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Approximate dynamic programming for automated vacuum waste collection systems☆

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A B S T R A C T

The collection and treatment of waste poses a major challenge to modern urban planning, particularly to smart cities. To cope with this problem, a cost-effective alternative to conventional methods is the use of *Automated Vacuum Waste Collection* (AVWC) systems, using air suction on a closed network of underground pipes to transport waste from the drop off points scattered throughout the city to a central collection point. This paper describes and empirically evaluates a novel approach to defining daily operation plans for AVWC systems to improve quality of service, and reduce energy consumption, which represents about 60% of the total operation cost. We model a daily AVWC operation as a Markov decision process, and use Approximate Dynamic Programming techniques (ADP) to obtain optimal operation plans. The experiments, comparing our approach with the current approach implemented in some real-world AVWC systems, show that ADP techniques significantly improve the quality of AVWC operation plans.

1. Introduction

As discussed in (Fernández et al., 2014) a smart city is a city in which information and communications technologies are merged with traditional infrastructures coordinated and integrated using new digital technologies. Awareness has arisen that cities have to develop in a greener and more sustainable way, since they consume the majority of the world resources. Advanced systems to improve and automate processes within a city will play a leading role in smart cities. From smart design of buildings to intelligent control systems the possible improvements enabled by sensing technologies are immense.

The collection and treatment of waste is a major challenge on modern urban planning due to the growth of urban population, as well as to the increasing amount of waste generated on wealthy areas (Eurostat, 2012). The environmental issues related to waste collection are believed to be related primarily to the emission of exhaust gases from the combustion process, noise and odor. In this paper we focus on Automated Vacuum Waste Collection (AVWC) systems, which are a cost-effective alternative to more conventional approaches. AVWC uses air suction on a closed network of underground pipes, to transport waste from the drop off points scattered throughout the city to a central collection point, reducing greenhouse gas emissions and the inconveniences of the conventional method of waste collection (odors, noise, combustion gas emissions, etc.), as well as allowing better waste reuse and recycling (Fernández et al., 2014).

Considering together the different technologies and companies, over 1600 AVWC solutions are under construction or in operation in over 30 countries in Europe, North America, Australia, South East Asia and the Middle East (University Transportation Research Center, 2013). The technology is evolving to give answer to greater areas and to be able to give answer to greater amounts of waste.

The advantages of the AVWC systems over the conventional ones have been widely described. In (Parriaux et al., 2006), a complete study highlighting the potential principal resources for

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underground use (space, water, geothermal energy and geomaterials) that could be used to increase the sustainability of cities is provided. The utilization of subsurface space for waste collection started in the 1960s and since then it has gained interest for an activity that might be difficult, impossible, environmentally undesirable or even less profitable to be installed above ground. The change allows to release valuable surface space for other uses and enhance living conditions (Kaliampakos and Benardos, 2008).

Life cycle analysis (LCA) methodology has been applied to estimate the environmental impact of several waste collection systems and show the benefits of AVWC (Iriarte et al., 2009; Aranda Usón et al., 2011; Wäger et al., 2011; Punkkinen et al., 2012; Usón et al., 2013). From an environmental and functional point of view, the substitution of trucks has a big influence in traffic congestion, accidents, and minimizes noise and CO_2 emissions (Kogler, 2007; Usón et al., 2013). The removal of containers from the streets minimizes hygienic problems as container overload is practically eliminated and odor issues are controlled by the vacuum system.

From an economical point of view, the major advantage of the AVWC system is the reduction in the operational costs for the waste handling. Although greater initial investments are required (Teerioja et al., 2012), in the long term the more economical operation of the system overcomes this disadvantage (Honkio, 2009). In (Kogler, 2007), it is presented a comparison regarding operational and investment costs between door-to-door truck collection and AVWC for a new development. In (Teerioja et al., 2012), it is presented an environmental and cost analysis for the same two systems but focusing on the development in an already built space with dense population and well-established city functions. In (Nakou et al., 2014), it is provided a financial assessment where heavy construction works were required within an already built space in the city. In all cases, the studies demonstrated that AVWC solutions have equivalent performance to conventional collection schemes, and the significantly lower operational costs by the system compensate the initial investment requirements.

