Evolutionary algorithm enhancement for model predictive control and real-time decision support [☆]

Andrea Zimmer [a, *], Arthur Schmidt [a], Avi Ostfeld [b], Barbara Minsker [a]

[a] Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, United States
[b] Civil and Environmental Engineering, Technion — Israel Institute of Technology, Israel

ABSTRACT

Effective decision support and model predictive control of real-time environmental systems require that evolutionary algorithms operate more efficiently. A suite of model predictive control (MPC) genetic algorithms are developed and tested offline to explore their value for reducing combined sewer overflow (CSO) volumes during real-time use in a deep-tunnel sewer system. MPC approaches include the micro-GA, the probability-based compact GA, and domain-specific GA methods that reduce the number of decision variable values analyzed within the sewer hydraulic model, thus reducing algorithm search space. Minimum fitness and constraint values achieved by all GA approaches, as well as computational times required to reach the minimum values, are compared to large population sizes with long convergence times. Optimization results for a subset of the Chicago combined sewer system indicate that genetic algorithm variations with a coarse decision variable representation, eventually transitioning to the entire range of decision variable values, are best suited to address the CSO control problem. Although diversity-enhancing micro-GAs evaluate a larger search space and exhibit shorter convergence times, these representations do not reach minimum fitness and constraint values. The domain-specific GAs prove to be the most efficient for this case study. Further MPC algorithm developments are suggested to continue advancing computational performance of this important class of problems with dynamic strategies that evolve as the external constraint conditions change.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

With increasing availability of data and information in near-real time, computationally efficient model predictive control (MPC) algorithms are needed to improve real-time management of large-scale, dynamic environmental systems (Maier et al., 2014). MPC (or receding horizon control) involves forecasting the future state of the system for an operational decision window and using a time-varying objective function to identify optimal solutions for the next decision window (Jin and Branke, 2005). This work focuses on a suite of genetic algorithm (GA) MPC approaches and tests their performance in optimizing hydraulics of combined sewer systems, which change rapidly due to shifts in rainfall and their forecasts. In pursuing these objectives, this work also presents new modifications to genetic algorithms that reduce the search space of the problem in order to improve computational efficiency.

Genetic algorithms (Holland, 1975; Goldberg, 1989) are search techniques that identify optimal or near-optimal solutions using operations analogous to natural selection with a population of chromosomes; each chromosome represents a possible solution. Genetic algorithm evolution is based on assembling building blocks, or components, of good solutions (Goldberg, 2002). A GA is implicitly parallel (Goldberg, 1989) because within a population, the GA can process many of these building blocks at the same time. Several different blocks can remain in solution that each represent a subset of a good solution; over time these building blocks are combined into the optimal solution. As a result of utilizing building blocks, GAs prove more efficient than enumeration algorithms (Goldberg, 2002) and avoid the curse of dimensionality encountered in dynamic programming (Michalewicz et al., 1992). Genetic algorithms undergo probability-based selection; the likelihood of an individual to undergo reproduction is a function of its fitness (Goldberg, 1989; Cai et al., 2001). Goldberg (1989) asserts that due

---

to inclusion of crossover, the GA does better than hill-climbing, or local search through incremental changes to the solution. Genetic algorithms are beneficial for solving environmental problems due to their ability to solve nonlinear and discontinuous optimization problems for which gradient-based methods can find only locally optimal solutions (Celeste et al., 2004; Nicklow et al., 2010). GAs also have extensive theory to support effective parameterization (Reed et al., 2000; Minsker, 2005), are easy to connect with non-linear physics-based models, and are widely used. Note that other evolutionary algorithms and non-population based methods could also be used to account for non-linearity within an optimization framework.

GAs have been implemented within MPC frameworks for several environmental applications. Muleta and Nicklow (2005) coupled a genetic algorithm and MPC within the United States Department of Agriculture's Soil and Water Assessment Tool (SWAT) model and an artificial neural network (ANN) to determine optimal crop types for a 3-year planning horizon. Dhar and Datta (2007) minimized the deviation between target and actual reservoir levels in order to control downstream water quality. Celeste et al. (2004) also used GA MPC to optimize reservoir operation releases, while Rauch and Harremoes (1999) applied GA MPC to maximize the mean dissolved oxygen concentration below an urban wastewater system. Additional work has applied GA MPC to a wide range of studies outside the environmental field: operation of an autonomous underwater vehicle (Naeem et al., 2005), a laboratory fermenter (Onnen et al., 1997), and real-time traffic control signals (Lee et al., 2005; Memon and Bullen, 1996). Hu and Chen (2005) apply GA MPC for aircraft arrival sequencing and scheduling.

