociation of H_2O_2 into free hydroxyl radicals [10], increasing the radical concentration by more than 3.7 orders of magnitude [6]. This increase in free radicals results in a 3.6 log reduction in fecal coliforms after only a 5s contact time with the H_2O_2/UV treatment [30]. The hydroxyl radicals also prevent the microbes from reactivating, which can occur after UV treatment [11]. Furthermore, this treatment process has been shown to oxidize the BOD in tomato processing waste [4], gallic acid [5], methyl-*tert*-butyl ether (MTBE) [12], and Na-EDTA [14]. In [14], Yang et al. also demonstrated that the H_2O_2/UV combination improves the mineralization of organic residuals in water. It is hypothesized that this process will be able to oxidize the degradable portion of the TSS, resulting in a net TSS reduction. Hence, the combination of H_2O_2 and UV radiation may be able to treat the wastewater to below all effluent standards while the CSO water is stored in-line.

These issues will be addressed during the course of this project.

Budget:

The investigators are requesting 1 month of summer support (each) and two graduate students for a 24 month period starting September 1st, 2006. Investigators are requesting $5000 in travel support (each). $25,000 in supplies is requested in the first year, with $20,000 of this amount going to Dr. Talley's effort and the rest going to Dr. Lemmon's effort. $20,000 in supplies is requested in the second year with $15,000 of this amount going to Dr. Talley's effort and the rest going to Dr. Lemmon's effort.

REFERENCES:

1. W.H. Fleming and R.W. Rishel, "Deterministic and stochastic optimal control," Springer-Verlag, 1975.

2. A. Jadbabaie, J. Yu, and J. Hauser, "Unconstrained receding-horizon control of nonlinear systems," IEEE Transactions on Automatic Control, 46, 2001, no. 5, 776-783.

3. C.E. Garcia, D.M. Prett, and M. Morari, "Model predictive control: theory and practice- a survey," Automatica 25, 1989, no. 3, 335-348.

4. Beltrán, F.J.; González, M.; and González, J.F., "Industrial wastewater advanced oxidation: Part 1. UV radiation in the presence and absence of hydrogen peroxide," Water Research, 31, 1997, 2405-2414.

5. Benitez, F.J.; Francisco, J. R.; Acero, J.L.; Leal, A.I.; and Garcia, C., "Gallic acid degradation in aqueous solutions by UV/H2O2 treatment, Fenton's reagent and the photo-Fenton system," Journal of Hazardous Materials, 2005, B126, 31-39.

6. Bianchini, R.; Calucci, L.; Lubello, C.; Pinzino, C., "Intermediate free radicals in the oxidation of wastewaters," Res. Chem. Intermed., 28, 2002, 247-256.

7. Chamarro, A.; Marco, A.; and Esplugas, S. "Use of fenton reagent to improve organic chemical biodegradability," Water Research, 35, 2001, 1047-1051.

8. Elston, R.; Colt, J.; Abernethy, S.; and Maslen, W., "Gas bubble readsorption in Chinook salmon: Pressurization effects," Journal of Aquatic Animal Health, 9(4), 1997, 317-321.

9. Geldert, D.A.; Gulliver, J.S.; Wilhelms, S.C., "Modeling dissolved gas supersaturation below spillway plunge pools," Journal of Hydraulic Engineering, 124 (5), 1998, 513-521.

10. Gogate, P.R. and Pandit, A.B., "A review of imperative technologies for wastewater treatment II: hybrid methods," Advances in Environmental Research, 8, 2004, 553-597.

11. Koivunen, J. and Heinonen-Tanski, H., "Inactivation of enteris microorganisms with chemical disinfectants, UV irradiation and combined chemical/UV treatments," Water Research, 39, 2005, 1519-1526.

12. Salari, D.; Daneshvar, N.; Aghazadeh, F.; and Khataee, A.R., "Application of artificial neural networks for modeling of the treatment of wastewater contaminated with methyl tert-butyl ether (MTBE) by UV/H2O2 process," Journal of Hazardous Materials, 125, 2005, 205-210.

13. Weitkamp, D.E.; Sullivan, R.D.; Swant, T.; and DosSantos, J., "Gas bubble disease in resident fish of the lower Clark Fork River," Transactions of the American Fisheries Society, 132(5), 2003, 865-876.

14. Yang, C.; Xu, Y.R.; Teo, K.C.; Goh, N.K.; Chia, L.S.; and Xie, R.J., "Destruction of organic pollutants in reusable wastewater using advanced oxidation technology," Chemosphere, 59, 2005, 441-445.