The main objective of this paper is to create and evaluate a new method for producing daily operation plans for AVWC systems in such a way that the energy consumption is reduced, and the quality of service is improved.

An AVWC system uses air suction on a closed network of underground pipes to transport waste from the drop off points, scattered throughout the city, to a central collection point. It typically covers an area of a few square kilometers. Among their advantages are the reduction of greenhouse gas emissions, the ability to mitigate the inconveniences of conventional waste collection systems (odors, noise, traffic congestion, …), and the achievement of higher levels of waste reuse and recycling.

AVWC systems are equipped with a control software that produces plans for determining the inlets that should be emptied during a time interval subject to a number of constraints (e.g., full inlets should always be emptied, inlets should be emptied at least once a day, air speed has upper and lower bounds, …). The quality of such plans is decisive for reducing costs in AVWC, and it is particularly important to reduce energy consumption because energy represents about 60 percent of the total operation cost of an AVWC system.

The present work is a continuation of our research on AVWC systems published in (Béjar et al., 2012a, 2012b; Fernández et al., 2014). In (Béjar et al., 2012b), we formally defined the problem of optimizing energy consumption in AVWC systems, describing the system operation, the dynamics (energy and time), and the operative constraints. Later, in (Béjar et al., 2012a; Fernández et al., 2014), we proposed a Constraint Integer Programming (CIP) encoding of the problem in order to take optimal real-time decisions. The proposed CIP-based approach is a single step in the quest for an optimal operation plan over an extended time horizon, typically a day, and was successful in finding optimal, or near optimal solutions, even for large systems. This paper makes a step forward: it presents an original approach to defining operation plans for AVWC systems, modelling a daily AVWC operation as a Markov decision process, and using Approximate Dynamic Programming (ADP) techniques to obtain optimal operation policies. Our proposal is tested against existing solutions by using disposal data of real-world AVWC deployments, and the empirical results obtained show that new operation policies not only improve the quality of service but significantly reduce energy consumption under different scenarios.

The paper is structured as follows. Section 2 contains the model of AVWC systems described in (Fernández et al., 2014), which is included here to make the paper as self contained as possible. Section 3 presents the model of a daily AVWC operation as a Markov decision process. Section 4 describes how ADP is applied for producing good quality, daily operation plans. Section 5 introduces the data used for benchmarking our solution. We present the data from two real-world plants used in the experiments, and the method for generating more synthetic data from real measurements. We also briefly describe the PLC controller algorithm used in real-world plants. Section 6 reports on the empirical investigation, and analyses the results obtained in our experiments. Section 7 concludes the paper and suggests future research directions.

2. Modelling AVWC systems

An AVWC system consists in a tree-shaped pipe network rooted at a central collection point. This central collection point has the means to split the collected waste by fraction (glass, organic refuse, paper, plastics, …), and is where waste is packed for disposal in containers that are then transported with trucks to a landfill area for recycling or performing mechanical biological treatment. The network usually has sector valves located on some of the branch junctions that can isolate one of the branches to reduce the volume of air that will be suctioned. The drop off points are located along the branches, and contain inlets for the different fractions. There are also air valves that act as air entry points that help produce the

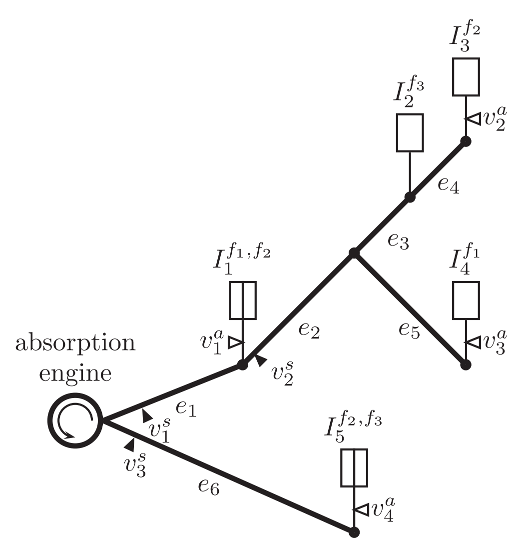

Fig. 1. Schematic example of an automatic vacuum waste collection plant.