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Event-driven model predictive control of sewage pumping stations for sulfide mitigation in sewer networks

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Chemicals such as $Mg(OH)_2$ and iron salts are widely dosed to sewage for mitigating sulfide-induced corrosion and odour problems in sewer networks. The chemical dosing rate is usually not automatically controlled but profiled based on experience of operators, often resulting in over- or under-dosing. Even though on-line control algorithms for chemical dosing in single pipes have been developed recently, network-wide control algorithms are currently not available. The key challenge is that a sewer network is typically wide-spread comprising many interconnected sewer pipes and pumping stations, making network-wide sulfide mitigation with a relatively limited number of dosing points challenging. In this paper, we propose and demonstrate an Event-driven Model Predictive Control (EMPC) methodology, which controls the flows of sewage streams containing the dosed chemical to ensure desirable distribution of the dosed chemical throughout the pipe sections of interests. First of all, a network-state model is proposed to predict the chemical concentration in a network. An EMPC algorithm is then designed to coordinate sewage pumping station operations to ensure desirable chemical distribution in the network. The performance of the proposed control methodology is demonstrated by applying the designed algorithm to a real sewer network simulated with the well-established SeweX model using real sewage flow and characteristics data. The EMPC strategy significantly improved the sulfide mitigation performance with the same chemical consumption, compared to the current practice.

1. Introduction

The production of sulfide in sewer networks by sulfate reducing bacteria (SRB) under anaerobic conditions causes pipe corrosion, health hazards and odour nuisance (Boon, 1995; Hvitved-Jacobsen, 2002). Several strategies are being used by the water industry to minimise the production or emission of hydrogen sulfide (H_2S). Chemical dosing is among the most widely used. Commonly used chemicals include oxygen and nitrate to oxidise sulfide, iron salts to precipitate sulfide, and alkali, such as magnesium hydroxide ($Mg(OH)_2$), to raise sewage pH to reduce the transfer of H_2S from sewage to sewer air (Ganigue et al., 2011).

To date, chemical dosing strategies for sulfide control have been mainly limited to single pipes (Ganigue et al., 2011). This approach is satisfactory if the number of corrosion and odour hot-spots is limited, and/or these are geographically isolated. However, sewer systems are rarely composed of a single pipe but rather exhibit a network structure consisting of interconnected pipes and sewage pumping stations (SPSs), with different flows conveying to main trunks. In this light, if hot-spots are widely distributed within a network, it would be more cost effective to address sulfide control on a network basis. This could lead to fewer dosage stations, less chemical consumption and/or improved sulfide control performance throughout the network. Despite these potential advantages, only a few studies have explored this possibility, which were based on experience rather than an automatic control methodology (Bentzen et al., 1995; Mathioudakis et al., 2006). Liu et al. (2013a,b) demonstrated a simple on-line control algorithm through a case study. While not generically applicable (as it relied on the specific features of a given network), the study clearly demonstrated the potential of achieving network-wide sulfide control through smart control algorithms.

Among the four commonly used chemicals for sulfide control,

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only iron salts and magnesium hydroxide are suitable for network-wide sulfide control. When dosed in a sewer pipe, oxygen and nitrate are quickly consumed, as their consumption is not limited to reactions with sulfide, and hence cannot reach far. In this light, oxygen and nitrate should only be used for local control (Jiang et al., 2009; Liu et al., 2013a,b). In comparison, magnesium hydroxide and iron salts are "conserved" chemicals suitable for network control. Magnesium hydroxide is dosed to raise sewage pH and prevent sulfide transfer from the liquid to the gas phase. $Mg(OH)_2$ is a weak base, and its solubility is affected by the pH of the wastewater, decreasing at more alkaline pHs. Thus, if dosed in excess, pH will increase until the equilibrium point (usually c.a. 9.2) is reached, with the excess remaining undissolved. This surplus will be available for further pH correction if sewage pH acidifies due to in-sewer bio-transformations or the mixing with sewage which had not receiving dosing. In this way, sewage pH can remain at a desirable level (8.5–9.0) (Sharma et al., 2013), if sewage 'mixing' in the network is controlled properly. Iron salts can be used to control sulfide. Fe^{3+} oxidizes sulfide to elemental sulfur while being reduced into Fe^{2+}. Fe^{2+}, either directly added or produced from Fe^{3+} reduction, precipitates with sulfide to form ferrous sulfide (Dohnalek and Fitzpatrick, 1983). While ferric and ferrous ions may interact with other anions such as phosphate and hydroxide, in the presence of sulfide these will become available for sulfide oxidation (Fe^{3+}) and precipitation (Fe^{2+}) due to the lower solubility of FeS in comparison to phosphate- or hydroxide-based iron precipitates at near-neutral pH conditions that are typical for sewage (Zhang et al., 2009). In this way, regardless of where iron salts are dosed, these are always 'conserved' and available for sulfide removal, when sulfide becomes available. For the effective use of both chemicals for network sulfide control, automatic control of the chemical dosing and sewage movement in the network is critical. It should also be highlighted that the stoichiometry of FeS precipitation is affected by both pH and Oxidation Reduction Potential (ORP) of the wastewater. For example, a higher Fe^{2+} to sulfide ratio is needed at lower pH conditions (Firer et al., 2008). Also, the presence of oxygen would lead to the oxidation of Fe^{2+} to Fe^{3+}, consequently changing the reaction stoichiometry. Therefore, different iron salts to sulfide ratios will be required under different pH and ORP conditions.

