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Dynamic UAV-based traffic monitoring under uncertainty as a stochastic arc-inventory routing policy

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ABSTRACT

Given the rapid advances in unmanned aerial vehicles, or drones, and increasing need to monitor at a city level, one of the current research gaps is how to systematically deploy drones over multiple periods. We propose a real-time data-driven approach: we formulate the first deterministic arc-inventory routing problem and derive its stochastic dynamic policy. The policy is expected to be of greatest value in scenarios where uncertainty is highest and costliest, such as city monitoring during major events. The Bellman equation for an approximation of the proposed inventory routing policy is formulated as a selective vehicle routing problem. We propose an approximate dynamic programming algorithm based on Least Squares Monte Carlo simulation to find that policy. The algorithm has been modified so that the least squares dependent variable is defined to be the "expected stock out cost upon the next replenishment". The new algorithm is tested on 30 simulated instances of real time trajectories over 5 time periods of the selective vehicle routing problem to evaluate the proposed policy and algorithm. Computational results on the selected instances show that the algorithm on average outperforms the myopic policy by 23–28%, depending on the parametric design. Further tests are conducted on classic benchmark arc routing problem instances. The 11-link instance gdb19 (Golden et al., 1983) is expanded into a sequential 15-period stochastic dynamic example and used to demonstrate why a naïve static multi-period deployment plan would not be effective in real networks.

Introduction

With the rise of Big Data analytics and urban informatics, there is an increasing interest to gather ever more real time data from a city's environment for real time traffic monitoring (Geroliminis and Daganzo, 2008), travel activity monitoring (Liu et al., 2014; Jiang et al., 2015), or humanitarian logistics (Ozguven and Ozbay, 2015), among others. Numerous monitoring sensor technologies exist for this purpose; some of the more promising among these are mobile sensors that can be deployed autonomously, such as Unmanned Aerial Vehicles (UAVs, i.e. drones) (Chen et al., 2007). For example, UAVs have been demonstrated as feasible tools for gathering real traffic and transportation data (Srinivasan et al., 2004). UAVs can substitute traditional methods for a number of uses in transportation including measuring level of service, average annual daily traffic, intersection operations, parking utilization (Coifman et al., 2006); traffic management (Huiyuan et al., 2007); origin-destination estimation (Braut et al., 2012); and goods delivery as a "flying sidekick" (Murray and Chu, 2015).

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Wu et al. (2016) proposed a cyber-physical sensing and learning framework called ADDSEN to handle drone swarms for urban sensing.

We focus on the traffic monitoring application. In this problem, we assume that traffic segments that have been monitored periodically with UAVs cost less to clear incidents that subsequently occur. A recent deployment of UAVs for traffic monitoring can be seen in Fig. 1, which illustrates the ongoing efforts to use UAVs in this context. The need for monitoring is assumed to be linked to traffic volumes, such that higher volumes would place a larger demand for monitoring. Realistically, however, these volumes will vary randomly over time.

There are few methods of drone deployment for addressing this problem. Kinney et al. (2005) noted that current practice in planning the routes of UAVs typically involves manual calculations. More recent studies sought to address the deployment problem in several ways. Initial studies treated the monitoring problem as a multiple traveling salesman problem (mTSP) with time windows (Ryan et al., 1998; Kinney et al., 2005; Rathinam et al., 2007). Since monitoring entails repeated visits over multiple periods, researchers introduced periodic coverage and timing of mobile sensors over different areas (Cheng et al., 2008; Du et al., 2010), called "sweep coverage" (see Gage (1992)). One study looked at multi-period UAV deployment as a dynamic vehicle routing problem (Bullo et al., 2011), and another as a time-space sensor assignment problem (Zhang et al., 2015).