During MPC, a strategy for the decision (in this case also the forecast) horizon is developed using the simulation model during the first time interval. The first interval of that optimized strategy is implemented while a new forecast is obtained and the next strategy is found. Although MPC approaches offer significant advantage for enabling near-real-time control, the computational demands of applying heuristic algorithms such as GAs using an MPC approach can be daunting, particularly for complex non-linear problems such as combined sewer overflow (CSO) control. To address this problem, a suite of model predictive control genetic algorithms are developed in this work and tested offline to explore their value for reducing computational time to minimize CSO volumes in near-real time. The MPC algorithms assign sluice gate positions and pumping rates that minimize CSO flows and limit high flows that lead to hydraulic instabilities during spatially and temporally variable storm events using a numerical hydraulic model.

This paper explores how MPC GAs computational performance can be improved, as recommended by Maier et al. (2014). Performance is improved by limiting fitness evaluations using the following algorithmic approaches: the micro-GA (Krishnakumar, 1989; Pico and Wainwright, 1994; Coello and Pulido, 2001), the probability-based compact GA (Mininno et al., 2008), memory enhancements specific to MPC (Onnen et al., 1997), and domain-specific methods that reduce the number of decision variables values. The latter approaches were inspired by multiscale GAs developed by Babbar and Minsker (2006) and Sinha and Minsker (2007) and noted by Maier et al. (2014) as important to reducing the search space. All new GA approaches are compared to simple genetic algorithms with larger population sizes determined by GA theory (Reed et al., 2000; Minsker, 2005).

The algorithms are tested on a hydraulic model that simulates flow in a portion of the Chicago combined sewer system and deep tunnel along the northern portion of the Chicago River. The fitness, or objective function value, of a chromosome (set of decision variable values, or real-coded genes) is computed using a hydraulic simulation model (Storage Routing Model, SRM; Zimmer et al., 2013).

2. Case study

This section presents the location of the case study in Chicago where the MPC GA algorithms were tested and information on the storm event used for comparing the algorithms.

2.1. Case study description

The GA MPC algorithms were tested on a portion of the Chicago combined sewer and interceptor system shown in Fig. 1. This section of the system flows to a deep tunnel directly under the North Branch of the Chicago River, which spans approximately eight miles to its junction with the Mainstream system, from which the discharge flows south. Fig. 1 portrays the vertical relationships between the components of three sequential dropshafts (CS-N08, CS-N05, and CS-N02) on the southern portion of the North Branch channel, which are the focus of the optimization, as they link the interceptor and deep tunnel sewers.

North Branch interceptor carries overland and sanitary sewer flows downstream (to the right in Fig. 1), connects to the northward flowing Mainstream interceptors, and then continues north to a pumping station and wastewater treatment plant. This connection is shown as the "Pumping Station Boundary" in Fig. 1. If conduit water levels get sufficiently high as a result of high water inflows and low pumping rates, water flows over weirs (N02, N05, and N08 in Fig. 1) and towards connecting structures. At the connecting structures, flow splits between a sluice gate to the deep tunnel and a CSO point. Sluice gate closures cause water levels to back up and flow to the CSO structure, and thus are critical to the instigation of overflows. Flows that go to the deep tunnel are captured in downstream reservoirs and then later pumped to treatment plants.

In this study, most of the Mainstream system is not included in the numerical SRM simulation in order to reduce computational effort for testing many GA configurations. The link between the smaller sub-system and the larger tunnel system is modeled through deep tunnel boundary conditions, depicted in the inset of Fig. 2. Deep tunnel boundary conditions must be defined for flow coming from upstream as well as water levels in the deep tunnel and downstream of the North Branch interceptor. Upstream flow into the North Branch tunnel, as well as water levels at the intersection of the North Branch and Mainstream tunnels, are interpolated from the results of offline simulations (prior to optimization) using SWMM 5.0 (Rossman, 2010) for the entire TARP deep tunnel system. EPA SWMM 5.0 in this case is used to simulate the effects of the changing boundary conditions and data. In this way, SWMM emulates the effects of a real-life case in which boundary conditions would be known; it is simply used as an "update" as would any observed conditions from this model. This approach was needed because of the lack of data on actual boundary conditions in the Chicago system; ideally a real-time implementation of the approach would use measured data at the boundaries instead.

The graph in Fig. 2 shows the logarithmic interpolation function that is used to interpolate Mainstream tunnel water elevation as a function of flow rate calculated (through optimized decisions) to enter the junction. The interpolation is done between flow points 2 and 1; point 2 represents a limiting low flow condition in which no flow arrives from dropshafts DSN02, DSN05, and DSN08. Point 1 in Fig. 2 represents the limiting high flow condition in which maximum (fully opened gate) flow occurs into the tunnel from DSN02, DSN05, and DSN08. The actual water surface elevation will be somewhere between these two points; coefficients A and B in Fig. 2 are adjusted for the maximum and minimum modeled flow rate and tunnel water elevation estimated by SWMM for each time step.