The development of network-based chemical dosing control is a complex task. First of all, the dosing locations should be selected carefully. In principle, dosing should be conducted in SPSs with relatively large flows. The enables relatively large amounts of chemicals to be carried into the downstream network to achieve more stable sulfide control. The number of dosing points should be determined such that all pipe sections or SPSs with corrosion and odour concerns will have access to sewage streams containing the dosed chemical, thereby enabling network-wide sulfide control. Secondly, sewage flows through the network should be controlled through varying the operation of at least some of the pumping stations to ensure adequate mixing of sewage streams with and without the dosed chemical. Thirdly, the rates of dosing at the selected stations should be controlled to provide adequate amounts of chemicals for sulfide control at downstream locations. Among the three steps, the second step is the most critical. The third step cannot be designed without the ability to manipulate the sewage flows. Similarly, the selection of dosing locations (the first step), while can be done initially based on experience, should be refined after the second and third steps. Therefore, in this paper, we focus on the second step, by assuming known dosing locations and dosing rates at these locations.

Chemical dosing typically occurs at upstream locations of a sewer network with the aim to have hydrogen sulfide controlled when the chemical-containing wastewater streams mixed with other streams not directly receiving chemical dosing, at a downstream location and at a future time. Such a problem would be best addressed through Model-based Predictive Control (MPC). MPC makes use of a set of mathematical models of the considered system to compute the control actions required to minimise an objective function in the future. Originally developed to meet the specialised control needs of power plants and petroleum refineries, the MPC technology can now be found in a wide variety of application areas including chemical, food processing, automotive, and aerospace applications (Qin and Badgwell, 2003; Selot et al., 2008; Bonis et al., 2012; Morales and Flores-Tlacuahuac, 2012). Some early work suggested that this approach could be applied to sewer network (Gelormino and Ricker, 1994).

SPSs are often operated intermittently, with a pump being turned on when the sewage level in the pumping station wet well reaching a pre-defined upper limit and turned off when the sewage level drops to a pre-defined lower limit. Such an intermittent operation makes sewer networks a hybrid system with both continuous and discrete dynamic behaviour. Such a feature challenge traditional MPC control theories, which were developed for either pure continuous systems or pure discrete systems. In the present work, we propose and apply an event-driven model predictive control (EMPC) methodology for the control of sewage flows at SPSs. However, one of the main bottlenecks for implementation of EMPC is the determination of the concentration of the dosed chemical at all locations in the sewer network. For this purpose, we develop a network-state model, which is able to predict such concentrations based on the network geometry and sewage flow data. The flow rates of the sewage entering the network, and consequently the future operation of the SPSs, are in turn predicted using the auto-regressive and moving average (ARMA) models that we previously developed (Chen et al., 2014). The control objective was to keep sewage in the entire sewer network to contain a proper level of the dosed chemical. Achieving this objective ensures that the dosed chemical is available to control sulfide at all locations. This objective is clearly different from that of a traditional MPC, which aims to achieve a tight control of a limited number of controlled variables at pre-defined set-points. The EMPC methodology simply requires some of the pumping stations in the network to hand over the pump operation to the EMPC controller, which would turn on/off the pumps at flexible sewage levels within the upper and lower limits rather than at pre-defined upper and lower levels. The remaining SPSs with fixed-level controllers form disturbance to the EMPC. A simple greedy algorithm was designed to search for optimal control regimes for the controlled SPSs by predicting the sewage flows to each of the SPSs (controlled and uncontrolled) and the pump operations of the uncontrolled SPSs over a prediction horizon. This methodology was validated through a simulation study using a real-life sewer network.

2. Material and methods

2.1. A simple sewer network

An example of a simple sewer network is presented in Fig. 1a to facilitate methodology illustration. In this simple example, the sewer network is divided into 5 different pipe sections and two SPSs. The flows from Pipe 1 and Pipe 5 are fed to Pipe 2, whereas the flow out of Pipe 2 is equally distributed to Pipe 3 and Pipe 4. When SPS1 is turned on (and assuming SPS2 is off), wastewater receiving chemical dosing at SPS1 is pumped into Pipe 1. Simultaneously, the sewage initially in Pipe 1 is pushed into Pipe 2, and the sewage initially in Pipe 2 is pushed, with equal flows, into Pipe 3 and Pipe 4. In a different situation, if SPS2 is also on when SPS1 is turned on, the only difference would be that Pipe 2 receives a mixture of the flows