However, these studies all treat monitoring destinations as nodes in a network. Since UAVs are mobile sensors that can monitor while in motion, it is more appropriate to monitor arcs instead of nodes. One study focused on the arc routing aspect of mobile sensors on infrastructure networks, ensuring that tours visit each critical arc in a network like in a rural postman problem (Sipahioglu et al., 2010). Although UAVs can travel over the air and are not physically restricted to a particular network, flying over uncharted space can lead to obstructions with unknown objects. As such, arc-based traversal over an agency's own known right-of-way makes sense when considering deployment policies. In fact, non-road right of way can be set up as access links that do not need monitoring (by setting the demand for monitoring to be zero for those arcs). The studies above are all static policies. A static policy refers to a deployment plan that does not change, for example using average historical traffic flow data to set fixed periodic deployment routes.

Yazici et al. (2014) extended the arc routing to a dynamic deployment problem where incidents require updating the routes of the autonomous sensors in real time. While these studies considered arc routing, they don't consider look ahead over multiple periods and are thus myopic. A myopic policy refers to a dynamic policy in which the system will adjust their decisions based on current traffic information with no anticipation of future costs. While dynamic, it has been shown in many studies (e.g. Chow and Regan (2011b)) that leaving out look ahead can be very costly, especially in very volatile settings.

In short, there is no one method that considers systematic UAV sensor deployment strategies with (1) arc routing or (2) periodic coverage. No study has considered UAV deployment with (3) uncertainty in demand via an online/dynamic deployment policy.

Three primary contributions are made in this study. First, we propose a new policy under uncertainty to solve this UAV traffic monitoring problem based on arc-inventory routing, where demand for monitoring is distributed over arcs instead of nodes. This is a generalized policy of which UAV deployment is one application. Other applications are also possible: mobile sensors, dynamic postal parcel deliveries, dynamic repairman problem, etc., although further customizations may be needed.

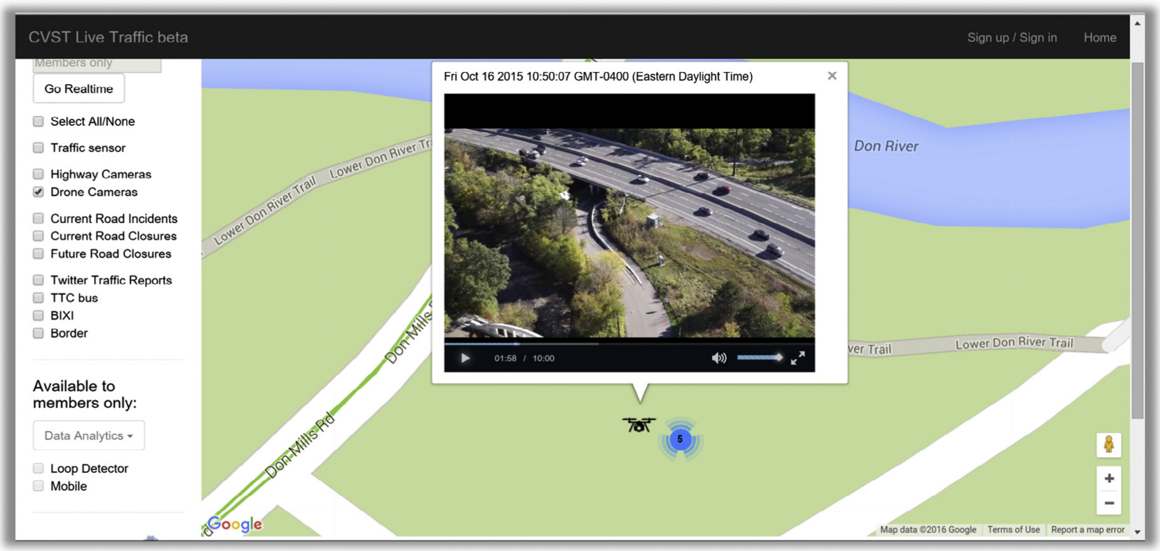

Fig. 1. Traffic data portal from Dr. Al Leon-Garcia's research group at University of Toronto (portal.cvst.ca; accessed Feb 2016).